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Why Manufacturing Digitalization Matters and How Countries Are Supporting It

BY STEPHEN EZELL | APRIL 2018

The digitalization of manufacturing is changing how products are designed, fabricated, used, and serviced, just as it's transforming the operations, processes, and energy footprint of factories and supply chains.

This report explains how digitalization is transforming manufacturing globally, detailing what exactly smart manufacturing (or "Industry 4.0") is and examining the productivity impacts that digitalized manufacturing promises to deliver. The report examines the small- to medium-sized enterprise (SME) manufacturing support programs and policies of ten nations—Argentina, Australia, Austria, Canada, China, Germany, Japan, Korea, the United Kingdom, and the United States—and provides insights countries can leverage to support the digitalization of their manufacturers. The report further examines how the development of common standards can facilitate technology adoption and proposes a typology that helps conceptualize different manufacturing production systems and strategies, showing how these need to be supported by varying digital toolsets.

The Digitalization of Modern Manufacturing

Whether it's called "Industry 4.0," as in Europe, the "Industrial Internet of Things (IIoT)," as in the United States, or just "smart manufacturing," the application of information and communication technology (ICT) to every facet of manufacturing is in the midst of reshaping modern manufacturing.[1] This digitalization of manufacturing is changing how products are designed, fabricated, used, operated, and serviced post-sale, just as it's transforming the operations, processes, and energy footprint of factories and the management of manufacturing supply chains.[2] This convergence of digital technologies with manufacturing industries also promises to recast the landscape of global manufacturing competition.

Smart manufacturing is being driven by the advent and maturation of many technologies, including: high-performance computing (HPC)-powered computer aided design (CAD) and engineering (CAE) software; cloud computing; the Internet of Things; advanced sensor technologies; 3D printing; industrial robotics; data analytics; machine learning; and wireless connectivity that better enables machine-to-machine (M2M) communications.

Amongst the most important of these are the marriage of sensors and software into the Internet of Things (IoT). In the factory environment, IoT refers to the use of sensors in production equipment (such as robots, stampers, actuators, 3D printers, computer numerical control (CNC) machines, etc.), and the products they make (such as jet engines, gas turbines, radiological equipment, vehicles, etc.) to enable a real-time flow of information about the operational status and condition of the equipment or product.[3] With IoT, devices are essentially enriched with "embedded computing" that allows them to interact and communicate with one another.[4] In this way, many of the "Things" in IoT are really sensors embedded within devices, machines, and products that measure everything from output, consumption, wear, load, position, and capacity to salient operating conditions such as temperature, humidity, and electrical flow. IoT will support manufacturing execution systems, warehouse management systems, warehouse control systems, and transportation management systems deployed in shop floors and warehouses.[5] Integrating this information from multiple machines on the plant floor—and then with information from other factories across the production chain, including those of suppliers—can equip manufacturing enterprises with real-time intelligence about their production processes and bestow them with the information needed to make better operational and production decisions. These sensors play a key role in creating the information streams upon which smart manufacturing techniques rely. Over the past decade, the cost of such sensors has declined over a hundredfold, while the number of sensors shipped globally increased from 4.2 billion in 2012 to 23.6 billion in 2014.[6] Such sensors will account for a significant share of the 50 billion "Things" expected to be connected to the Internet by 2020.[7]

The application of IoT is projected to generate $1.2 to $3.7 trillion of value globally by 2025, in four primary forms: 1) operational efficiency; 2) predictive and preventative maintenance; 3) supply chain management; and 4) inventories and logistics.[8] While manufacturers' IoT implementations often address multiple facets of these manufacturing processes, the following paragraphs provide specific examples of IoT being used to facilitate each of these four types of manufacturing processes. Several case studies then follow examining how manufacturers have comprehensively leveraged IoT into their manufacturing systems and go-to-market business models.

Of the four IoT application forms listed above, analysts anticipate the application of IoT to maximize factory floor efficiency will have the largest impact, increasing productivity by as much as 25 percent.[9] There are many compelling examples. For instance, consider General Electric's $170 million manufacturing plant in Schenectady, New York, which makes massive batteries for equipment such as cellphone towers and power plants. More than

10,000 IoT-enabled sensors spread across 180,000 square feet of manufacturing space collect temperature, humidity, air pressure, and machine operating data in real time.[10] This allows GE to monitor production as it occurs and permits process adjustments to be executed on the fly, enhancing production efficiencies and conserving costs. Additionally, battery performance can be traced back to specific batches of raw material at each step of the manufacturing process. GE can thus trace a product's entire genealogy, from containers of dirt, sand, and salt, to a bank of high-tech batteries supporting a nation's electric grid.[11] Likewise, General Motors leverages sensors to monitor humidity conditions while vehicles are being painted; if the environmental conditions are unfavorable, the vehicle or part can be moved elsewhere in the facility or the ventilation systems adjusted as necessary.[12] Similarly, Harley Davidson tracks fan speeds in its motorcycle painting areas and can algorithmically adjust the fans based on environmental fluctuations.[13]

Firms are likely to see significant improvements in operational efficiencies as intelligent devices connect machines on many different factory floors across the supply chain.

Closely related to maximizing a factory's operational efficiency is the application of IoT to facilitate predictive and preventative maintenance; that is, using sensors to monitor machinery in real-time, thus "transforming the maintenance model from one of repair and replace to predict and prevent."[14] For instance, Ford has placed IoT sensors on virtually every piece of production equipment at its River Rouge facility outside Detroit. At Ford, downstream machines can detect if work pieces they receive from an upstream machine deviate in even the minutest dimension from specifications, thereby indicating possible problems in upstream machines that can be immediately identified and fixed.[15] (Indeed, in the future, it's likely that all individual parts and work pieces produced will have a distinct identification code to facilitate this sort of instantaneous detection of faulty inputs.) Similarly, Toyota reduces the time and cost of recalls by knowing exactly which machine produced each component of each vehicle, enabling it to track and isolate the defective part (or defective equipment that produced it) much more rapidly.

Firms are likely to see significant improvements in operational efficiencies as intelligent devices connect machines on all the factory floors across a supply chain. For instance, BMW has set a goal of knowing the real-time status of all major production equipment at each company that produces key components for each of its vehicles. Accordingly, upstream Tier 1 and 2 suppliers such as Austrian brake-pad manufacturer Miba AG have IoT-enabled their production equipment in order to track and communicate production machines' operational status to its original equipment manufacturer (OEM) customers.[16] Germany's automotive manufacturers don't want to receive a call from a supplier informing them a brake pad or engine-part delivery will be late, throwing an entire production cycle off schedule; they want to know in real time of any problems upstream so they can immediately evaluate how production schedules will be affected. This suggests that competitiveness going forward will be increasingly based around the strength of entire industrial supply chains (e.g., OEMs orchestrating their supply chains to maximize efficiency and to most quickly get innovative products to market). Elizabeth Fikes, Proctor & Gamble's (P&G's) director of product supply engineering notes that P&G calls this "synchronization" that speeds time-to-market and observes this has become as important as productivity, cost, and product quality at P&G.[17]

Finally, IoT can facilitate inventory optimization. For instance, Wurth USA, an auto-parts supplier, developed an "iBins" system that leverages intelligent camera technology to monitor the fill level of supply boxes and wirelessly transmit the data to an inventory-management system that automatically reorders supplies as needed.[18] In the future, IoT-enabled autonomous transport vehicles will likely work with consignment robots to zip around the factory floor and automatically find and select proper materials for upcoming production processes, significantly enhancing factory logistics systems.[19]

Manufacturer Case Studies

The following five case studies illustrate how both large and small manufacturers have leveraged IoT solutions to enhance their manufacturing processes and go-to-market business models. These case studies feature Kaeser Kompressoren, HIROTEC, Kuka, Lido Stone Works, and a Rockwell Automation client.

Kaeser Kompressoren

Manufacturers' IoT implementations often impact many facets of their manufacturing processes and go-to-market business models simultaneously. Consider the experience of Kaeser Kompressoren, a German-based manufacturer of compressed air systems and services that enable the downstream manufacturing operations of customers in a variety of sectors including automotive, chemicals, and pharmaceuticals. Kaeser has over 100,000 compressors being actively used by customers. Anytime a compressor goes down it ripples through customers' production systems, grinding them to a halt. To avoid unplanned outages and system downtime, Kaeser began equipping its compressed air equipment with IoT sensors to capture key environmental and performance data such as temperature, humidity, and vibration.[20] With equipment continuously transmitting its operational status in-real time, Kaeser conducts predictive analytics to determine whether parts might be prone to failure, and so can identify and replace faulty parts during regularly scheduled maintenance instead of after an outage has occurred. Kaeser estimates this approach has resulted in a 60 percent reduction in unscheduled equipment downtime as well as an estimated annual savings of $10 million in break-fix costs, as the company can better predict its inventory needs.[21]

But while the ability to track the operational status of its deployed equipment has yielded substantial operating efficiencies, it's also enabled Kaeser to launch an "air-as-a-service" business model in which customers no longer purchase Kaeser compressors but rather lease the compressors and pay for the compressed air used. This benefits Kaeser's customers, who can shift more of their costs from capex to opex (capital to operating expenses) and also track their usage in real-time and manage their consumption more effectively. It also means customers can scale consumption up or down as the needs of their manufacturing operations change, without needing to purchase new compressor equipment. (Kaeser brings or takes away the compressors as a customer's needs evolve.) Kaeser reports that this "air-as-a-service" business model produced a 28.5 percent reduction in compressed air usage for a representative building supplies manufacturer and €30,000 in annual savings for a paint manufacturer.[22] This case study shows how IoT can enhance operational efficiency, improve inventory and supply chain management, and even change a company's business model entirely.

HIROTEC

HIROTEC is a Japanese-based automation manufacturing equipment and auto parts supplier with 26 facilities in nine countries that designs and builds approximately 7 million doors and 5 million exhaust systems annually.[23] The cost of unplanned downtime for automotive OEMs is staggering, estimated at $1.3 million per hour, or $361 per second. As Justin Hester, a senior researcher at HIROTEC's IoT Laboratory, observes, "If it takes a 3 minute phone call to report an issue, you've lost $70,000 just telling someone you have a problem."[24] To address a pattern of "reactive maintenance," HIROTEC sought to develop a competitive strategy to capitalize on the potential benefits of the Internet of Things.[25] It piloted and then built out a cloud-based IoT platform. HIROTEC first IoT-enabled, captured, and analyzed data from eight CNC machines at its Detroit, Michigan plant. It then leveraged the IoT platform to perform remote visualization of an automated exhaust-system inspection line, sensor-enabling inspection robots, force sensors, laser measurement devices, and cameras in order to perform real-time visualization and automatic, paperless report generation for the entire production line of an automobile door production facility.[26] The implementation gave HIROTEC real-time visibility into its business operations and will enable it to leverage machine learning functionality to predict and prevent critical systems failures going forward. HIROTEC reports it has virtually eliminated time devoted to manual inspection of production systems, freeing up workers for more productive, higher-value added assignments. As Hester concludes, "In just six short weeks, we gained more visibility into our operations than we ever had before."[27]

Just outside Detroit, industrial robotics manufacturer Kuka has leveraged IoT to create a highly automated plant making Jeep Wrangler auto bodies.

Kuka

As its plant in Warren, Michigan, just outside Detroit, industrial robotics manufacturer Kuka has leveraged IoT to create a highly automated plant making Jeep Wrangler auto bodies that connects over 60,000 devices, including 259 assembly-line robots, into a central data-management system.[28] By linking the devices, line-of-business applications, and back-end systems together, Kuka has achieved an automated manufacturing process capable of producing one of eight different Jeep Wrangler auto bodies every 77 seconds off the same production line without interrupting production flow. Moreover, all central control tasks and diagnostic processes can be performed directly on robots from the control panel's interface.[29] Kuka believes this automation will enable continuous uptime on the order of 24 hours of production per day for over eight years.

Lido Stone Works

Lido Stone Works, a small, family-run, upstate New York manufacturer of high-end architectural stone products (e.g., stone fireplaces, fountains, floors, etc.) for clients worldwide, wanted to accelerate and streamline design and production of its premium stone products. Seeking to realize a more-automated production environment, it leveraged IoT to craft an intelligent manufacturing system that directly links Lido, engineers at companies like Italy-based Breton (which manufactures the stone-cutting machines Lido uses), and their clients' architects into a seamless, IoT-enabled cloud platform. By IoT-enabling its stone-cutting machines, thus generating a real-time stream of information as the stone is actually being cut, both the client and Breton technicians (located thousands of miles away in Italy) can monitor a job's progress in real-time, detecting, and even fixing, problems as they may unfold. Lido estimates that its IoT-based solution has increased its productivity by 30 percent (largely by reducing downtime), boosted revenues by 70 percent, saved a half-million dollars in travel costs annually, and helped it grow its workforce by 67 percent.[30]

Rockwell Automation

Rockwell Automation, a leading supplier of industrial automation software, has helped numerous clients with smart manufacturing implementations. Manufacturing coffee at scale is challenging, as over time vapors contaminate the machines and they must be taken offline for cleaning. Working with a major coffee manufacturer, Rockwell's IoT solution enabled the client's coffee-production equipment to generate a real-time information stream regarding its operational state. Rockwell found that at any given point about 40 percent of the client's machines were offline, and that as many as 100 extra machines were needed to compensate for the offline equipment to keep production rates steady. Analytics revealed there were significantly different fouling rates between the machines producing caffeinated vs. decaffeinated coffee, and this intelligence enabled the company to more effectively predict downtime and significantly decrease the extent of surplus equipment needed on the production line.[31]

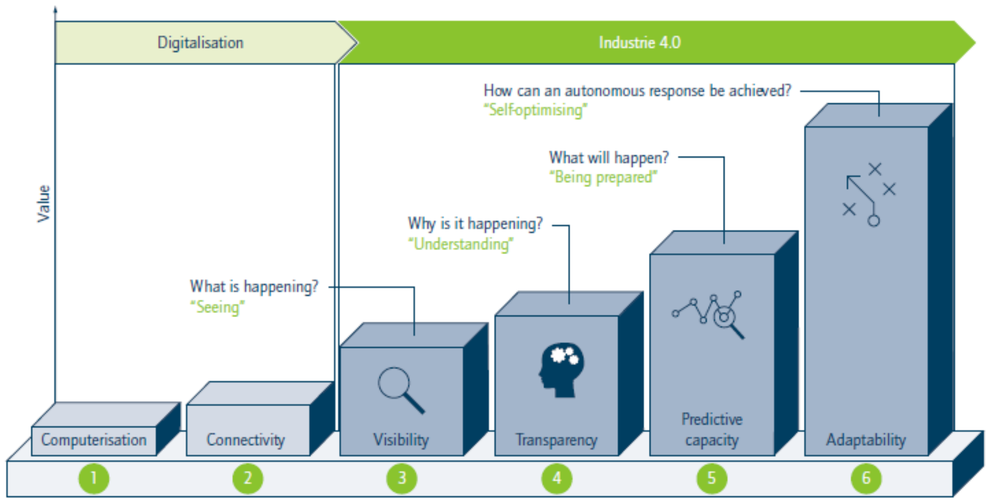
Overcoming the Barriers

The previous case studies demonstrated the potential that digitalization of modern manufacturing portends, but there remains a long way to go before this vision is fully realized across a national (or global) economy. For instance, despite all of smart manufacturing's promise, U.S. manufacturing productivity grew just 1 percent from 2011 to 2016, the slowest recorded rate since 1948 when the statistic was first measured. Similarly, over the past decade (December 2007 to December 2017), U.S. labor productivity grew at an anemic annualized rate of 1.1 percent.[32] Even in Germany, which introduced the term Industry 4.0 into the lexicon, a 2015 survey of 4,500 German SME manufacturers found that less than 20 percent had even heard of Industry 4.0, much less taken steps to implement it.[33] Likewise, a June 2017 survey of 250 U.S. SME manufacturers found 77 percent reporting that they still had no plans to implement IIoT technologies.[34]

In other words, it's still early, and manufacturers large and small alike face a number of hurdles in moving toward realizing smart manufacturing's promise. The SME manufacturers in Sikich's survey cited a lack of awareness, internal expertise, and requisite internal workforce skills to support the digital technologies as the primary reasons for their low rates of IIoT investment.[35] More broadly, IoT still faces interoperability and standardization challenges, and some of the software and technology itself still has bugs and technical issues to be ironed out. Finally, many manufacturers (especially SMEs) simply don't know where to start or how to deploy digital technologies to solve specific business problems in a way that generates a positive return on investment.

Accordingly, one of the most important approaches countries have taken to facilitate smart manufacturing has been to build "how to playbooks" and maturity indices. For instance, America's Digital Manufacturing Design and Innovation Institute (DMDII, one of America's Institutes of Manufacturing Innovation within Manufacturing USA, located in Chicago) is working to develop a "digital playbook," essentially an "on-ramp menu" for small companies that shows them how to start their digital transformation, including assessing the operational challenges the manufacturer faces and analyzing how digital technologies can be deployed to help solve them.[36]

Figure 1: Stages in the Industrie 4.0 Development Path[37]



Graphic Courtesy: FIR e. V. at RWTH Aachen University

Similarly, a key product of Germany's Industry 4.0 efforts has been the identification of over 300 "use cases" of how Germany's manufacturers can digitalize their production processes.[38] Further, Acatech (Germany's Academy of Science and Engineering) has produced an "Industrie 4.0 Maturity Index," which describes a six-stage Industry 4.0 development path that starts with the basic requirements for Industry 4.0 and supports companies throughout their transformation into agile, learning organizations.[39] As Figure 1 shows, the six stages are: Computerization, Connectivity, Visibility, Transparency, Predictive Capacity, and Adaptability. These steps chart the evolution of firm capabilities from simple digitalization (adopting computers and connecting them online) to being able to collect data, to understanding what's happening and why in real-time on the factory floor, to reaching a point of anticipating and predicting (whether for machine fault modes or changes in demand that will affect orders and thus production levels), to self-optimizing factories in which autonomous responses can be achieved. Appropriately, the Industrie 4.0

Maturity Index report approaches manufacturers' transformations from "a technological, organizational, and cultural perspective, focusing on the business processes of manufacturing companies" and notes that organizational and cultural factors are often more difficult to address than the technological ones.[40] That's particularly important, because as a wide range of firm-level research shows, the benefits of digitalization are best realized when digital investments are combined with organizational adjustments.[41]

Productivity Impacts from the Digitalization of Manufacturing

The adoption of new digital manufacturing technologies can generate meaningful productivity impacts for the companies that successfully integrate these technologies into their operations. The following section examines the productivity information available to date. To start, though, it's important to note, as the McKinsey Global Institute (MGI) observes, that the majority of value (80 to 90 percent by some estimates) created in prior industrial revolutions came from replacing old machines with new ones. However, such capex-intensive replacements are expected to account for only about half the value creation with regard to digital manufacturing, as in many cases it'll not necessarily be about replacing existing machines but rather equipping them with sensors that collect and communicate data so those machines can be used more efficiently and productively and so that the enterprises will be equipped with needed information to facilitate better decisionmaking. Thus, even when not linked to machinery replacement, digital technologies will enable productivity gains and new business models.[42]

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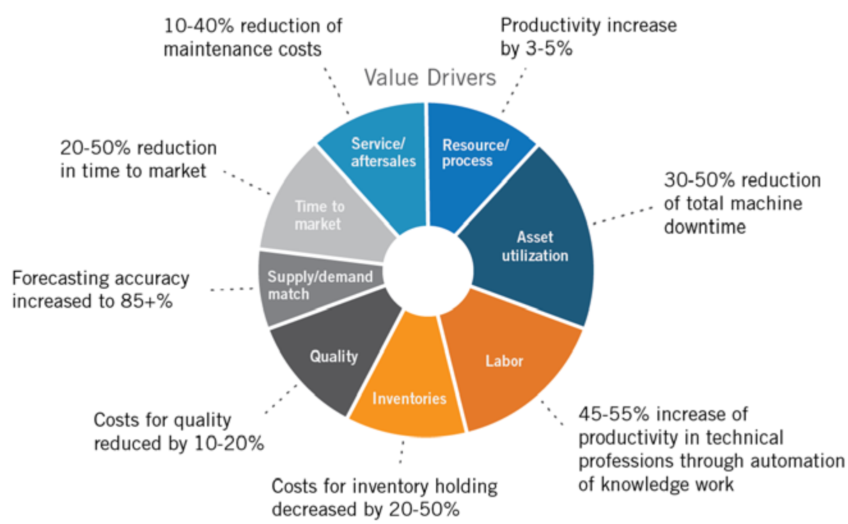
A June, 2015 MGI report, "The Internet of Things: Mapping the Value Beyond the Hype," predicted that the application of the Internet of Things in the manufacturing context alone—in other words, using sensors to bring intelligence to each piece of production equipment on the factory floor to optimize their collective use—would increase manufacturing productivity by 10 to 25 percent, with the potential to create as much as $1.8 trillion in new value per year across the world's factories by 2025.[43] This concords reasonably well with a General Electric report, "Industrial Internet: Pushing the Boundaries of Minds and Machines," which estimated that the Industrial Internet could boost annual U.S. productivity growth by 1 to 1.5 percentage points and add $10 to $15 trillion to global GDP over the next 20 years.[44]

Returning to the MGI report and its analysis of the sources of those productivity gains, it found that value from the application of the Internet of Things in the factory setting would arise chiefly from productivity improvements, including a 10 to 25 percent improvement in labor efficiency and energy savings of 10 to 20 percent.[45] The report also found that the impact of IoT to facilitate predictive and preventive factory equipment maintenance would be an important driver of value. It estimated that IoT would reduce factory equipment maintenance costs by up to 40 percent, reduce equipment downtime by up to 50 percent, extend machine life by 20 to 40 percent, and reduce needed capital equipment investment costs (to replace defective equipment) by 5 percent, generating $630 billion in economic value annually by 2025.[46] As MGI explains, "once machines are interconnected and managed by IoT sensors and actuators, it's possible to improve asset utilization significantly by using auto-sensing equipment to eliminate many of the human and machine errors that reduce productivity."[47] The report further estimated that IoT-enabled inventory-optimization measures could save 20 to 50 percent of factory-inventory carrying costs and that IoT-enabled sensing technologies can be applied to alert or to halt equipment or individuals if they come too close to one another; this could reduce worker injuries in factory environments by 10 to 25 percent, generating savings of as much as $225 billion per year globally by 2025.[48]

Those estimates came from survey-based research in McKinsey's 2015 report "Industry 4.0: How to Navigate Digitization of the Manufacturing Sector." It found that, for existing sites, end-to-end optimization of the "digital thread," (i.e., making better use of information not captured/made available/used today) and eliminating inefficiencies caused by information losses at the interfaces of functions, sites, and companies—all the way from raw materials through to final product delivery—would yield a productivity improvement of as much as 26 percent.[49] That report summarized the predicted productivity benefits from digital manufacturing implementations as shown in Figure 2.

Figure 2: Anticipated Value Drivers from Digital Manufacturing Technology Implementations[50]



The United States' Smart Manufacturing Leadership Coalition (SMLC), a non-profit organization that is building the United States' first Open Smart Manufacturing Platform for collaborative industrial-networked information applications through at-scale demonstrations, estimates that the demand-driven, efficient use of resources and supplies in highly optimized plants leveraging smart manufacturing techniques will lead to a number of benefits, including a:

- 10 percent improvement in overall operating efficiency;
- 25 percent improvement in energy efficiency;
- 25 percent reduction in consumer packaging;
- 25 percent reduction in accidents;
- 40 percent reduction in cycle times; and
- 40 percent reduction in water usage.[51]

Similar findings are being generated around the world. A European Commission report estimates that Industry 4.0 will increase production by 20 percent (while cutting downtime by an estimated 50 percent) and increase total value added from manufacturing to a targeted 20 percent of all value added by 2020.[52] According to Vodafone, companies "adopting the IoT" brings average cost savings for industry of 18 percent, with nearly 10 percent of IoT adopters reducing their costs by over 25 percent, in addition to realizing other benefits including: process efficiencies; speed and agility in decisionmaking; better customer service; consistency of delivery across markets; transparency/predictability of costs; and better performance in new markets.[53] In Japan, one study found that the use of big data and analytics in some divisions of major Japanese manufacturers was lowering maintenance costs by almost ¥5 trillion, corresponding to more than 15 percent of sales in those companies.[54] Similarly, a 2014 Fraunhofer study estimated that the application of Industry 4.0 could boost value-added in Germany's mechanical, electrical, automotive, chemical, agricultural, and ICT sectors by an additional €78 billion, or 15 percent, by 2025.[55] A recent Deutsche Bank report, "Industry 4.0: Huge Potential for Value Creation Waiting to Be Tapped," went further, estimating that, "Thanks to Industry 4.0, German gross value added could well be boosted by a cumulative €267 billion by 2025."[56] For its part, the Boston Consulting Group estimates Industry 4.0 will add 1 percent per year to Germany's GDP from 2015 to 2025, create 390,000 jobs, and spur $250 billion in manufacturing investment.[57]

Companies implementing digital manufacturing are realizing up to 25 percent improvements in productivity and 40 percent faster innovation and time-to-market speeds.

While the above are estimates, McKinsey has subsequently developed a "Digital Compass" diagnostic tool to guide companies in their adoption of Industry 4.0 and has worked with the Digital Manufacturing Design and Innovation Institute to evaluate the actual returns companies are realizing from digital manufacturing implementations. A 2017 study of a client in the refrigeration compressor value chain, which McKinsey/DMDII deemed "emblematic of companies aiming to pursue a "resource productivity and efficiency strategy" found its digital manufacturing implementation to drive an EBIT (earnings before interest and taxes) improvement of 20 to 25 percent.[58] Decomposing the specific sources of value creation from the client's digital implementation, the report found: Increased labor productivity accounted for 5 to 7 percent of the value; their products' speed to market, tailored to customers' individual needs, accounted for 4 to 7 percent; asset utilization of factory equipment accounted for 6 to 15 percent of the value realized; and efficiencies in raw materials and ordering and inventory management accounted for 4 to 5 percent of the value created.[59] In related research DMDII and McKinsey undertook in collaboration with the Product Development and Management Association (PDMA) in 2017, they found that companies deploying digital solutions to speed time to market were improving their product innovation speed by up to 40 percent. Specifically, studied companies were accelerating their "product conception and evaluation" period from ten weeks to five weeks; were reducing their "product design & prototyping" period from 29 weeks to 19 weeks; and were accelerating "product sourcing and manufacturing" timelines from 12 weeks to 6 weeks, thus improving their overall time-to-market speed by 40 percent, from 51 to 30 weeks.[60]

What's attractive about the McKinsey/DMDII data is that it's based on results from actual client implementations, although the results are congruous with positive productivity (and value-added) impact estimates generated elsewhere. As a specific, firm-level example, one U.S. automaker estimated it saved $2 billion in costs from 2011 to 2015 by developing a significant IoT and data analytics capability.[61] The company estimated its greatest savings came from changes in the automaker's supply chain and increased efficiency in working with dealerships, although it also realized significant gains from vehicle designs, including improving the selection of vehicle colors and features and improving their fuel efficiency.[62] The company estimated the investments required to achieve the costs savings ranged from $350 million to $500 million over five years, with about $200 to $300 million allocated to setting up a software-defined architecture to support the data analytics and IoT capability and the remainder to salaries. The company thus estimated its return on investment in the internal IoT and data analytics capability to be somewhere from 300 to 470 percent.[63]

A core benefit of digital manufacturing besides increased productivity on the factory floor is that it bolsters an organization's ability to process intelligence faster.

GE estimates its "Digital Thread"—the connection of data throughout its value stream—generates approximately $700 million in annual productivity gains for the company.[64] For 2016, GE estimates the digital thread produced $510 million in services productivity, $90 million in its manufacturing/supply chain, $70 million from engineering, $30 million for "Cross-thread" (i.e., better connecting across the value chain), and $30 million from commercial applications.[65]

A core benefit of digital manufacturing besides increased productivity on the factory floor (e.g., less machine downtime, faster production processes, etc.) is that it bolsters an organization's ability to process intelligence faster (e.g., flexibly adjusting production and output to correspond to changes in customers' tastes and preferences or to rapid increases or decreases in overall demand). Economists find significant benefits from this type of efficiency as well. For instance, research from the Organization for Economic Cooperation and Development (OECD) finds that leveraging what it calls data-driven innovation—the use of big data to significantly improve products, processes, and organizational methods—raises labor productivity approximately 5 to 10 percent faster than occurs in non-using firms.[66] The research found those firms also perform better in terms of asset utilization, return on equity, and market value. Likewise, a recent study by Branstetter et al. finds that software-oriented manufacturing firms generate more patents per R&D dollar and achieve better valuations of their innovation investments in equity markets.[67] Similarly, Barua, Mani, and Mukherjee suggest that improving data quality and access by 10 percent—that is, presenting data more concisely and consistently across platforms and allowing it to be more easily manipulated—can increase labor productivity by 14 percent on average (albeit with significant cross-industry variations).[68] Brynjolfsson, Hitt, and Kim find that output and productivity in firms that adopt data-driven decision-making are 5 to 6 percent higher than expected given those firms' other investments in ICT.[69] More broadly, ICTs boost labor productivity. For instance, Eden and Gaggl calculate that ICTs accounted for 47 percent of U.S. labor productivity growth from 2000 to 2010 and 35 percent of labor productivity growth from 2010 to 2016.[70]

It should also be noted that robotics represents a digital manufacturing technology that has had sizeable impacts on manufacturing productivity. In "Robots at Work," Graetz and Michaels examined 17 manufacturing industries across 13 countries from 1993 to 2007, finding that robots increased the annual growth of labor productivity and GDP by 0.36 and 0.37 percent per year, respectively.[71] The study further found that robots accounted for 10 percent of GDP growth in studied countries and that productivity in robot-enabled industries in these countries increased by 13.6 percent.[72] As the authors conclude, "For the industries in our sample, robot adoption may indeed have been the main driver of labor productivity growth."[73] They also find that robot densification is associated with increases in both total factor productivity and wages, and reductions in output prices.[74] The authors estimate that industrial robots exerted a greater economic impact over that 14-year period than did the steam engine from 1850 to 1910, a harbinger of the impact the newest generation of far more capable industrial robots—and indeed digital manufacturing technologies more broadly—may have in the future.[75]

Another area where smart manufacturing can yield productivity improvements for manufacturers is in the R&D and design phase, especially as more-collaborative and higher-powered CAD and CAE software as well as web-based innovation management systems are deployed. For instance, a recent McKinsey study found that by using social technologies manufacturers can capture value equivalent to 12 to 15 percent of their R&D costs.[76] The report further found that when manufacturers effectively apply collaborative tools in business-support functions (e.g., hiring, retraining, etc.) they could improve their labor productivity by 10 to 20 percent.[77]

Smart Manufacturing Standards

The development of voluntary, industry-led, consensus-based, market-driven global standards for products and technologies benefits producers and consumers alike. Internationally compatible standards enable businesses to leverage technologies and manufacture products efficiently at economies of scale by reducing the cost that would otherwise be involved in producing specific variations of products to meet different jurisdictions' standards.[78]

Unfortunately, some nations are increasingly using mandatory standards as a mercantilist tool to block or limit foreign companies' access to their markets and to support domestic industries, especially ICT industries.[79] By imposing unfair standards-related measures on imports, foreign governments may game the international trading system on behalf of their domestic industries and impose additional costs that both harm consumers as well as a country's own competitiveness in digital sectors. The OECD estimates that complying with country-specific technical standards can add as much as 10 percent to the cost of an imported product.[80] It's therefore important that countries avoid isolated, proprietary standards and siloed solutions and that policymakers encourage the use of globally relevant standards for ICTs, including those applied to digital manufacturing.

If the smart manufacturing vision is to succeed, a series of standard protocols will be indispensable to allow factories, machines, and products made by vendors from all over the world to communicate and interact with each other and to ensure solutions can be used in any country.[81] As the excellent report "Industrie 4.0 in a Global Context: Strategies for Cooperating with International Partners explains, "individual modules, components, devices, production lines, robots, machines, sensors, catalogues, directories, systems, databases, and applications will need common standards for the connections between them and the overall semantics, or how data gets seamlessly passed from one device to another."[82] Thus, standardization of architectures, data exchange formats, vocabularies, taxonomies, ontologies, and interfaces will be key to creating interoperability between different digital manufacturing technologies.

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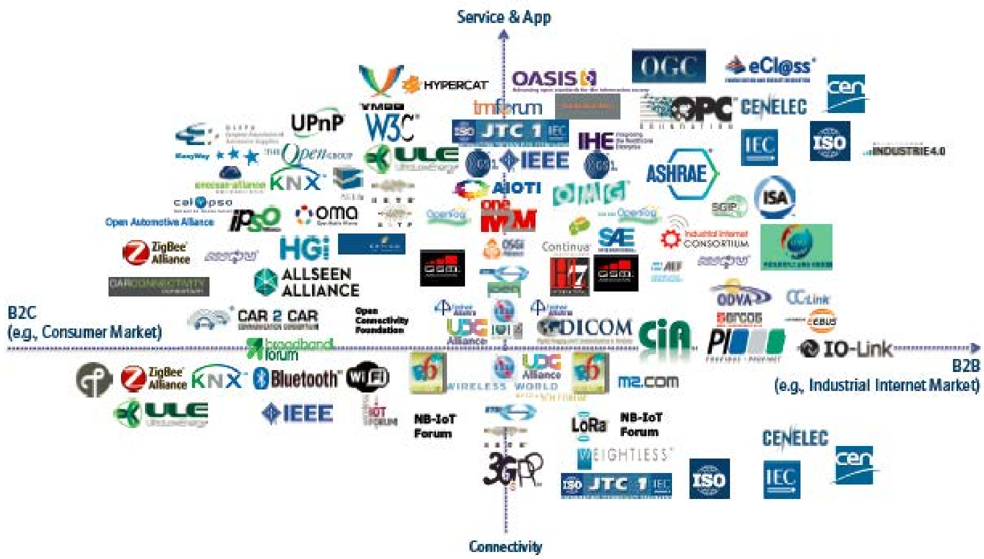
Accordingly, as the same report notes, the two key issues standardization must address are ensuring interoperable interfaces between solutions from different manufacturers; and establishing open standards, which are essential for the emergence of open, flexible, and successful ecosystems spanning not only different manufacturers but also different countries and continents.[83] The authors note that, "whoever is first to define such internationally accepted standards will likely gain a long-term competitive advantage."[84]

A number of risks arise if the international community fails to achieve standardization around Industry 4.0. First, the inability of sensors, machines, and software produced by a variety of different global vendors to seamlessly exchange data, information, and intelligence in real-time would leave the smart manufacturing vision stillborn. Moreover, if no international standards or universal solutions exist to provide interoperability between different systems, individual companies run the risk of suffering technological lock-in. This in particular affects SMEs, which may be reticent to make the requisite investments in Industry 4.0 technologies or systems, fearing that if they acquire proprietary standalone or siloed solutions they could become dependent on the technology of one particular supplier.[85]

The international competition with regard to the establishment of norms and standards for Industry 4.0 actually means that close cooperation will be required between businesses and institutions.[86] As Figure 3 shows, more than 100 different standardization initiatives currently exist for the Internet of Things and Industry 4.0. As Figure 3 also shows, some of these organizations are more involved in the business to consumer (B2C) and others in the business to business (B2B) dimension, while still others focus on underlying connectivity or the application layer. Some, like the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), and their joint initiative JTC1, which focuses on integrating diverse and complex ICT technologies, are active across the entire spectrum.[87] One important overarching initiative is the World Wide Web Consortium's (W3C's) Web of Things initiative, which seeks to establish a "cross-domain technology stack," with a goal to describe "connected things" using "thing descriptions" and enable them to be addressed interoperably via standard protocols.[88]

Figure 3: Standards Organizations Involved in Developing the Internet of Things and Industry 4.0[89]



Graphic Courtesy: The Alliance for Internet of Things Innovation

The following provides a brief overview of countries' smart manufacturing (i.e., Industry 4.0) standards-development environments and approaches.

United States

In general, the United States has approached the development of smart manufacturing standards just as it has with regard to other ICTs, which is to say favoring a voluntary, industry (or industry consortia)-led, consensus-based, market-driven approach.[90] This approach favors a role where government agencies participate in the standards-making process by being invited to the table and bringing their expertise, needs, concerns, and requirements but not by overtly directing the standards-development process.[91] The United States has been described as taking a "pragmatic, implementation-oriented approach" to developing smart manufacturing standards.[92]

Several key private-sector-led consortia are involved in smart manufacturing standards development in the United States, chief among them the Industrial Internet Consortium (IIC).[93] The IIC spans a number of fields including energy, healthcare, manufacturing, the public sector, and transportation. The IIC has two key objectives: 1) Promoting innovation through the establishment of use cases and testbeds to enable rapid testing of ideas and technologies in real-world applications; and 2) Facilitating the development of the reference architectures, frameworks, and open standards required for the interoperability of industrial systems.[94]

Also involved is the Smart Manufacturing Leadership Coalition (SMLC), which is building America's first Open Smart Manufacturing Platform for collaborative industrial-networked information applications through at-scale demonstrations.[95] SMLC's mission is to enable manufacturing companies of all sizes to gain easy, affordable access to modeling and analytical technologies that can be tailored to meet cross-industry business-case objectives without having to retrofit existing systems. Among SMLC's key missions are establishing industry test beds for smart manufacturing applications and developing a standards-based reference architecture.

Another important player is the Association for Manufacturing Technology (AMT), which has supported the development of MT Connect, a free, open standard that enables manufacturing equipment to provide structured, contextualized data with no proprietary format.[96] Essentially, MT Connect provides a semantic dictionary, such that when data comes off of a piece of machinery or sensor package (particularly in discrete manufacturing environments) the standard defines the data and gives it meaning, structuring it to go forward to something else, whether that's a robot, material handler, Excel spreadsheet, Web-based dashboard, etc.[97] Thus, MTConnect provides domain-specific vocabulary and data models in the context of a scalable system architecture. MT Connect is a practicable, operational smart manufacturing technology standard that is presently being used by manufacturers from the United States to Europe Brazil and China.

Rather than regarding each other as competitors, the various consortia that exist in the United States view the development of smart manufacturing standards as a collective endeavor.

It should be noted that rather than regarding each other as competitors, the various consortia that exist in the United States view the development of smart manufacturing standards as a collective endeavor.[98] The American approach is perceived as likelier than others to provide quicker and less-complicated solutions that can quickly and pragmatically demonstrate the value added offered by smart manufacturing.[99] It should also be noted that the American National Standards Institute (ANSI) plays an important role in overseeing how standards are developed by individual U.S. industry sectors. ANSI harmonizes the standards across sectors to ensure that there is consistency from a U.S. point of view and helps communicate these standards to the international community.[100]

Germany

A top-down approach to Industry 4.0 (and Industry 4.0 standardization) predominates in Germany, led by government, pioneering companies, and academia.[101] Overall, Germany's key initiative is Plattform Industrie 4.0, which develops joint recommendations for all stakeholders and serves as the basis for a consistent and reliable Industry 4.0 framework. The platform was originally created by the business associations BITKOM, VDMA, and ZVEI but in 2015 the program was expanded and is today steered by Germany's Federal Ministry for Economic Affairs and Energy and Federal Ministry of Education and Research as well as high-ranking representatives from industry, science, and trade unions.[102] More than 300 players from 159 government (state and federal), business, science, association, and union organizations participate in Plattform Industrie 4.0.[103] The platform aims to identify all relevant trends and developments in the manufacturing sector and to combine them to produce a common overall understanding of Industrie 4.0.

Plattform Industrie 4.0 supported development of The Reference Architectural Model for Industrie 4.0 (RAMI), essentially Germany's guide to Industry 4.0 standards and interoperability, which centers on a three-dimensional map showing how control devices, production equipment, field devices, etc. can interconnect and communicate data to one another.[104] RAMI endeavors to combine all elements and IT components in a "layers and life-cycle model" and to break down complex processes into easy-to-grasp packages related to data transmission, data privacy, and IT security.[105] Work is being done to ensure that Plattform Industrie 4.0's RAMI is compatible with America's Industrial Internet Consortium's IIRA (Industrial Internet Reference Architecture).

Compared to other countries, the German approach to Industry 4.0 standards development has been characterized by a strong focus on technology, whereas less attention has been paid to commercial factors and opportunities such as new business models and smart products.[106] An international survey of stakeholders in Industry 4.0 standards development found that "while expectations regarding reference architectures and standard programming interfaces (APIs) are significantly higher, the speed of standardization is rated much more negatively in Germany than in other countries."[107] The risk for Germany is that, while its standards-development process is intensely rigorous, comprehensive, and inclusive, it may take too long, such that by the time the standard is set the technology and the market have moved on to something better.

Germany essentially wants to create a center of gravity in Industry 4.0 standards development.[108] It has worked hard to internationalize its standards, including recently forging a trilateral cooperation that seeks to bring together the key digitalizing manufacturing initiatives of France, Germany, and Italy—France's Alliance Industrie du Futur, Germany's Plattform Industrie 4.0, and the Italian initiative Piano Industria 4.0—and collaborate on three core subjects of shared interest: standardization, engagement of SMEs, and testbed development.[109] Finally, Germany wants to "use China as a multiplier for German standards", implementing German beta standards into Sino-German cooperation initiatives in order to improve their chances of being adopted on the global market.[110]

China

China's standards-development activities are characterized by a strong top-down approach that is principally driven by government actors (although representatives of business and academia are also involved).[111] China's institutions of standardization place the state at the center—making China's government the initiator, financer, and leader of most standardization projects.[112] China has made the development of indigenous technology standards a central component of its technological upgrading and economic development strategies, seeking to use home-grown standards as a way to gain competitive advantage.[113] As part of this effort, China has committed to developing unique national standards in dozens of high-technology areas, even where international standards already exist.[114] For instance, China has adopted or sought to develop unique Chinese standards across a wide range of ICTs, including Internet protocols, mobile telephony, wireless local area networks, digital video players, audio-visual codec standards, home networking, radio frequency identification technology, encryption, software asset management, mobile TV, mobile phone charging, and the Internet of Things.[115] A core component of China's strategy is to remove or change key portions of international standards for the purpose of creating China-unique standards.[116] China has developed many of these standards without international consensus and with limited foreign input.

With regard to smart manufacturing, China's Made in China 2025 initiative clearly calls for the country to develop its own smart manufacturing standards, which have the potential to be trade-distorting. Under Made in China 2025 smart manufacturing products may be required to meet vague and undefined standards.[117] For instance, in 2015 and 2016, China's Ministry of Industry and Information Technology (MIIT) issued separate notices for "Smart Manufacturing Pilot Demonstrations" that call for "indigenous and secure and controllable equipment and software."[118] In 2016, MIIT and China's National Development and Reform Commission (NDRC) issued a three-year plan on the smart hardware industry calling for a "secure and reliable" framework and platform from cloud to end user. And China's "2016-2020 Informatization and Industrial Development Strategy" calls for "secure and controllable" industrial infrastructure hardware and software, high-end industry application software, embedded systems, new industrial application platforms, and industrial Internet network equipment. It further recommends "establishing testing services" to verify a product's compliance with standards and security and reliability. This, combined with China's "secure and controllable" requirements for all important network products and services purchased for networks and information systems that are pertinent to "national security," suggests that China is laying the groundwork for further development of its own "Industry 4.0" standards that meet its own internal "secure and controllable" standards.[119]

China's Made in China 2025 initiative clearly calls for the country to develop its own smart manufacturing standards, which have the potential to be trade-distorting.

Thus, it appears clear that, over the long-term, China intends to develop distinct technical standards for Industry 4.0. However, China is also pragmatic; it recognizes that much of the advanced production equipment and machine tools it needs to underpin its manufacturing-led economy are currently produced elsewhere, so in the near-term it needs to ensure interoperability with existing machines, whether produced in China or elsewhere. It's been an eager adopter of MT Connect and in August 2015 launched Sino-German intergovernmental consultations between China's MIIT and Germany's Federal Ministry for Economic Affairs and Energy to collaborate on various facets of Industry 4.0, including standards development.[120] In summary, China appears to be playing a short and a long game with smart manufacturing standards development: collaborating now where necessary, but in the background developing standards for the future that are designed to give Chinese manufacturers strategic advantage.

Japan

The Japanese government, in collaboration with various private business initiatives, is driving smart manufacturing standardization. Like Germany's, Japan's standardization strategy is largely based on a top-down approach where the overall direction is determined by government together with a handful of researchers and pioneering thinkers. However, there are also some initiatives (e.g., IVI, e-F@ctory, and Industry 4.1J) that have adopted a bottoms-up approach and concentrate on the concerns of the research community or industry. In particular, Japan's Industrial Value Chains Initiative (IVI) attaches particular importance to the concept of "loose coupling," promoting a modular approach instead of a single Industry 4.0 standard.[121] Many Japanese companies (though particularly SMEs) have stated a disinclination to tie themselves to commercial products from a single supplier, due to fear of technology lock-in, explaining why "many Japanese companies have been reluctant to invest in Industry 4.0 because of the lack of standards."[122] Japan regards it as particularly important to lead in the development of standards for robotics.[123] As it develops smart manufacturing standards, it will be important that Japan avoid the "Galapagos Island Syndrome," which historically has seen many of the country's ICT enterprises develop quite advanced ICT products based on unique standards that were isolated from global markets, which made it difficult for Japanese companies to bring their products to international markets.[124]

South Korea

South Korea's standardization agency, KATS (the Korean Agency for Technology and Standards), has tended to pursue a bottoms-up standards-development approach, working closely with industry to ensure that its standardization activities mainly benefit national suppliers.[125] South Korea's government and industry have called for rapid standardization solutions to enable interoperability. Korean government agencies, including the South Korean Ministry of Trade, Industry, and Energy (MOTIE); the South Korean Ministry of Science, ICT, and Future Planning (MISP); the Korean National IT Promotion Agency (IIPT); and the Korea Institute for Industrial Economics and Trade (KIET) have been keen to engage in international cooperation and dialogue and to involve the private sector in Industry 4.0 standards setting.[126] Ensuring interoperability, both nationally and internationally, and especially for SMEs, has been a touchstone of the South Korean smart manufacturing standards development approach.[127]

Typology of Manufacturing Production Approaches, Systems, and Strategies

Virtually all manufacturers desire to boost productivity, decrease costs, and increase revenues. The factors that most affect/motivate technology investments in different industries are not exclusively sector-specific, but also pertain to the dynamics of enterprises' production systems and strategies, cost dynamics, go-to-market strategies, and business/operational environments. This perspective notes that many of the most significant applications of smart manufacturing—such as predictive maintenance, operations optimization, or inventory optimization—will accrue to manufacturers whether they measure their output by the unit or by the gallon; that is, by whether they compete in batch vs. continuous or discrete vs. process manufacturing sectors. In other words, whether a piece of equipment on the factory floor is helping manufacture a discrete aircraft or vehicle or brewing beer or processing oil and gas, the IoT-enabling of equipment to facilitate real-time communication of their operational status, detect faults, avoid downtime, etc. will be equally relevant in all types of manufacturing environment. In other words, IoT-enabled manufacturing execution systems, inventory management systems, asset management systems, or transportation management systems deployed on shop floors, or in warehouses, and vehicles will be equally relevant across manufacturing sectors.[128]

Table 1: Share Within U.S. Manufacturing Industry Cohort Investing in Automation Technologies in Five Years Before or Three Years After December 2015[129]

	Prior 5 Years	Coming 3 Years		Prior 5 Years	Coming 3 Years
Food, Beverage, and Tobacco	81%	77%	Nonmetallic Mineral Products	89%	89%
Textile Mills and Textile Product Mills	94%	86%	Primary Metals	87%	89%
Apparel, Leather, and Allied Products	88%	78%	Fabricated Metal Products	91%	75%
Wood Product	87%	85%	Machinery	90%	79%
Paper Products	94%	77%	Computer and Electronic Products	89%	80%
Printing and Related Support Activities	90%	78%	Electrical Equipment, Appliances, and Components	98%	91%
Petroleum and Coal Products	90%	87%	Transportation Equipment	83%	77%
Chemical Products	81%	85%	Furniture and Related Products	100%	86%
Plastics and Rubber Products	92%	83%	Other	71%	59%

Table Courtesy: Waldman, Manufacturers Productivity and Innovation Alliance (MAPI)

One reason why a non-industry-specific framework might be preferable is that a recent survey of 402 U.S. manufacturers revealed that there's no significant evidence of different levels of "automation investment" across major manufacturing subsectors.[130] (The study asked about manufacturers' investments whose intent was to "automate any aspect of your product-producing process through labor enhancement, labor substitution, or both.")[131] As the 2015 report from the Manufacturers Alliance for Productivity and Innovation (MAPI), "Automation Investment in U.S. Manufacturing: An Empirical Picture" found (and Table 1 shows), "Automation activity appears to be widespread across industries—not the high-productivity industries and not the low-productivity industries—but across all industries."[132] The research revealed that global macroeconomic pressures affecting every manufacturing industry had a larger catalyzing effect on manufacturers' automation investment than more industry-specific factors.[133]

To the extent there are differences between firms it appears to be based more on size, rather than industry or type of production process. Indeed, the MAPI survey found that "automation activity is a function of increasing firm size." Specifically, whereas 97 percent of manufacturers with over $10 billion in sales and 91 percent of manufacturers with sales of $1 billion to $10 billion had engaged in automation investment from 2010 to 2015, 79 percent of manufacturers with revenues of $200 million to $1 billion and 74 percent of manufacturers with less than $200 million in revenues had done so.[134] (Ten percent of firms in the study had revenues greater than $10 billion, 33 percent of the firms had revenues of $1 billion to $10 billion, 29 percent of the firms had revenues from $200 million to $1 billion, and 28 percent of the firms had revenues less than $200 million.)[135]

As the MAPI report notes, the mid-sized manufacturers' high levels of automation likely result from supply chain pressures, as suggested by the fact that the top-five drivers of automation investment by surveyed U.S. manufacturers over the prior five years included: "use by our competitors" (ranked the leading driver of investment), "use by our customers" (second), and "use by suppliers" (fifth).[136] (The third and fourth were "credible evidence of impact on product quality" and "Credible evidence of impact on workforce productivity," respectively.) In other words, mid-sized manufacturers' adoption of automation technologies seems principally driven by supply chain pressures and competitive forces.

Small manufacturers in the United States continue to lag with regard to IIoT adoption.

Yet small manufacturers in the United States continue to lag with regard to IIoT adoption. As noted, the "Sikich 2017 Manufacturing Report" surveyed 250 U.S. SME manufacturers, of which 23 percent had revenues less than $10 million, 24 percent revenues of $10 to $20 million, just under 29 percent revenues of $20 to 50 million, and 25 percent revenues from $50 to $200 million.[137] Of these SME manufacturers, 77 percent reported they still had no plans to implement IIoT technologies.[138] (These manufacturers were also investing relatively little in R&D, with 78 percent of the surveyed manufacturers reporting investments of less than 5 percent of sales.)[139] The SME manufacturers surveyed cited a lack of internal expertise and a lack of internal workforce skills to support the digital technologies as the primary reasons for their low rates of IoT investment.[140]

But if sector mix and firm size aren't the only guides to manufacturers' technology adoption levels, what other unique factors drive manufacturers' adoption of new technologies? The following lays out several explanatory factors, including: 1) production volume and mix; 2) production strategy; 3) extent of supply-chain technology adoption; 4) go-to-market business model; 5) extent of industry regulation; and 6) input costs.[141]

1. **Production Volume and Mix:**
   A. **High-Volume / Low-Mix Manufacturers (i.e., "Mass Production")** These are manufacturers that crank out thousands of units of the same product, with very low variability: for instance, packaged goods industries making razors or diapers, or products like strip steel and packaged milk. These manufacturers are interested in robotics and related automation technologies because they desire shaving milliseconds off cycle times and ensuring repeatability. Such manufacturers need sophisticated Manufacturing Execution Systems (MES) to control operations on the factory floor. This is the scenario that comes to mind where we envision Industry 4.0/Smart Manufacturing: highly automated factories with machines "talking" to each other, adapting to disruptions, optimizing their performance, etc.

A good example is Procter & Gamble, whose diaper-manufacturing factories produce 1,000 diapers per minute, with high-speed converters integrating 30 different materials (including elastics, cuffs, non-wovens, absorbent gel materials, etc.). P&G needs to detect anomalies in milliseconds, so it uses cameras, sensors, and digital imaging to perform 15 to 20 quality checks on every single diaper. As Elizabeth Fikes, P&G's director of product supply engineering, notes, P&G fully integrates product and process innovation: they innovate the product, which drives the process transformations, which drives the (internal) design of the high-speed converters, and subsequently the process controls.[142] Fikes further notes that while of course productivity, cost, and revenues have always been key touchstones, P&G has become increasingly focused on time-to-market and what the company calls "synchronization." She notes that while customers have always wanted high-quality, competitively priced products, now they also want them on their time terms (e.g., overnight delivery, or even delivery within hours). P&G now operates 25 plants across the United States—and insists upon synchronization with its suppliers, most of which are situated close to regional plants—because time-to-market has become an increasingly important aspect of its business.[143]

B. **Low-Volume / High-Mix Manufacturers:** These manufacturers produce low-volume, highly customizable products, and are particularly interested in the application of technologies to facilitate production flexibility and economical shifts from producing one stock-keeping unit (SKU) to another. An example would be a manufacturer of prosthetic limbs. Digital manufacturing technologies (e.g., CNC, CAM, 3D printing) are key to this. Automation is less critical in these environments because volumes are low. Reflecting this, as a recent National Institute of Standards and Technology (NIST) report, "Costs and Cost Effectiveness of Additive Manufacturing," observes, additive production still only makes economic sense for production runs of a few thousand units (in part because the equipment to automate a plant is expensive, as is configuring the equipment to its optimal level.)[144]

C. **High-Volume / High-Mix Manufacturers: (i.e., "Mass Customization")** The convergence of digital technologies and manufacturing increasingly enables a third dimension to be added to the "volume-mix" paradigm: a high-volume, high-mix approach. When Tesla opened its Freemont, California plant, its production line could make only one model of vehicle (e.g., sedan vs. SUV). Now, Tesla has automated its production system to the extent that robots and workers can dynamically adjust to produce a sedan or an SUV as it rolls down the line, of course with the specific features a customer has pre-ordered. (Toyota had initially pioneered such a flexible manufacturing system in the early 2000s with its Global Body Line (GBL) approach, a common vehicle-assembly platform that allowed plants worldwide to work on multiple auto body types on production lines.)[145] Advanced manufacturing technology has long enabled more flexible production, and current innovations move closer to an era of mass customization, in which enterprises can produce one-off products (or, more accurately, customized versions of them) at scale, deploying the full panoply of digital technologies: ERP and MES to facilitate tailored customer orders; robotic automation on the production line; and IoT deployed in production equipment on the factory floor to facilitate machine-to-machine communication, ensure the production line is operating optimally, and communicate production status to the MES and back to the ERP so customers can actually track the progress of their order as it rolls down the production line.

2. **Production Strategy:** This recognizes that manufacturers (*even if in the same industry sector)* may use different production strategies, because either they are fielding different business models or because they have different market segmentation. There are four types of production strategy:

    A. **Engineered-to-Order (ETO):** The highest level of customization possible: products are *designed* (i.e., engineered) specifically for a customer and are typically produced in low volumes. An example might be structural materials produced for a new bridge. This requires a tight integration between sales, engineering, and manufacturing disciplines (as well as tools). Product development looks more like a project, so collaboration technologies are key (e.g., amongst customer, engineers, manufacturers, supply chain, etc.).

    B. **Make-to-Order (MTO) / Build-to-Order (BTO) / Assemble-to-Order (ATO):** Products are made, built, or assembled only when a customer order comes in. For example, a clothing manufacturing might produce made-to-order clothing. These manufacturers need tight integration between their sales (CRM, Configure-Price-Quote) and ERP systems to achieve the responsiveness needed to satisfy orders.

    C. **Make-to-Stock (MTS):** Typical of high-volume production. Manufacturer estimates how much of a product to manufacture, manufactures in bulk, and either ships the product to customers on a regular basis or shelves the product (e.g., at a retailer or warehouse) until the products are purchased by customers. These manufacturers need more technologies that help forecast demand and optimize inventories and supply chains.

    D. **Standard-Manufactured Upon Order:** A blend of the previous two production strategies. Consider how Dow Corning built a new business model, Xiameter, to sell silicone (which was increasingly becoming a commodity) to lower-margin, price-driven, smaller customers without cannibalizing sales to existing high-end customers.[146] With Xiameter, selection and order size were standardized and limited, customers had to accept that their order wouldn't be produced until after it was placed (enabling Dow Corning to cut standing inventory costs), all sales would be online, credit terms would be fixed, and the price of each order would be set by the spot market, not negotiated in advance. The Xiameter business model allowed the company to capture a low-margin segment it had previously ignored, increased demand for silicone products, and drove up prices (which in turn increased profits for Dow Corning as a whole). Moreover, new orders facilitated better use of underutilized manufacturing capacity, allowing Dow Corning to earn its investment back in just three months.[147]

3. **Extent of technology adoption in the supply chains:** Technology adoption among smaller and mid-sized firms will depend in part on the extent they sell to other firms or final customers; and to the extent suppliers exert pressure for modernization. More networked, deeply layered manufacturing sectors (i.e., aerospace/automotive) will thus likely experience greater levels of technology adoption, because supply chain pressures are stronger, as suggested by the prior example of BMW and Miba AG in Germany/Austria's automotive supply chain.

4. **Go-to-market business model: Subscription model or arms-length product sale?** A small, but increasing, number of manufacturers are moving to a "products-as-a-service" (or subscription-based) business model. Kaeser Kompressoren's compressed-air-as-a-service business model or Rolls Royce's jet engines "Power by the Hour" (i.e., selling airlines guaranteed thrust instead of a jet engine) are examples. Even if the business model doesn't change, many manufacturers of equipment (e.g., industrial equipment, turbines, vehicles, etc.) are being pressured to deliver after-market services such as predictive maintenance, monitoring, and performance optimization. Embedding IoT *in these products* is often indispensable to making the business model possible, but a number of companies have found that as they deploy the "*infostructure"* to support these types of business models—e.g., including cloud computing, wireless networking, machine intelligence, data analytics, etc.—that they've now enabled the application of IoT-based solutions *within* their factories as well (e.g., predictive analytics for production equipment failure modes). In other words, as they move from a world of selling products at arm's length to marketing subscription and services-based business models, their technology needs may also drive application of smart-manufacturing practices within their production environment.

5. **Level of regulation:** Many manufacturers in heavily regulated industries—such as aerospace, defense, medical/pharmaceutical, chemicals—have found that maintaining a digital thread of the product's information throughout its lifecycle is critical to quick and economical response to audits, certifications, recalls, etc. In other words, the need to understand who designed a product and its parts, which machine(s) created them, in which factories, where they are deployed or located in the field, etc. has become a key driver of smart-manufacturing technology adoption in these industries.

6. **Cost of inputs, notably for labor and energy:** The high cost of labor makes the deployment of automation and other smart-manufacturing technologies increasingly attractive in high-wage industries (and nations). And for energy-intensive manufacturing processes, or in regions where energy is expensive, manufacturers are particularly incentivized to look for technologies to reduce the use of energy required to manufacture the product.

Framing How Companies Make Manufacturing Automation Investment Decisions

The previous section addressed key factors impacting technology adoption across manufacturing sectors and industries with different production and business strategies; the following shares recent research on how manufacturers are evaluating return on investment (ROI) for two different types of manufacturing-technology investments: 1) those with a "fixed" technology frontier, under which all technologies are known as previously employed capital; and 2) and those in an "expanding" technology frontier.[148] The latter are unique because, as MAPI's Cliff Waldman notes in his report, "Productivity Dynamics: Decision Criteria for New Technology Investment," from which much of the following section is drawn:

> Automation implementation is a hybrid, exhibiting characteristics of both capital investment and innovation investment. In the sense of deploying machinery into a production line, it has characteristics of capital equipment investment. But it does not appear to be as short-term oriented as capital investment. Rather, automation is more like process innovation whose principal goals are cost reduction and product-quality improvement.[149]

Standard capital investment analysis and ROI-based project-decision frameworks assume the technological frontier is fixed (i.e., that technology is a known quantity.) But when decisions are being made regarding the purchase and implementation of technologies that are new to the company (and often new to the world) and whose benefit depends in part on the effective implementation of a suite of other related technologies, the company's knowledge framework (and even purpose or timeframe for investment) are likely to be different. In other words, manufacturers confront a broader set of unknowns and risks with new technologies than with established technologies.[150]

Accordingly, as Waldman observes, "automation investment is one case of new technologies being implemented and used in a way that is distinct from capital investment."[151] In other words, especially for mid-size and larger manufacturers, new technology investments aren't evaluated solely for their expected immediate financial return, but often they consider a "discovery element." This is different for smaller manufacturers. For them, one of the most-significant reasons given for not investing in automation is their inability to clear an ROI hurdle, and so be able to justify the high up-front financial and nonfinancial costs.[152]

Thus, as Figure 4 shows, in a fixed-technology environment, short-term economic dynamics—primarily the economic and product demand outlook, the after-tax cost of capital, and the desired payback period for the new capital asset—drive investment decisions. Projects should be undertaken only if net benefits over a time-definite period exceed fixed costs and the ROI rate is cleared. Investments should be rejected otherwise.

In contrast, as Figure 5 shows, in an expanding-technology frontier environment, the drivers of new technology investment aren't short-term shifts in market conditions but rather long-term changes in business pressures. Decision factors start to include production costs and product-quality pressures as well as the diffusion of new technologies throughout industrial supply chains. Thus, the ROI equation changes, as "costs" now include considerations such as labor-force adjustment, stranded costs, and the risks associated with unknown technologies; while the benefits are factored in terms of competitiveness, supply-chain viability, worker and capital productivity, etc. In particular, ROI assessments must consider if the failure to invest, even as a technology works its way into the industry-production structure, would significantly harm the firm's competitiveness. Similarly, the accept/reject determination becomes based more on considerations such as the acceptable payback period and whether to invest "now vs. later" (i.e., when more ROI information is available because the technology has been more broadly deployed/proven). Thus, manufacturers have to balance whether they want to differentiate themselves with an early-adoption approach or take a "wait-and-see" approach; the latter strategy is increasingly risky with the advent of technologies that have such potential to boost productivity, cut costs, and help manufacturers integrate seamlessly into industrial supply chains.

Figure 4: ROI Analysis for Fixed-Technology Frontier Investments[153]

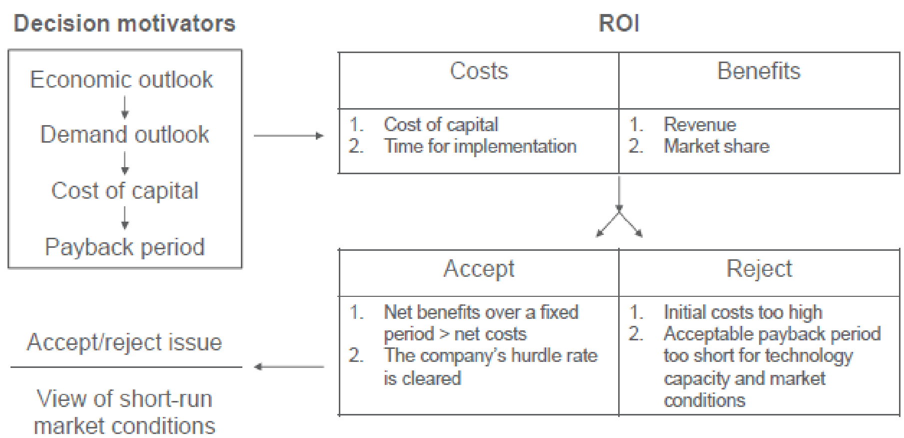
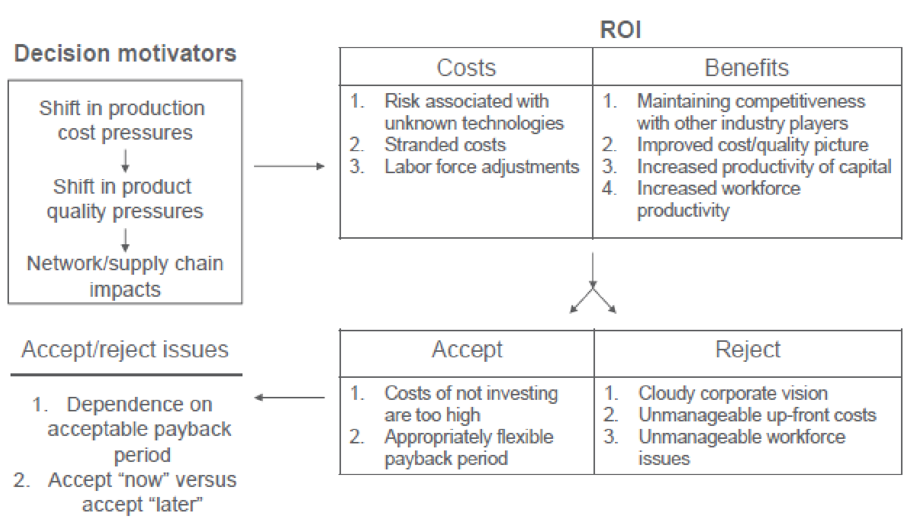


Figure 5: ROI Analysis for Expanding-Technology Frontier Investments[154]



Figures 4 and 5 Courtesy: MAPI

COUNTRIES' MANUFACTURING SUPPORT PROGRAMS

The following provides an analysis of manufacturing support programs and practices for small and medium sized enterprises that have been implemented in foreign countries including Argentina, Australia, Austria, Canada, China, Germany, Japan, Korea, and the United Kingdom, and the United States.

Argentina

Manufacturing accounts for 17.2 percent of Argentina's economy and 13.1 percent of its employment; while Argentinean SMEs account for 45 percent of manufacturing-sector employment and 36 percent of the sector's production.[155] The main government entity in charge of SME support services is the Ministry of the Industry through its Secretary of Small and Medium Enterprises and Regional Development (SEPYME). The Instituto Nacional de Tecnología Industrial (National Institute of Industrial Technology, or INTI), provides technology extension services.

Founded in 1997, INTI is an autonomous, self-governing body reporting to Argentina's Ministry of Production that represents a national network of innovation, quality support, and technical development for Argentina's manufacturing industry. Eighty percent of INTI's programs support Argentina's SME manufacturers. INTI's services include technical assistance; R&D support; guidance on quality and industrial processes; training and skills development; product quality and certification; environmental protection; and tests, analyses, and calibrations.[156] INTI's roughly $78 million annual budget supports 895 employees, and operates as part of a national network of 51 "Research and Development Hubs" that specialize in the following sectors or themes: food and beverages; textiles, fabrics, and leather products; aeronautics and space; quality, design, and development of products; construction, materials, and processes; electronics and metrology; chemistry; and natural resources and the environment.[157] INTI's centers offer services such as: access to laboratories for analysis and tests of products; certification assistance; technical assistance for technology transfer; audits to improve processes; R&D; capacitation of human resources to improve the quality of products; and machinery calibration. In addition to these services, INTI also provides technical assistance on agricultural machinery through diagnosis and implementation of improvements in processes and innovation and assistance for the adoption of sustainable energies; studies of the technological and economic feasibility of projects; and optimization of bioprocesses.

Argentinean SME manufacturers also receive support from SEPYME, which seeks, with an annual budget of $88 million, to increase productivity and innovation, create business clusters, and favor local development.[158] SEPYME's most important programs include: provision of assistance and information to facilitate access to export markets; diagnostics of SMEs' operational processes and economic support to implement improvement recommendations; subsidies for expenditures related to improving competitiveness; product and process innovation and quality certifications; seed capital for the creation of new companies; refunds on investment expenditures made in human resources training; technical and economic assistance to groups of SMEs to implement, develop, and strengthen productive projects; creation of business clusters; financial assistance to reduce the cost of credit and loans to build industrial parks; provision of infrastructure to connect industrial parks; and credit for purchases of working capital.[159]

Argentina's Ministry of Science, Technology, and Innovation also plays a role in promoting innovation and productivity in Argentina's SME sector. Created in 2007 to increase R&D investment and help bolster innovation, the Ministry creates synergies among enterprises, universities, and research centers to increase the adoption of technology in Argentina's economy. The main program under the Ministry is the Technological Fund (FONTAR), which has an annual budget of at least $4 million.[160] The fund provides financing for projects focused on technological modernization of products or processes, integration of personnel with doctoral degrees, or adoption of IT technologies. FONTAR seeks to promote R&D by linking SMEs to public R&D labs, offering R&D tax credits, and providing direct subsidies to public R&D projects. That's especially important for Argentina, because, as the World Bank's Kristina Thorn notes, "Comparative data reveal that Argentina underinvests in R&D. Notably, private sector involvement in R&D is very low by international standards. In part, this can be attributed to the prevalence of SME enterprises with few innovative sales."[161] Thorn further notes that, "Comparative data reveal that Argentina underinvests in R&D. Notably, private sector involvement in R&D is very low by international standards. In part, this can be attributed to the prevalence of SME enterprises with few innovative sales."[162] That also explains why Argentina's technology extension services focus more on innovation and R&D than do comparator Latin American countries, with Argentina investing 38 percent of technology extension funds there, compared to Mexico's 20 percent.[163]

Argentina's private sector involvement in R&D is very low by international standards. In part, this can be attributed to the prevalence of SME enterprises with few innovative sales.

One other program of note in Argentina is the Programa de Apoyo a la Reestructuracion Empresarial (or "PRE"). Argentina created the PRE to increase SME productivity by developing the market for professional services for SMEs and promoting access to those services. PRE seeks to strengthen the competitiveness of Argentinean SMEs by providing access to technical assistance and by improving and diversifying the supply of services such as "development services for organizational and information systems, human resources, production infrastructure, and quality control." PRE co-finances up to half of the technical assistance services. From 1999 through 2007, PRE assisted 1,200 SMEs with over $16 million in financing. Of those firms, roughly half the beneficiaries were manufacturing firms.[164] Another new program offered by Argentina's Ministry of Production in the province of Buenos Aires is the "SME Experience Program," which links entrepreneurs to SMEs that are looking to expand or professionalize.[165]

Australia

In the early 2010s, Australia had a stand-alone manufacturing extension service called Enterprise Connect that served as the country's primary vehicle for providing firm-level support to SME manufacturers.[166] Australia replaced Enterprise Connect in 2013 with an "Entrepreneur's Program" that has three core components: 1) A Business Advisory Service; 2) Research Connections; and 3) Accelerating Commercialization.[167] The Entrepreneur's

Program stands alongside Australia's Industry Growth Centers (IGCs) and Cooperative Research Centers (CRCs) as the key triumvirate guiding and executing industrial and competitiveness policy in Australia.

The Business Advisory Service is effectively the successor to Enterprise Connect and has objectives similar to those of America's Manufacturing Extension Partnership. The Business Advisory Service serves only existing firms, not new businesses, and participants have to show three years' operating record and a certain amount of turnover to participate. Advisors work hand-in-hand with businesses to boost their productivity and adopt lean manufacturing practices; they also facilitate business opportunity development and provide coaching in growth, innovation, and new product development skills. (Business advisors are now mostly outsourced on a contract basis.) Business Advisory is complemented by a program initially called Research Connections (now renamed Innovation Connections) that serves individual businesses and also provides funding for businesses to access research infrastructure (i.e., universities or research institutes). These are akin to innovation vouchers and are provided in the A$25,000 to A$50,000 range. The premise is to have an advisor who works with a business to assess its particular needs and opportunities, and to provide funding accordingly. Finally, a third prong of the Entrepreneur's Program is called "Accelerating Commercialization," which provides large-scale commercialization funding grants of up to $1 million.

The Entrepreneur's Program focuses on key strategic industries (providing services to enterprises in these sectors only) as identified by the Australian government in its "Industry Innovation and Competitiveness Agenda," released in 2014. It identified six sectors of potential competitive advantage for Australia:[168]

1. Advanced manufacturing;
2. Mining, equipment, technology and services (the manufacturing part of mining);
3. Food and agribusiness;
4. Oil, gas, and energy resources;
5. Medical technologies;
6. Cybersecurity.

Advanced Manufacturing was intentionally addressed to the highest level, because Australian policymakers wanted industry to ascertain the aspects of advanced manufacturing in which it felt Australia has the strongest competitive advantage. But, collectively, these sectors represent 35 percent of R&D intensity in the Australian economy and 24 percent of engagement with universities, so these were viewed as the most important manufacturing sectors contributing to Australia's competitiveness. For FY 2017-2018, the Entrepreneurs Program will receive A$120 million. The Entrepreneur's Program provides services to about 3,300 businesses annually.[169]

Standing alongside Australia's Entrepreneur's Program is its Industry Growth Centers initiative, which will receive A$213 million for FY 2017-2018. Australia's Industry Growth Centers, which were modeled along the lines of America's Manufacturing USA Institutes, were designed to set the strategic direction for the six key sectors. They are government funded, but industry-led, with boards pretty equally representing industry and academia. Their key mission is setting a ten-year plan for anticipated growth opportunities with regard to: 1) collaboration; 2) regulatory reduction; 3) new markets; and 4) workforce skills.[170] Essentially, the IGCs do the "where do we want to be in ten years" analysis and the Entrepreneurs Program represents the firm-level response to execute that vision.

The third leg is Australia's Cooperative Research Centers, which receive 10 years' worth of funding for industry-led research. Thus, the Industry Growth Centers set the strategic direction, and the Entrepreneur's Program draws on that strategic direction to provide advice to individual firms so they are aligned with the strategy. Under the 10-year direction, if there is a 10-year research program required, they can go and bid for a CRC grant. The intention is that the three parts of the circles work together, and that all these components align with the six strategic sectors. The whole approach is about shaping and prioritizing funding to maximize the competitive advantage of these strategic sectors.

Over two-thirds of all employees in Austria, and every fifth euro is tied directly or indirectly to the country's manufacturing sector.

Several other Australian initiatives are relevant and worth mentioning. First, Australia's Department of Industry, Innovation, and Science launched in Fall 2017 a Small Business Digital Taskforce whose mission is to talk with small businesses across Australia about their concerns and ideas on how they can better engage in the digital economy.[171] The task force was established with the recognition that "many small businesses are not taking advantage of the opportunities that the digital economy offers" despite the fact that "when a small business begins to digitise and use digital tools it creates new growth opportunities and diversifies revenue streams."[172] It should be noted that the task force is not manufacturing-sector specific but rather is collecting feedback from small Australian business across all sectors. The outcome of the task force will be an Australian Digital Economy report due out during the first half of 2018.

Finally, CSIRO, Australia's single national laboratory, has created ON-Incubator. "ON is Australia's national science and technology accelerator, powered by CSIRO." ON is supported by an A$200 million (public and private) commercialization fund that companies may access to commercialize early-stage innovation and get their products to market. CSIRO invests in start-up companies across the key strategic sectors mentioned previously.

Austria

Austria's manufacturing sector, comprised of 29,000 companies employing 640,000 workers, generates $74 billion in value-added annually, accounting for approximately 19 percent of the country's GDP.[173] Over two-thirds of all employees in Austria, and every fifth euro (i.e., 20 percent of Austrian GDP), is tied directly or indirectly to the country's manufacturing sector.[174] Austria does not operate a formal, nationwide manufacturing extension service such as America's Manufacturing Extension Partnership, but it does have a formal "Industrie 4.0" strategy in addition to a range of other programs that support the R&D and innovation activities of Austrian SME manufacturers.

In 2014, the Austrian Federal Ministry for Transport, Innovation, and Technology (BMVIT) announced it would dedicate €250 million ($300 million) for R&D projects associated with Industry 4.0.[175] The country also launched the Association Industry 4.0 Austria: The Platform for Smart Production ("Industrie 4.0 Österreich"), a membership-based, not-for-profit organization that brings together companies (16), academic institutions (6), research organizations (6), and non-government organizations (18) to advance the implementation of digital transformation in Austria and to unify Austria's Industry 4.0 community.[176] Industrie 4.0 Österreich has seven working groups focused on various aspects of Industry 4.0, including: pilot factories, standards, R&D and innovation, qualifications and skills, regional strategies, the human in the digital factory, and smart logistics.[177] Austria's Mechatronik Cluster and Institut fur Intelligent Produktion have created their own Industrie "4.0 Maturity Modell" designed to determine the current maturity level of SME manufacturers and provide specific recommendations on how companies can enhance their manufacturing digitalization. Several hundred Austrian companies have used the model, enabling the organizations to build a database that allows benchmarking of Austrian companies' extent of digitalization; this, in turn, facilitates more precise prescriptions for individual firms.[178]

According to Roland Sommer, managing director of "Verein Industrie 4.0: The Platform for Intelligent Production," a key focus of Austria's Industry 4.0 program is facilitating human-machine symbiosis; that is, empowering workers with automation technology, but ensuring that people (i.e., Austrian manufacturing workers) are always kept first in mind. Thus, even if a worker's job is replaced by technology or automation, thought is given to how that worker may be retrained or reemployed elsewhere in the organization or the production system. In short, the Austrian Industry 4.0 approach emphasizes people and machines collaborating together.[179]

In 2011, Austria launched a new research, development, and innovation (R&D&I) initiative called "Production of the Future", which provided €20 million in annual funding for projects seeking to increase innovation capacity in the national production of real assets; to develop flexible production lines; and to manufacture high-quality products. From 2011 to 2014, more than 600 projects related to manufacturing were funded with €375 by BMVIT and managed by the Austrian Research Promotion Agency (FFG).[180] Further, in 2014, BMVIT established a new funding instrument to promote endowed professorships at universities in areas such as advanced manufacturing and "Steel as a High-Performance Material" with the goal of strengthening important areas of knowledge for Austria's innovation system and promoting cooperation between science and industry.

Austria's BMVIT has established five pilot fabs—realistic models of a factory, e.g., a lab with real machinery and new technologies where energy- and resource-saving manufacturing can be developed and tested—in an effort to set up a common infrastructure for Industry 4.0.[181] The fabs are viewed as test-beds to facilitate the vertical integration of networked production systems and the establishment of horizontal value-added networks for production in the future. The first three fabs have been focused on smart, electronic-based systems, discrete manufacturing, and process engineering. Three further pilot factories are expected to be built in Austria in through 2018.[182]

But Austria still has work to do when it comes to Industrie 4.0. Only 10.5 percent of Austrian manufacturers report using cloud computing services and, according to the OECD, "a large majority of businesses [in Austria] still consider that benefits linked to the reduction of ICT costs are not noticeable, or are limited."[183]

Canada

Established in 1962, Canada's Industrial Research Assistance Program (IRAP), administered by the National Research Council (NRC), serves as Canada's primary technology support program for SME manufacturers, with a mission to "stimulate wealth creation for Canada through technological innovation."[184] IRAP works with both manufacturing and high-tech services SMEs, serving approximately 11,000 SMEs annually with C$290 million in FY15-16 funding. IRAP's core mission is providing advisory services, or "business and technical advice and referrals to SMEs through every aspect of the innovation process, from conceptualization to commercialization."[185] Uniquely (and in distinction to America's MEP program) IRAP also provides direct funding to firms through "non-repayable contributions" that support SMEs' R&D and technology adaptation and/or adoption up to the point of pre-commercialization. An evaluation of the IRAP program found that this "complementarity of offering advisory services and funding together is the essence of IRAP; this is unique and is critical in supporting successful SME innovation."[186]

IRAP delivers its services through a network of over 250 Industrial Technology Advisors (ITAs) located across five regions—Atlantic & Nunavut, Quebec, Ontario, Prairies, and Pacific—and based in technology communities, local associations, universities, and colleges across the country.[187] IRAP's Industrial Technology Advisors focus primarily on assisting Canadian SMEs with technology development, innovation, and new product development activities (as opposed to mostly lean manufacturing principles, although they do that as well) and play a special role in connecting technologies and knowledge emerging from Canadian universities and national laboratories with SMEs. The ITAs provide advisory services to SMEs, but unlike the U.S. MEP program, do not engage as much in deep firm-level interventions to transform SMEs' manufacturing practices. (The ITAs would be more likely to connect the SME to a private-sector provider for such workouts.)[188] IRAP's ITAs partner with over 100 "Network Member" organizations at the regional level, all providing advice and assistance to SMEs.

A 2016-2017 evaluation of the IRAP program by KMPG confirmed that IRAP delivers positive results for Canada's economy.[189] The evaluation estimated IRAP delivered economic benefits at least $10 billion above the cost of the program from 2005-06 and through 2015-16. The ratio of IRAP's economic benefits to the cost of the program during this period was at least 4.9/1.[190] Likewise, a 2012 IRAP client survey found that 90 percent of IRAP clients reported enhanced technical knowledge or capabilities, while 82 percent reported an increase in scientific and technical knowledge. Seventy percent reported an increase in the firm's business skills and knowledge, and 62 percent reported an enhanced ability to perform R&D.[191]

The evaluation further found that IRAP funding yielded additionality, providing firms with the means to undertake innovation projects that otherwise would not have proceeded or would have been significantly downsized in the absence of IRAP funding. Noting that the "2013 Global Competitiveness Index" found that "Canada's greatest weakness is SMEs' limited access to financing and insufficient capacity to innovate" the evaluation justified IRAP's role because "Canadian SMEs lack access to key resources such as funding, business advice, and technical advice."[192]

IRAP is also working with other government agencies to meet SMEs' needs, including through a new Accelerated Growth Service (AGS) program, which gives ITAs the ability to gather other government agencies together, including Global Affairs Canada, the Business Development Bank of Canada, the Canada Export Program, and the Canadian International Innovation Program to coordinate their support programs to assist SMEs.[193]

Canada has launched a number of additional programs to assist its SME manufacturers. Beyond the Industrial Research Assistance Program, the Business Development Bank of Canada (BDC) in 2011 realigned its SME-support programs to focus in particular on ICT adoption. The program has three focus areas:

- Raising awareness of the importance of ICTs for SME manufacturers through success stories and testimonials, as well as providing a free assessment of a company's information and communications technology situation in relation to other Canadian SMEs;
- Financial support for consulting services to help SMEs tailor ICT solutions to their business, and to address financial challenges more specifically;
- Loans to purchase hardware, software, and consulting services (with a budget of CAD 200 million).[194]

In the first 18 months of the initiative's existence, from October 2011 to May 2013, the BDC SmartTech website received over 220,000 visitors; two e-books were downloaded over 10 000 times; and BDC undertook more than 35, 000 online web assessments, including around 900 ICT assessments, and over 300 consulting mandates. In addition, BDC averaged 130 ICT loans per month.[195]

In February 2018, Canada announced it would create an Advanced Manufacturing Supercluster, as part of the Canadian government's $950-million Innovation Superclusters Initiative.[196] The Advanced Manufacturing Supercluster will help develop next-generation advanced manufacturing capabilities in Canada, such as advanced robotics and 3D printing, helping to facilitate Canada's digital industrialization and competitive position in global markets. Canadian policymakers expect the strategy to support the creation of at least 13,500 new jobs and contribute $13.5 billion to Canadian GDP over 10 years.

China

In 2014, manufacturing in China accounted for 19 percent of global manufacturing value-added and for 35.9 percent of China's gross domestic product.[197] China surpassed the United States in manufacturing value-added in 2011 and today China ranks first worldwide in terms of output in more than 220 categories among 500 major types of industrial products.[198] China hosts the world's largest market for industrial robotics, with 428,000 units deployed in 2017 (although its robot density per 10,000 workers is about half the global average). Research firm IDC predicts China will become one of the world's leading IoT markets, with nearly one out of every five of its industrial units (e.g. machines, tools and components) connected by 2020.[199]

China does not have a government agency akin to the United States' Manufacturing Extension Partnership that supports the process and innovation capabilities of Chinese SME manufacturing base.[200] However, this does not mean that the country has not moved aggressively to support its SME manufacturers. Rather, China's approach has focused on providing funds (and in many cases, subsidies) to its manufacturing SMEs. China's government provides direct funds, loan guarantees, loan interest repayments, and even equity investments to manufacturing SMEs.

China will become one of the world's leading IoT markets, with nearly one out of every five of its industrial units connected by 2020.

In May 2015, China announced the "Made in China 2025" (MIC 2025) initiative, a national plan focused on the integration of information technology and industry that seeks to make China an advanced manufacturing power across 10 key strategic sectors: next-generation information technology; high-end numerical control machinery and robotics; aerospace and aviation equipment; maritime engineering equipment and high-tech maritime vessel manufacturing; advanced rail equipment; energy-saving and new vehicles; electrical equipment; new materials; biomedicine and high-performance medical devices; and agricultural machinery and equipment.[201] Notably, these 10 industries constitute nearly 40 percent of China's entire industrial value-added in manufacturing.[202] Made in China 2025 reflects a top-down policy framework headed by the "Leading Small Group for Constructing a Manufacturing Superpower" which includes the China State Council and Ministries such as MIIT and the Multilateral Investment Fund (MIF), in interaction with research institutes and industry groups.[203] According to Jonas Nahm, an assistant professor at Johns Hopkins University, Made in China 2025 reflects a, "a new strategy introduced in 2015 that entails a shift from forging industrial leadership through innovation toward a more German-inspired model of upgrading manufacturing through a rolling series of technological advances."[204]

Made in China 2025 specifically designates a CNY 20 billion ($3 billion) Advanced Manufacturing Fund (the "Modern Manufacturing Industry Investment Fund") with CNY 6 billion provided by China's central government; CNY 4 billion from China's State Development and Investment Corporation; and CNY 5 billion from the Commercial Bank of China; and the remainder representing investments from industry (including first investments from electric vehicle manufacturer BYD [CNY 1.5 billion] and the Shanghai

Robotics Consortium) as well as subnational governments.[205] Made in China 2025 further called on MIIT to establish 40 Manufacturing Innovation Centers (closely modeled on America's Manufacturing USA approach) utilizing public and private funds and focused on creating domestic technologies. Two such Centers have been operationally launched, one focused on additive manufacturing; and one on advanced batteries, which has received a commitment of $400 million in funding through 2020. Beyond this, China's central government claims to have already invested more than $3 billion in 300 enterprise-level experimentation programs focused on various sorts of advanced manufacturing-related technologies, from radio frequency identification (RFID) in components to cloud technologies and beyond.[206]

Made in China 2025 also started a scheme of "experimental cities" where selected cities are encouraged to identify and develop their comparative advantages in manufacturing. Ningbo and Wuhan were among the first cities selected. Another facet of the program is a commitment of CNY 40 billion in subsidies to support industrial robotics, including a pledge to open 40 industrial parks for robotics development.

The Made in China 2025 strategy includes nine strategic goals:

1. **Enhancing innovation capability** and boosting innovation in manufacturing;
2. **Promoting the integration of industrialization and IT** (e.g., promoting digitalization);
3. **Strengthening the fundamental capacity of industry** in basic components, basic processing technologies, basic materials, and basic industrial services;
4. **Boosting the quality and recognition of Chinese brands**;
5. **Making Chinese manufacturing practices greener**;
6. **Targeting priority technologies and products** (across the 10 key strategic industries listed above);
7. **Restructuring industry** (including by dealing with applications of new technologies in enterprises, overcapacity, co-ordination between large enterprises and SMEs, and regional industrial planning);
8. **Developing manufacturing as a service and services for manufacturing**; and
9. **Identifying opportunities for international collaboration**.[207]

Promoting indigenous innovation, domestic production, and import substitution, with MIC 2025 setting explicit global sales growth and market share targets to be filled by "domestic producers" are key objectives of the initiative.[208] By 2025 China wants "less than 30 percent of key manufacturing technologies dependent on import"; less than 20 percent by 2035; and less than 5 percent by 2045.[209]

Made in China 2025 has established indicators for industry on innovation, quality, and digitalization, such as: by 2025, the percentage of R&D spending relative to manufacturing sales should reach 1.68 percent; labor productivity is expected to increase by 7.5 percent annually to 2020, and thereafter by 6.5 percent to 2025; and energy consumption per unit of added value should fall by 34 percent by 2025.[210]

Complementing MIC 2025 is China's implementation-oriented Internet Plus Initiative, launched in July 2025, which seeks to tap into the potential of new business opportunities, economic models, and high value-added activities by promoting greater integration of the Internet in traditional industries. Internet Plus promotes digitalization across 11 sectors and seeks for China to develop an interconnected service-oriented industrial ecosystem by 2025. In manufacturing, "integrating the Internet" includes developing "intelligent factories" by promoting cloud-computing, IoT, industrial robotics, and additive manufacturing, with achieving large-scale customized manufacturing a key priority.[211] Complementing Internet Plus, China's Ministry of Industry and Information Technology collaborated with the Ministry of Finance in 2011 to launch a $75 million IoT development fund. Further, in 2016, China's central government launched the National Key Technology R&D Program, which invested $58 million in cloud computing and big data R&D and a further $46 million for high-performance computing R&D.

A key consideration of MIC 2025 and the Internet Plus initiative is for the Chinese government's role to "increasingly shift to strategic planning, policy implementation, and the improvement of public services."[212] "There is also a growing focus on enabling and promoting technological upgrading and innovation in SMEs, along with better framework conditions, such as access to loans. Since 2006, 150 percent of the costs of technological innovation and of R&D have been deducted from the calculation of corporate income tax, and in 2015 this program was widened to become more accessible for SMEs.[213]

China's Innovation Fund for Small Technology-based Firms (InnoFund), founded in 2002, is an innovation fund for small-technology based firms (STFs) that "facilitates and encourages the innovation activities of STFs and the transformation of research achievements by way of financing."[214] Starting with CNY 100 million (C$ 20 million) in 2007, by 2014 the fund had grown to CNY 1.3 billion (C$ 254 million). Finally, the National Fund for Technology Transfer and Commercialization (NFTTC) aims to promote research transfer and commercialization, especially for research projects supported by government investments. Additional compensation is available to banks that support SMEs engaged in transferring or commercializing technologies.[215]

Germany

Germany does not operate a formal manufacturing extension service similar to America's Manufacturing Extension Partnership to provide technology support services specifically to SME manufacturers to boost their productivity, efficiency, and innovative capacity.[216] However, Germany supports its SME manufacturers through other channels and instruments. Germany's approach is much more focused on collaborative industry research and solving common industry technological challenges, with Germany's Fraunhofer Institutes spearheading this role.

Germany's 72 Fraunhofer Institutes, with a staff totaling 25,000 who work with an annual research budget totaling €2.3 billion, undertake applied research of direct utility to private and public enterprise and of wide benefit to society.[217] In effect, they perform applied research that translates technologies into commercializable products. Specifically, Fraunhofer Institutes provide joint pre-competitive research, bilateral applied research with individual firms, prototype manufacturing, and pre-production and cooperative technology transfer arrangements with companies.[218] The Fraunhofer Institutes bring together cutting-edge research in an industrially relevant way across a number of sectors and technology platforms, including digital manufacturing, advanced machining, optics, photonics, microelectron-mechanical systems, robotics, nanotechnology, advanced materials and surfaces, wireless technologies, and many others.[219] All firms within Germany, including SME manufacturers, can avail themselves of these shared ecosystem support networks, participating in research programs to develop their capabilities/expertise in these functions and sectors. Several Fraunhofer Institutes are involved in Germany's Industry 4.0 development, most notably the Fraunhofer Institute for Systems and Innovation Research (ISI) in Karlsruhe; the Fraunhofer Institute for Experimental Software Engineering (IESE) in Kaiserslautern; and the Fraunhofer Institute for Factory Operation and Automation (IFF) in Magdeburg.

None other than German President Angela Merkel extolled the importance of Industry 4.0 to Germany's industrial future.

Germany coined the term Industry 4.0, referring to the convergence of digital technologies and manufacturing industries. In Germany, the term Industry 4.0 describes a strong, technology-based vision of the future.[220] The "holistic, conceptual basis" of the term Industry 4.0 is viewed as one of its key strengths, encapsulating the vertical integration of smart machines, products, and production resources into flexible manufacturing systems and their horizontal integration into cross-industry value networks.[221] Industry 4.0 envisions "networks of manufacturing resources (e.g., manufacturing machinery, robots, conveyor and warehousing systems, production facilities, etc.) that are autonomous, capable of controlling themselves in response to different situations, self-configuring, knowledge-based, sensor-equipped and spatially dispersed and which further incorporate relevant planning and management systems."[222] Industry 4.0 focuses on optimizing production processes in terms of quality, price, and flexibility and delivering better financial returns overall, with a strategic goal of maintaining Germany's traditionally strong position in manufacturing and mechanical engineering throughout the coming digital transformation.[223] Notably, however, "the development of new business models and smart products is considered to be less important" in Germany's Industry 4.0 formulation.[224] Still, a 2016 Acatech study concluded that, "Germany is currently around two to three years ahead of other countries in the field of Industrie 4.0."[225]

None other than German President Angela Merkel extolled the importance of Industry 4.0 to Germany's industrial future, stating, "We have reached a critical moment, a point where the digital agenda is fusing with industrial production."[226] Accordingly, the German government has pledged more than €500 million (C$770 million) to help industry associations, research institutes, and companies create implementation strategies for Industry 4.0.[227] This investment has supported a variety of R&D efforts to advance "smart-factory" technologies, ranging from sensor-embedded systems to artificial intelligence platforms that can help operate Internet-connected machinery.

A key product of Germany's Industry 4.0 efforts has been the identification of over 300 "use cases" of how Germany's manufacturers can digitalize their production processes.[228] Further, as noted, Acatech (Germany's Academy of Science and Engineering) has produced an "Industrie 4.0 Maturity Index," which describes a six-stage Industry 4.0 development path that starts with the basic requirements for Industry 4.0 and supports companies throughout their transformation into agile, learning organizations.[229] As Figure 1 illustrated, the six stages are: Computerization, Connectivity, Visibility, Transparency, Predictive capacity, and Adaptability. These steps chart the evolution of firm capabilities from simple digitalization (adopting computers and connecting them online) to being able to collect data, to understanding what's happening and why in real-time on the factory floor, to reaching a point of anticipating and predicting (whether for machine fault modes or changes in demand that will affect orders and thus production levels), to self-optimizing factories in which autonomous responses can be achieved. Appropriately, the Industrie 4.0 Maturity Index report approaches manufacturers' transformations from "a technological, organizational, and cultural perspective, focusing on the business processes of manufacturing companies" and noting that organizational and cultural factors are often more difficult to address than the technological ones.[230]

The backbone of Germany's industrial base are the *Mittelstand*, mid-size manufacturers, 90 percent of which operate in business-to-business markets (e.g., manufacturing tools and equipment) and 70 percent of which are found in Germany's countryside; but such is their dominance that 80 percent of the world's medium-sized market leaders are based between Germany and Scandinavia.[231] To specifically assist German *Mittelstand* manufacturers' Industry 4.0 adoption efforts, Germany's Federal Ministry of Economic Affairs and Energy has launched the Mittelstand-Digital Initiative, whose mission is to show SMEs and skilled crafts people the importance of using software for business processes and to provide support for digitalising their businesses.[232] In part, the Mittelstand-Digital Initiative recognizes the challenge that many countries have faced in assisting their SME manufacturers with implementing smart manufacturing techniques.[233]

Germany created the Mittelstand-Digital Initiative in part in recognition that creating networks between stakeholders, through which SMEs and entrepreneurs can learn from each other, has helped to create trust, acceptance, and buy-in among SMEs for Industry 4.0 adoption. As the OECD report "The Next Production Revolution" documents, the Mittelstand-Digital Initiative includes three key pillars:[234]

German Mittelstand 4.0: Digital production and work processes. This pillar seeks to support SMEs and skilled crafts people in digitalising business processes and deploying Industry 4.0 applications via competence centers. The pillar places particular focus on raising awareness of opportunities and challenges, enhancing technological and organizational competences, and providing opportunities for demonstration and testing.

Simply intuitive: Usability for SMEs. This pillar aims to provide development and testing support mechanisms for SMEs to increase quality and usability of business and production software. It is motivated by the recognition that software for SMEs has mostly ignored aspects of usability, even though this has become an important aspect of end-user software.

E-standards: This pillar focuses on standardizing business processes, aiming to develop a common language for SMEs across different fields of business so as to facilitate data exchange. The pillar recognizes that SMEs face considerable initial costs when implementing e-standards.

As noted, unlike the Anglo-American approach to intervening at the firm level to boost SME manufacturer productivity, efficiency, and innovative capacity, the focal point of Germany's (and Austria's) SME manufacturer support programs is to support SMEs' R&D (e.g., innovation) efforts, in largest part by enrolling them in collaborative R&D consortia.[235] As Rainer Jäkel, then-deputy director general of technology and innovation policies for Germany's Federal Ministry of Economics and Technology (now the Ministry of Economic Affairs and Energy), elaborated regarding Germany's SME manufacturing support programs, "The main focus is on giving incentives for cooperation between SMEs and universities and research organizations."[236]

Here, Germany's Central Innovation Programme for SMEs (ZIM), a funding program operating since 2008 (through Germany's Federal Ministry for Economic Affairs and Energy), serves as the principal instrument for SMEs with business operations in Germany that wish to develop new or to significantly improve existing products, processes, or technical services.. ZIM's goal is to sustainably increase the innovative capacity and competitiveness of SMEs, with all businesses with less than 500 employees eligible to participate.[237] ZIM funds three types of projects: 1) Individual projects: R&D projects advanced by a single SME; 2) Cooperation projects: cooperative R&D projects proposed between SMEs or between SMEs and external research and technology organizations; and 3) Cooperation networks: innovative company networks and R&D projects in which at least six German SMEs participate.[238] The maximum project costs eligible for funding are €380,000 per company, €190,000 per research institute, and €380,000 for network management.

From 2015 to 2017, Germany's Federal Ministry for Economic Affairs and Energy provided about €1.4 billion (C$2.16 billion) for the ZIM program, which funded 298 cooperation networks, 7,184 cooperation projects, and 1,717 individual projects.[239] The number of individual projects represents 0.4 percent of the total number of German SMEs and 2.4 percent of the manufacturing SMEs. A 2015 evaluation of the ZIM program found that, from 2012 to 2015, more than half the projects were completed by SMEs alone or in collaboration: and that the funded companies experienced an average increase in their sales of nearly 12 percent, while the number of employees rose by 15 percent.[240] Interestingly, the evaluation found that the level of technical achievement was greater in individual projects than in cooperative projects, possibly owing to the higher complexity involved in cooperative projects.[241]

One other institution of note is Germany's Federation of Industrial Research Associations (AiF), which promotes R&D in all industrial sectors on behalf of German SMEs.[242] AiF is Germany's leading organization for the promotion of applied R&D in SMEs; it and its research associations provide comprehensive support in R&D activities to help SMEs meet challenges associated with technological change.[243] Since its 1954 founding, AiF has provided more than €10 billion in funding for more than 200,000 research projects for SMEs, including disbursements of €532 million in 2016 alone.[244] AiF funds R&D efforts particularly focused on: pre-normative standardization; product standardization; technical tools; environmental solutions; generic industry demand; basic and process technologies.[245]

Japan

Japan operates several initiatives designed to prepare the nation for an advanced manufacturing future. The country's prefecture-led Public Industrial Technology Research Institutes, or Kohsetsushi Centers, represent the principal entities that work with SME manufacturers in hands-on technology development and innovation activities. However, driving digitalized manufacturing more broadly is Japan's Industrial Value Chains Initiative (IVI) as well as a Cross-Ministerial Strategic Innovation Promotion (SIP) Program focused on Innovative Design/Manufacturing Technologies. Finally, Japan's Small and Medium Enterprise Agency (SMEA) operates several programs designed to bolster the professionalization and business operations of all SMEs, including SME manufacturers. As of 2014, Japan had 413,339 SME manufacturers, which accounted for 11 percent of SMEs in the country.[246] However, Japanese policymakers are concerned that the productivity of Japan's SMEs manufacturers has been stagnating, with the productivity gap between SMEs and large enterprises already significant and continuing to expand.[247]

Japan's Public Industrial Technology Research Institutes, the Kohsetsushi Centers, were established in the first decade of the 20th century, and modeled after the U.S. agricultural extension and engineering experimentation stations. The Kohsetsushi Centers are generally funded and managed by local prefectures, although they are operated under the guidance of Japan's Ministry of Economy, Trade, and Industry (METI).[248] More than 6,000 staff operate out of 180 Kohsetsushi Centers, which in total have over 260 field offices. As of 2012, the Kohsetsushi Centers received $2.14 billion in funding, meaning that Japan invests about 30 times more in its Kohsetsushi Centers than the United States does in its MEP.

The Kohsetsushi Centers provide Japanese SME manufacturers with a range of services including: technology guidance; technical assistance and training; networking; testing, analysis, and instrumentation; and access to open laboratories and test beds. They even undertake applied research and R&D projects in conjunction with SMEs. They also provide facilities for prototyping and trial industrial production using new machines and technologies, with the centers making their specialized equipment available for research, prototyping, and training. The Kohsetsushi Centers have established most Japanese regions as viable production locations, and they have proven especially effective in quality, testing, "catch-up" research, and acting as a bridge to SMEs.

Each of Japan's 47 prefectures has at least one Kohsetsushi Center, and there is usually a combination of general centers alongside sector-oriented centers targeted to upgrading particular industries through the adaptation of emerging technologies. For example, the Tokyo Metropolitan Industrial Technology Research Institute (TIRI) serves about one-quarter of Tokyo's 40,000 manufacturers across three locations, primarily by providing services, information, and testing equipment and facilities to SMEs. The Iwate Industrial Research Institute (one of Japan's oldest, dating to 1873) envisions a "Silicon Valley in Iwate" by assisting SMEs with manufacturing technology research in areas including "electronics, software, IT, surface finishing of industrial materials, paint application, joining materials together, plastic processing, metallic casting, machine processing, precision measurement, chemical analysis, electropolishing, and 3D scanning and printing."[249] That's representative, as the Kohsetsushi Centers broadly support Japanese SME manufacturers' adoption of a range of emerging technologies, including sensor-enabled (e.g., smart) devices; embedded intelligence; advanced machining; nanotechnology; robotics; automation; MEMS (microelectromechanical systems); and computer numerically controlled machines.

Japan's Kohsetsushi Centers appear to be unique among manufacturing extension services in terms of participating in undertaking R&D research projects in direct partnership with and in service of local SMEs.

Staff at each Kohsetsushi Center spends up to half their time on research, mainly on applied projects focused toward and often undertaken in direct conjunction with local industries.[250] Small manufacturers often send one or two of their staff members to actually work on Kohsetsushi Center projects, providing opportunities for company research personnel to gain research experience, develop new technical skills, and transfer technology back to their firms.

Japan's Kohsetsushi Centers appear to be unique among manufacturing extension services in terms of participating in undertaking R&D research projects in direct partnership with and in service of local SMEs. The Kohsetsushi Center research staff attends annual meetings of scientific societies in order to exchange technical information with professors at universities or scientists at national laboratories. Kohsetsushi Center staff then provides knowledge learned to SME manufacturers through technical consultations, seminars, and joint research efforts. Finally, the provision of budget for the Kohsetsushi Centers by Japan's regional governments encourages skills and capability-based competition among Japan's prefectures, incenting the prefectures to realize economic growth by helping locally situated businesses grow. Japanese prefectures have the attitude that they cannot co-opt a firm from another prefecture; they can only grow their economy from within through superior technology development, transfer, and commercialization.

In June 2015, Japan's Ministry of Enterprise, Trade, and Investment and the Manufacturing Systems Division of the Japanese Society of Mechanical Engineers (JSME-MSD) launched the Industrial Value Chains Initiative (IVI), a collaborative forum promoting the development and adoption of "smart manufacturing" solutions, in part by bringing large and small enterprises together to develop "smart manufacturing scenarios" showing how the combination of manufacturing and ICT technologies can lead to improvements in common industrial operations.[251] IVI has developed 25 such "smart manufacturing scenarios" across four areas: 1) production process engineering; 2) production planning and control; 3) quality systems management; and 4) maintenance planning. IVI has thus far run over 20 projects involving use cases such as: 1) Emerging IoT technologies for production line management; 2) Platforms for the connected world in design and manufacturing; 3) New era of human-centric manufacturing powered by IoT; and 4) Reactions to changes in globally and locally connected factories.

The IVI's objective is to develop solutions—including tools, software, and databases—that combine manufacturing and ICT technologies developed according to "loosely defined standards," thus promoting the agile development of solutions and facilitating their adoption, adaptation, and uptake.[252] One of the most significant products of the IVI effort has been the development of "Advanced Manufacturing IoT Kits for SMEs." The goal is to increase the adoption of IoT solutions by cash-strapped SMEs through the development of low-cost ¥100,000 (C$ 1,125) IoT kits that provide competitive pricing by incorporating low-cost components (such as the Raspberry Pi single-board computer). IVI works with municipalities to hold seminars across Japan to distribute the IoT kits and train SMEs on their use.[253]

Other relevant Industry 4.0 activities in Japan include the Mitsubishi-led e-F@ctory Initiative, which focuses on factory automation and the Industry 4.1J program, led by NTT, which focuses on secure, cloud-based data processing. Japan's government, business, and academic sectors (led by Hitachi and Keio University) have come together to launch the IoT Acceleration Consortium (IOTAC) to link IoT with big data and artificial intelligence. The Robot Revolution Initiative (RRI) focuses on R&D in industrial and applied robotics.[254]

A study undertaken in 2014 by the Japanese Prime Minister's office, "Revitalization of Japanese Industry," led to the creation of the Cross-Ministerial Strategic Innovation Promotion Program and a project that focused on Innovative Design/Manufacturing Technologies.[255] Broadly, the Revitalization Strategy called for placing emphasis on the integration of advanced robotics and artificial intelligence capabilities across specialist supply chains, with Japan's government setting a goal to lead the world in "robots in the IoT era."[256] The initiative has focused on manufacturing innovation policies addressing: global standards for common infrastructure (e.g., operating systems) for robots in manufacturing sites; the utilization of robots and accumulation of data in various fields such as infrastructure; and relevant AI technologies for robotics that may create value opportunities from accumulated data.[257] The country has also placed importance on innovative design and production methodologies that provide customers with superior levels of customer satisfaction. Further, Japan has defined the following priority manufacturing-related R&D clusters and themes as part of the Innovative Design/Manufacturing Technologies program:[258]

Optimized design/manufacturing:

- idea support for general view and product design

- upstream design based on topology optimization
- bio innovative design
- 3D-anisotropy customized design and manufacturing
- rubber 3D printing and value co-creation

Upstream delightful design/manufacturing:

- advanced 3D modelling technology platform
- delightful design platform
- interactive upstream design management
- new manufacturing by additive manufacturing

Innovative materials and 3D molding:

- molecule adhesive agent
- designable gel 3D printing
- fluidic material 3D printing

Innovative complex modelling:

- nano-assembly technique of advanced materials
- multiscale/multi-material manufacturing
- high-value ceramics modelling technology
- high-value laser coating
- glass component advanced processing technology

Combined and intelligent machining technology:

- intelligent machine tool by CAM-CNC integration
- next-generation electrochemical machining
- multi-turret integrated processing machine

Field-oriented R&D:

- fusion of data mining, GA and rapid prototyping
- snow sports gear using computational chemistry

At the federal (national) level, Japan's Small and Medium Enterprise Agency has enacted cross-sectoral policies that assist SMEs across-the-board, although it does not operate manufacturing-sector specific policies. However, in 2017 it did launch the "Act for Facilitating New Business Activities of Small and Medium-sized Enterprises," which has as its key focus enhancing the productivity of Japanese manufacturers, with plans developed for 16 specific business and industrial fields. SMEs may seek to obtain the government's "approval" (i.e., vetting) of their business plans—that is, their "plans for improving management skills"—with regard to: 1) review of products/services through customer data analyses; 2) sophistication of financial management utilizing ICT; and 3) human resources development strategy. Enterprises that receive "approval" of their business plans can qualify for specific financial and taxation support measures, including: immediate depreciation; a 7 percent tax exemption; reduction of fixed asset taxes by 50 percent for 3 years; and loan guarantees and/or low-interest loans made available by entities such as the Japan Finance Corporation and the Organization for Small & Medium Enterprises and Regional Innovation.[259]

A second component of the Act seeks to support overseas expansion efforts through individual consultation services provided by Japan's External Trade Organization (JETRO); trade insurance and export credit financing; and local coordinators stationed across 21 locations in 15 countries to facilitate Japanese exports. Recognizing that managers of Japanese SMEs are rapidly aging (most managers are now 65 or older) a third component of the Act seeks to ensure smooth business succession by providing "business succession diagnosis support" and developing a new business succession taxation scheme that defers payment of inheritance taxes and gift taxes on non-listed shares. Finally, the fourth component of the Act focuses on workforce skills by sharing guidelines and best practices among SMEs that are "establishing workplaces where diverse employees can maximize their potentials and promote productivity improvements."[260] In short, Japan's Small and Medium Enterprise Agency, and the "Act for Facilitating New Business Activities of Small and Medium-sized Enterprises" are focused on broadly improving the business operations environment and professionalism of Japanese SMEs.

One final initiative to mention is the Japan Science and Technology Agency-led Impulsing Paradigm Change through Disruptive Technologies (ImPACT) Program, a ¥55 million (C$ 620 million) initiative spanning 2013 to 2018 that supports disruptive innovations expected to transform Japanese industry and society through the promotion of high-risk, high-impact R&D.[261] The ImPACT program seeks "to build a new science and technology system in which universities and corporations boldly tackle challenging research issues and open new areas for growth."[262] A key goal is to alleviate resource constraints (e.g., energy and commodity inputs) in manufacturing activities. Very much modeled on the program manager-led approach of America's Defense Advanced Research Projects Agency (DARPA), ImPACT has thus far established 16 R&D programs in areas such as ultra-thin and flexible tough polymers; green IT devices with long-life batteries; artificial cell reactor technology; and "Bionic Humanoids Propelling New Industrial Revolution."

South Korea

An official visit by then-South Korean President Park Geun-hye to Germany in 2014 inspired South Korea's government, specifically the Korean Ministry of Trade, Industry, and Energy (MOTIE), to launch the "Manufacturing Industry Innovation 3.0" program in June 2014.[263] The initiative represents one component of Korea's Creative Economy Initiative (CEI), through which Korea has launched 17 "Creative Economy and Innovation Centers" nationwide in an effort to promote digital innovation, with several centers focused explicitly on digital innovation in production.[264] A key facet of the Manufacturing Industry Innovation 3.0 initiative features the development of R&D roadmaps for several key Industry 4.0 technologies, including: design technology, technology to identify defective products, software-integrated operating techniques, IIoT platforms, smart sensors, data collection and data processing technologies, and industrial standards. Succeeding President Park, President Moon has made smart manufacturing and the fourth industrial revolution a key theme of his Presidency. Commendably, President Moon has also launched a Ministry for SMEs and Startups specifically focused on supporting SMEs' innovation capacity, across all industries.[265]

That matters because SMEs dominate South Korea's economy: South Korea has over three million in total and 99 percent of Korean manufacturers are SMEs, meaning that encouraging SME uptake of digital manufacturing practices will be crucial. Accordingly, in 2014, MOTIE launched The Korea Smart Factory Initiative as part of the Manufacturing Industry Innovation 3.0 strategy, which set a goal to build 10,000 Smart Factory Sites for Korean small businesses by 2020.[266] In 2017, Korea's public and private sectors updated these targets, agreeing to increase the number of domestic smart factories operating with the latest digital and analytical technologies to 30,000 factories by 2025. Further, Korea seeks for 10 key sectors to have at least 4,500 smart factories operating by 2025.[267] As part of this effort, Korea's government has committed to investing $189.3 million through 2020 into R&D projects developing technologies related to smart factories, with research and testbed projects sponsored with federal dollars including projects related to IIoT, big data, cyberphysical systems, smart sensors, and collaboration projects.[268] (Those investments stand within the Korean government's plan to invest $1.4 billion in 2018 in core technology development of artificial intelligence, IoT, cloud, big data, intelligent sensors, 5G mobile, and semiconductors.)[269] In November 2017, Korea's Institute of Science and Technology Information (KISTI) announced it would develop a cloud-based facility to enable Korean manufacturing SMEs' access to online high-performance computing-powered CAD, CAE, and other modeling and simulation software tools.[270]

As of November 2016, Korea had implemented some 2,600 model "smart, digitalized factories" as part of the Korea Smart Factory Initiative.

As of November 2016, Korea had implemented some 2,600 model "smart, digitalized factories" as part of the Korea Smart Factory Initiative, and those factories reported significant quality and operational improvements, with one study finding that these factories' product design quality improved by 51.4 percent, their production costs decreased by 24.6 percent, and their proportion of defective products coming off the line decreased by 27 percent.[271] In essence, factories participating in the Korea Smart Factory Initiative are demonstrating 25 percent productivity improvements.[272] MOTIE's Smart Factory initiative represents the principal government instrument to assist Korean SME manufacturers with funding, technology development, and know-how to adopt digital manufacturing practices.

However, Korea's aforementioned 17 Creative Economy and Innovation Centers are also playing an important role. Local governments and large Korean corporations (e.g., Samsung, Hyundai-Kia, LG, SKT, GS, Doosan, and Lotte) jointly operate these regional centers. The centers' tasks include: supporting start-ups and SMEs in each specialty area, organizing the partnership or ecological relations between the relevant big corporations and regional enterprises, arranging funds for SMEs to overcome financial difficulties, encouraging managerial and technological innovation and advisory services (i.e., mentoring), promoting communication and co-operative work among participants, and exploring new markets at home and overseas.[273] More than 2,000 Korean SMEs have already joined the CEI program, allowing some to achieve significant improvements in product quality, with participants having already received over $1.8 billion in the form of investments, guarantees, and loans.[274]

Korea's Smart Factory Standard Research Council also plays an important role; its task is to effectively respond to international trends and activities and to undertake efforts to standardize locally developed regulations.[275]

An especially important consideration of Korea's Manufacturing Industry Innovation 3.0 program is to enable South Korean businesses to enhance their manufacturing technology.[276] That's particularly important for two reasons. First, because, South Korea's manufacturing sector has come under growing pressure because of its low capacity and the steadily improving quality of Chinese manufacturers.[277] In essence, Korean factories find themselves somewhat in the middle between mass production through automation in China and customized production through flexible automation in Germany.[278] Second, Korea has long been characterized by an "ICT dualism" in that its manufacturers make fantastic consumer electronics, but its companies, including manufacturers, are less effective at utilizing ICTs for innovation. That's why, in 2011, ICT investments in Korea were just 10 percent of total business investments compared to over 30 percent in the United States.[279] It also explains why, from 2005 to 2010, IT capital contributed just 0.2 percentage points to total Korean growth, and overall to just 8 percent of growth. Contrast that with the United States, where it contributed 0.3 percentage points and 30 percent of growth. Of 20 OECD nations, 12 nations, including Germany, Japan, and the United States, demonstrate more growth from ICT investments than non-ICT investments. But for Korea, ICT investments contributed only about 40 percent of the level of growth as did non-ICT investments.[280] For these reasons, effectively adopting digital manufacturing will be vital for Korea's future.

South Korea has made some progress with digital manufacturing. A 2016 report ranked Korea's manufacturing technology innovation third out of the G20 countries, behind the United States and Germany.[281] With regard to the R&D status of industries based on Industry 4.0, a recent study by the Hyundai Research Institute ranked Korea fourth, with an industrial technology score of 77.4 points out of 100. The United States led with a score of 99.8, followed by Europe with 92.3, and Japan with 90.9, while China placed fifth with a score of 69.[282] The scores were based on a nation's development according to five detailed industry specifications: IT services, communication services, electronics, mechanical equipment, and biomedical products. Korea scored highest (79.4) in the field of electronics, which includes the development of devices in semiconductors, electronic components, and computers.[283]

However, South Korea does have further to go. A 2016 UBS study ranked Korea just 25th out of 139 countries "most capable of adapting to Industry 4.0."[284] The report found that sales in Korea's Industry 4.0-related companies rose at an annual average rate of 1.8 percent from 2011 to 2015, a substantial drop-off from the 9.7 percent growth realized in the five years before. Profitability also declined; between 2011 and 2015; these companies' operating profit ratio dropped by 0.4 percentage points, after increasing 0.6 percentage points from 2006 to 2010. That stood in contrast to peers such as Germany, Japan, and the United States, all of which saw gains in both sales and profitability. Beyond the aforementioned support programs, the report noted greater diversification was key, as 20 percent of Korea's Industry 4.0-related sales were in one area: "technological hardware and equipment" (i.e., smartphones).

United Kingdom

The UK's manufacturing sector, the world's 11th largest, contributed £177 billion in gross value-added (GVA) to the UK economy in 2016, representing 11 percent of UK GVA, and accounting for over 50 percent of UK exports and 70 percent of UK R&D.[285] The sector employs 2.6 million workers; 133,000 manufacturers operate in the United Kingdom, 99 percent of which are SMEs.[286] But the United Kingdom has struggled with productivity and innovation in recent years. Britain's productivity has long lagged behind that of major competitors, and output per hour worked in the British economy has remained virtually unchanged since the Great Recession.[287] Moreover, a recent UK Innovation Survey found that just over half of UK businesses can be classified as innovative and that fewer UK SMEs introduce new products and services than their European competitors.[288]

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As the November 2017 report by the UK's Department for Business, Energy, and Industrial Strategy (BEIS), *Industrial Strategy: Building a Britain Fit for The Future*, reveals, the United Kingdom's approach to manufacturing and industrial support continues to evolve. The *Industrial Strategy* proposed the establishment of "Sector Deals," in which individual sectors come together under clear leadership to negotiate sector-specific deals with the government to boost the earning power and productivity of the sector. The *Industrial Strategy* announced five completed Sector Deals focused on industrial digitalization, artificial intelligence and the automotive sector, life sciences, construction, and the creative industries.[289]

The Sector Deal for Industrial Digitalization essentially calls for the UK to develop a formalized "Industry 4.0" strategy going forward, building upon the findings of the industry-led *Made Smarter 2017* review, which found that industrial digitalization could be worth as much as £455 billion to Britain's manufacturers and support the development of 175,000 jobs over the next decade.[290] The *Made Smarter* review called on the United Kingdom to create twelve "Digital Innovation Hubs," eight large-scale demonstrators, and five digital research centers focused on developing new technologies as part of a new National Innovation Programme.[291] It further called for this innovation to be complemented with the diffusion and adoption of industrial digital technologies, in part by creating a National Adoption Programme, to be piloted in the North West, and focused on increasing the capacity of existing growth hubs and providing more targeted support. (The *Made Smarter* review suggested such a pilot would allow 20 start-ups to work with industry on new projects and increase value-added by 15 percent over three years for participating firms.)[292] The review further called on the United Kingdom to re-skill or up-skill one million industrial workers over the next five years to enable digital technologies to be deployed and successfully leveraged through a Single Industrial Digitalization Skills strategy. Finally, the report called for establishing a national body, the Made Smarter UK (MSUK) Commission, to be comprised of industry, government, academia, and leading research and innovation organizations, that would be responsible for developing the UK as a leader in industrial digitalization technologies and skills, with a mandate to develop the UK's own Industry 4.0 domestic and global brand.[293]

The United Kingdom's network of 10 Catapult Centers—not-for-profit, independent, physical centers that focus on the commercialization of new and emerging technologies and that connect businesses with the UK's research and academic communities—will also play an important role in the United Kingdom's smart manufacturing future.[294] In particular, the High Value Manufacturing Catapult (HVMC), which itself is comprised of seven individual centers, facilitates the application of leading-edge technical knowledge and expertise to the creation of products, production processes, and associated services that have strong potential to bring sustainable growth and high economic value to the UK. The seven HVM centers have capabilities and competences that span basic raw materials through to high-integrity product assembly processes. The seven HVM centers include: The Advanced Forming Research Centre (AFRC); the Advanced Manufacturing Research Center (AMRC); the Centre for Process Innovation (CPI); the Manufacturing Technology Centre (MTC); the National Composites Centre (NCC); the Nuclear AMRC; and the WMG Catapult.[295] Analysts regard the HVMC as a particular success, as since its inception in 2012 it has tripled the impact of government spending, generating £655 million of additional income from industry by working with over 3,000 businesses every year to bring new technologies to market.[296] The Catapults work with manufacturing businesses of all sizes (though in practice it's often difficult to engage SMEs), providing them access to leading-edge equipment, expertise, and an environment of collaborative innovation.[297] The November 2017 *UK Industrial Strategy* committed £178 million of interim funding for the Catapults, as the May government works toward developing a long-term funding strategy for the Catapult network.[298]

Until November 2015, the United Kingdom operated the Manufacturing Advisory Service (MAS), which through nine regional centers helped English SME manufacturers increase their competitiveness by boosting productivity and efficiency through the adoption of best practice manufacturing solutions, particularly around lean manufacturing.[299] However, with Britain's shift from a coalition to a conservative government in 2015, the Cameron government made the decision to cease small-business support programs specifically funded by the British federal government; thus, the Manufacturing Advisory Service was disbanded (although Scotland's continues to operate).[300]

One specific SME support instrument does remain: a local and regional support structure, the Local Enterprise Partnerships (LEPs).[301] Established in 2010, Britain's 39 LEPs, supported by £15 million in funding, are comprised of local authorities, governments, and businesses and provide support to local businesses in the interest of spurring local and regional economic growth. The Local Enterprise Partnerships are not specifically manufacturing-sector focused (although many former Manufacturing Advisory Service personnel have reportedly moved to the LEPs and have in some ways reconstituted a channel to provide manufacturing extension services to British SME manufacturers.)[302] In part, the decision to disband MAS and to rely on LEPs was an intentional devolution to local and regional officials to empower them with taking a greater role in local and regional economic development, but it has left Britain without a nationwide support instrument for SME manufacturers.

However, some other SME support programs have emerged. The *UK Industrial Strategy* promises to increase the diffusion of best practices "so that small and medium-sized enterprises have the tools to become more productive" including "by trial[ing] innovative approaches to driving up the adoption of modern business practices."[303] For instance, a new Business Basics Programme will explore improving SME productivity through enhancing management practices and improving skills and by working to encourage SMEs to adopt technologies and practices such as new accountancy software or performance management systems.

In July 2015, senior British leaders established the Productivity Leadership Group (PLG), which set a mission to identify practical steps to raise productivity among British businesses. In 2016, the May government announced it would provide £13 million to support the PLG, and in July 2017 PLG launched the "Be the Business" campaign, which will assist businesses across the UK with benchmarking their current level of productivity, accessing best-practice advice, and improving through structured management training.[304] Alongside the "Be the Business" campaign, PLG has also developed a "Productivity through People" campaign, through which large businesses (such as BAE Systems, GlaxoSmithKline, the John Lewis Partnership, Rolls-Royce, Siemens, and other large manufacturers) reach out to SMEs in their supply chain, inviting them to a 12-month co-funded development program (driven by regional business schools) with the aim of improving SME skills to boost their productivity.[305] Also notable is the University of Central Lancashire's launch of a Centre for Small and Medium Enterprises Development, which will deliver £10 million worth of business support projects and is set to reach almost 1,000 SMEs in the region. Finally, the *UK Industrial Strategy* announced it would invest over £20 billion over the next ten years to support high-growth innovative businesses, including a £2.5 billion investment fund to "ensure businesses can get access to the capital they need to scale" and providing innovative, knowledge-intensive businesses access to funding through the Enterprise Investment Scheme (EIS) and Venture Capital Trusts (VCTs). While promising, this initiative appears more oriented toward establishing new high-potential businesses than enhancing the capabilities of existing SME manufacturers.

United States

Manufacturing contributes 12.3 percent of U.S. GDP.[306] America's more than 230,000 SME manufacturers form the backbone of U.S. manufacturing supply chains and employ a considerable share of America's overall manufacturing workforce.[307] In fact, as of 2014, 98.5 percent of U.S. manufacturing establishments were SMEs (defined by having fewer than 500 employees).[308] America's SME manufacturers intensively export; in fact, as of 2013, 96.5 percent of manufacturing exporters were from SMEs and they contributed 19.1 percent of total U.S. manufacturing exports.[309]

America's Hollings Manufacturing Extension Partnership (MEP), which operates out of the National Institute of Standards and Technology at the U.S. Department of Commerce, works with small and mid-sized U.S. manufacturers to help them create and retain jobs, increase profits, and save time and money.[310] MEP is a public-private partnership with centers in all 50 states (and Puerto Rico) dedicated to increasing the technical and innovation capacity of America's small- to medium-sized (SME) manufacturers.[311] MEP operates 600 field offices comprised of 1,300 technical experts and 2,300 allied service providers serving as trusted business advisors focused on solving manufacturers' challenges and identifying opportunities for growth.[312] MEP offers its clients a wealth of unique and effective resources centered on five critical areas: technology acceleration, supplier development, sustainability, workforce, and continuous improvement.[313] MEP centers tailor services to meet critical needs, ranging from process improvement and workforce development to specialized business practices, including supply chain integration, innovation, and technology transfer. MEP assists U.S. manufacturers in embracing productivity-enhancing, innovative, manufacturing technologies; navigating advanced technology solutions; and recruiting and retaining a skilled and diverse workforce.[314] Further, by placing technologies and innovations developed through research at federal laboratories, educational institutions, and corporations directly in the hands of U.S. manufacturers, MEP serves an essential role in sustaining and growing America's manufacturing base.

It is estimated that for every dollar of federal investment, the Manufacturing Extension Partnership generates $19 in new sales growth and $21 in new client investment.

MEP delivers a significant return on investment for U.S. taxpayers.[315] In fact, it is estimated that for every dollar of federal investment, the MEP generates $19 in new sales growth and $21 in new client investment. This translates into $2.2 billion in new sales annually. And for every $1,978 of federal investment, MEP creates or retains one manufacturing job.[316] In 2016, the MEP National Network connected with 25,445 manufacturers, leading to $9.3 billion in sales, $1.4 billion in cost savings, and $3.5 billion in new client investments, and helping to create and retain more than 86,602 U.S. manufacturing jobs.[317] Since 1988, MEP has worked with 94,033 manufacturers, leading to $98.7 billion in sales and $17.1 billion in cost savings, and has helped create or retain more than 884,596 jobs.[318]

MEP has achieved these successes despite the fact that the United States substantially underinvests in MEP relative to both its own historical norms and compared to investments made by competitor nations. MEP's budget in 2016, $130 million, was scarcely more than its 1998 budget of $113.5 million, meaning that, as a share of GDP, the United States invested 1.58 times more in supporting its SME manufacturers in 1998 than it did in 2016.[319] Moreover, as a share of GDP, Japan invests 30 times more in its Kohsetsushi centers than the United States invests in its MEP; Germany invests approximately 20 times as much; and Canada invests almost 10 times as much in its Industrial Research Assistance Program (IRAP).[320]

In 2017, MEP released its "MEP National Network Strategic Plan 2017-2022", which sets short-, mid-, and long-term measures of success. In the short term, it calls for: piloting an integrated MEP National Network approach to delivery systems engaging 50 percent of MEP Centers in multi-center delivery projects, increasing small/rural engagements through 3rd-party partnerships by 10 percent, and attaining operational excellence in 25 percent of center operations. Over a five-year period, the plan calls for increasing MEP market penetration as an integrated national network by 20 percent. And over the long-term, MEP seeks to triple the number of manufacturers it serves annually and increase its impact numbers four-fold.[321]

Launched in 2012 by the Obama administration, and renamed in September 2016, Manufacturing USA, consists of 14 manufacturing innovation institutes that represent public-private partnerships focused on developing advanced manufacturing product and process technologies, facilitating their commercialization, and developing workforce skills around advanced manufacturing technologies.[322] Manufacturing USA plays a pivotal role in revitalizing America's industrial commons, enhancing America's industrial competitiveness, and helping ensure U.S. leadership across a range of advanced-manufacturing process and product technologies.[323]

At least four Institutes of Manufacturing Innovation (IMIs) within Manufacturing USA address smart manufacturing-related technologies and processes. The first IMI, America Makes: The National Additive Manufacturing Innovation Institute, launched in 2011, focuses on expanding manufacturers' additive manufacturing (i.e., 3D printing) capabilities. The Digital Manufacturing and Design Innovation Institute encourages factories across America to deploy digital manufacturing and design technologies, so America's factories can become more efficient and cost competitive.[324] The Institute for Advanced Composites Manufacturing Innovation (IACMI) accelerates development and adoption of cutting-edge manufacturing technologies for low-cost, energy-efficient manufacturing of advanced polymer composites for vehicles, wind turbines, and compressed gas storage.[325] Finally, the Clean Energy Smart Manufacturing Innovation Institute (CESMII) focuses primarily on innovations such as smart sensors, data analytics, and controls in manufacturing that can dramatically reduce energy expenses in advanced manufacturing.[326]

Of these, DMDII may play the most important role in helping digitalize American manufacturing. DMDII has four key technology focus areas: 1) Design, Product Development, and Systems Engineering, which focuses on creating improved design tools and processes, integrating data across the manufacturing lifecycle, and developing automated manufacturing planning; 2) The Future Factory, referring to enabling digital integration and control in the manufacturing environment and implementing tools to increase flexibility though the production cycle; 3) Agile, Resilient Supply Chain, facilitating access to digital information, supply chain visibility, and design collaborations; and 4) Cybersecurity in Manufacturing, referring to designing and deploying assessment tools and establishing a collaborative network for sharing best practices.[327]

A key focus for DMDII has been democratizing SME manufacturers' access to scalable computing resources and applications. DMDII envisions its Digital Manufacturing Commons (DMC) as a free, open-source software project to develop a collaboration and engineering platform that can serve as an online gateway for digital manufacturing.[328] Akin to an "app store for manufacturing," the DMC will become a digital services marketplace with a software development kit and collaboration platform at its core, essentially equipping SME manufacturers with the modeling and simulation tools they need to address technical design challenges as well as to access shared HPC resources. DMC thus facilitates SMEs' access to a variety of productivity-enhancing applications that SME manufacturers would have difficulty assessing if they had to purchase and maintain all the requisite hardware and software in-house.[329]

DMDII has also developed a real-time, data-driven "Visual Decision Support System" for manufacturers. This represents a shop-floor decision support system that will convert thousands of existing real-time data points into a collection of cloud-based dashboards to facilitate decision-making about what to produce, when to produce it, and with what components and production resources. Pilot studies of similar concepts have resulted in 98 percent reduction in line stoppages, 86 percent reduction in on-site inventory, and a 50 percent reduction in indirect material handling labor, all while increasing manufacturers' productivity by nearly 10 percent. DMDII expects to have the solution available online by early 2018.[330]

CONCLUSION

Nations are competing fiercely for advanced manufacturing leadership. Countries will need to introduce a comprehensive national manufacturing digitalization strategy and make the requisite investments if they wish to keep pace. Small manufacturers, especially, can't be expected to go-it-alone in this environment and will need to benefit from both smart collaborations with suppliers as well as from government programs that encourage and incentivize their adoption and uptake of digital and other advanced-production strategies and technologies.

ENDNOTES

1. These terms will be used mostly interchangeably in this report.
2. Stephen J. Ezell, "A Policymaker's Guide to Smart Manufacturing," (Information Technology and Innovation Foundation, November 2016), 1, http://www2.itif.org/2016-policymakers-guide-smart-manufacturing.pdf.
3. Daniel Castro and Jordan Misra, "The Internet of Things" (Center for Date Innovation, November 2013), http://www2.datainnovation.org/2013-internet-of-things.pdf.
4. Michael Rüßmann et al. "Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries" (Boston Consulting Group, April 2015), 6, https://www.zvw.de/media.media.72e472fb-1698-4a15-8858-344351c8902f.original.pdf.
5. Sikich, "2017 Manufacturing Report" (Sikich, June 2017), 7, https://www.sikich.com/2017-manufacturing-report-download/.
6. Adam Lesser, "Declining Sensor Costs Open Up New Consumer Applications," Gigaom, January 25, 2015, https://gigaom.com/2015/01/25/declining-sensor-costs-open-up-new-consumer-applications/.
7. Scott A. Nelson and Paul Metaxatos, "The Internet of Things Needs Design, Not Just Technology," *Harvard Business Review*, April 29, 2016, https://hbr.org/2016/04/the-internet-of-things-needs-design-not-just-technology.
8. James Manyika et al., "The Internet of Things: Mapping the Value Beyond the Hype" (McKinsey Global Institute, June 2015), 66, http://www.mckinsey.com/~/media/McKinsey/Business%20Functions/McKinsey%20Digital/Our%20Insights/The%20Internet%20of%20Things%20The%20value%20of%20digitizing%20the%20physical%20world/Unlocking_the_potential_of_the_Internet_of_Things_Executive_summary.ashx.
9. Ibid.
10. Michael Fitzgerald, "An Internet for Manufacturing," *MIT Technology Review*, January 28, 2013, https://www.technologyreview.com/s/509331/an-internet-for-manufacturing/.
11. John Koten, "A Revolution in the Making," *The Wall Street Journal*, June 10, 2013, http://www.wsj.com/articles/SB10001424127887324063304578522812684722382.
12. Manyika et al., "IoT: Value Beyond the Hype," 68.
13. James R. Hagerty, "How Many Turns in a Screw? Big Data Knows," *The Wall Street Journal*, May 15, 2013, http://www.wsj.com/news/articles/SB10001424127887324059704578472671425572966.
14. Manyika et al., "IoT: Value Beyond the Hype," 70.
15. Ibid.
16. Ezell, "A Policymaker's Guide to Smart Manufacturing," 17.
17. Remarks of Elizabeth Fikes, director, product supply engineering, Proctor & Gamble, (ITIF Event: "Trade, Technology and the Future of U.S. Manufacturing," Washington, DC, December 1, 2017), https://www.youtube.com/watch?v=eJnXorvmbME&feature=youtu.be.
18. Manyika et al., "IoT: Value Beyond the Hype," 71.
19. Rüßmann et al., "Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries," 11.
20. Hewlett Packard Enterprise, "A Heavy Equipment Provider Uses the Industrial IoT to Cut Customers' Downtime by 60%," https://www.hpe.com/us/en/customer-case-studies/kaeser-iiot.html.
21. Ibid.
22. Ibid.
23. Günther Schuh et al., "Industrie 4.0 Maturity Index: Managing the Digital Transformation of Companies," (Acatech, 2016), 17,

http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Projektberichte/acatech_STUDIE_Maturity_Index_eng_WEB.pdf.

24. Hewlett Packard Enterprise, "HIROTEC: From Smart Manufacturing, to Smart Factory—to Smart Enterprise," https://h20195.www2.hpe.com/V2/GetDocument.aspx?docname=A00003335ENW.
25. Schuh et al., "Industrie 4.0 Maturity Index," 17.
26. Hewlett Packard Enterprise, "HIROTEC: From Smart Manufacturing, to Smart Factory—to Smart Enterprise."
27. Schuh et al., "Industrie 4.0 Maturity Index," 17.
28. Control Solutions Inc., "Smarter, Not Harder: How Smart Technology is Changing Manufacturing in Michigan," December 26, 2017, http://controlyourbuilding.com/blog/entry/smarter-not-harder-how-smart-technology-is-changing-manufacturing-in-michig.
29. Microsoft, "Customer Stories: Kuka Robotics," https://www.microsoft.com/en-us/cloud-platform/customer-stories-kuka-robotics.
30. Microsoft, "Customer Stories: Lido Stone Works," https://www.microsoft.com/en-us/cloud-platform/customer-stories-lido-stone-works.
31. David Vasko, director, advanced technology, Rockwell Automation, remarks made at ITIF event "Trade, Technology and the Future of U.S. Manufacturing," (Washington, DC, December 1, 2017), https://www.youtube.com/watch?v=eJnXorvmbME&feature=youtu.be.
32. Shawn Sprague, "Below Trend: The U.S. Productivity Slowdown Since the Great Recession" Bureau of Labor Statistics *Beyond the Numbers* Vol. 6, No. 2 (January 2017), https://www.bls.gov/opub/btn/volume-6/below-trend-the-us-productivity-slowdown-since-the-great-recession.htm.
33. Matthew Karnitsching, "Why Europe's Largest Economy Resists New Industrial Revolution," *Politico EU*, July 6, 2016, http://www.politico.eu/article/why-europes-largest-economy-resists-new-industrial-revolution-factories-of-the-future-special-report/.
34. Sikich, "2017 Manufacturing Report," 9.
35. Ibid., 5, 10,
36. Phone interview with Caralynn Collens, CEO, UI Labs, January 19, 2018.
37. Schuh et al., "Industrie 4.0 Maturity Index," 16. Source: (FIR e. V. at RWTH Aachen University).
38. Statement by Mr. Matthias Machnig, Staatssekretär im Bundesministerium für Wirtschaft und Energie, Germany at OECD Conference on Smart Industry: "Enabling the Next Production Revolution," November 18, 2016.
39. Schuh et al., "Industrie 4.0 Maturity Index," 14.
40. Ibid.
41. Erik Brynjolfsson and Lorin Hitt, "Beyond Computation: Information Technology, Organizational Transformation, and Business Performance" *Journal of Economic Perspectives* 14(4): 23–48 (2017), https://repository.upenn.edu/oid_papers/290/.
42. McKinsey and Company, "Industry 4.0: How to Navigate Digitization of the Manufacturing Sector," (McKinsey and Company, August 2015), 7, https://www.mckinsey.de/files/mck_industry_40_report.pdf.
43. Manyika et al., "IoT: Value Beyond the Hype," 68.
44. Peter C. Evans and Marco Annunziata, "Industrial Internet: Pushing the Boundaries of Minds and Machines" (GE, November 26, 2012), 3, www.ge.com/docs/chapters/Industrial_Internet.pdf.
45. Manyika et al., "IoT: Value Beyond the Hype," 8.

46. Ibid., 68.
47. Ibid.
48. Ibid., 71.
49. McKinsey and Company, "Industry 4.0: How to Navigate Digitization of the Manufacturing Sector," 16.
50. Ibid., 25.
51. "Economic Benefit," Smart Manufacturing Leadership Coalition, https://www.smartmanufacturingcoalition.org/economic-benefit; "About SMLC," Smart Manufacturing Leadership Coalition, https://smartmanufacturingcoalition.org/about.
52. European Parliament Member's Research Service, "Industry 4.0: Digitalisation for Productivity and Growth," (European Parliament, September 2015), http://www.europarl.europa.eu/RegData/etudes/BRIE/2015/568337/EPRS_BRI(2015)568337_EN.pdf.
53. Vodafone, "M2M Barometer 2015 Report" (Vodafone, 2015), http://m2m-mktg.vodafone.com/barometer2015; OECD, "Enabling the Next Production Revolution," 86.
54. Organization for Economic Cooperation and Development (OECD), "Enabling the Next Production Revolution: Implications for Government and Business" (OECD, May 2017), 77, http://www.oecd.org/sti/the-next-production-revolution-9789264271036-en.htm.
55. Ibid.
56. Stefan Heng, "Industry 4.0: Huge Potential for Value Creation Waiting to Be Tapped" (Frankfurt: Deutsche Bank, May 23, 2014), https://www.dbresearch.com/PROD/DBR_INTERNET_EN-PROD/PROD0000000000335628/Industry+4_0%3A+Huge+potential+for+value+creation+waiting+to+be+tapped.PDF.
57. Rüßmann et al. "Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries," 2.
58. Data courtesy Caralynn Collens, CEO UI Labs. Data from a proprietary DMDII/McKinsey & Company report called *The Digital Blueprint*.
59. Ibid.
60. Ibid.
61. OECD, "Enabling the Next Production Revolution," 86-87.
62. Ibid.
63. Ibid.
64. GE, "Digital Thread Activates $700M+ in Productivity Gains for GE," https://www.ge.com/digital/sites/default/files/Digital-Thread-Activates-Productivity-Gains-Infographic.pdf.
65. Ibid.
66. OECD, "Enabling the Next Production Revolution," 79.
67. Lee G. Branstetter, Matej Drev, and Namho Kwon, "Get With the Program: Software-Driven Innovation in Traditional Manufacturing," National Bureau of Economic Research Working Paper 21752 (January 2016), http://www.nber.org/papers/w21752.
68. A. Barua, D. Mani, and R. Mukherjee, "Measuring the Business Impacts of Effective Data," (The University of Texas at Austin, 2015), http://middleman.heltenkelt.se/anvandbart.se/images/drupalbilder/blogsource/div/EffectiveDataStudyPt1-MeasuringtheBusinessImpactsofEffectiveData-WP.pdf.
69. E. Brynjolfsson, Lorin M. Hitt, and Heekyung Hellen Kim, "Strength in Numbers: How Does Data-Driven Decisionmaking Affect Firm Performance?" (Cambridge, MA: Massachusetts Institute of

Technology and National Bureau of Economic Research, April 22, 2011,) http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1819486.

70. Maya Eden and Paul Gaggl, "On the Welfare Implications of Automation," World Bank Policy Research Working Paper No. 7487, April 20, 2016, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2690016.

71. Georg Graetz and Guy Michaels, "Robots at Work," (Center for Economic Performance, November 11, 2017), http://personal.lse.ac.uk/michaels/Graetz_Michaels_Robots.pdf.

72. Ibid.

73. Ibid., 22.

74. Ibid., 33.

75. Ibid., 5, 30.

76. Michael Chui et al., "The Social Economy: Unlocking Value and Productivity Through Social Technologies" (McKinsey Global Institute, July 2012), https://www.mckinsey.com/industries/high-tech/our-insights/the-social-economy.

77. Ibid., 100.

78. Stephen J. Ezell and Robert D. Atkinson, "The Good, The Bad, and the Ugly (and the Self-destructive) of Innovation Policy: A Policymaker's Guide to Crafting Effective Innovation Policy" (Information Technology and Innovation Foundation, 2010), http://www.itif.org/files/2010-good-bad-ugly.pdf.

79. Julie A. Hedlund and Robert D. Atkinson, "The Rise of the New Mercantilist: Unfair Trade Practices in the Innovation Economy," (Information Technology and Innovation Foundation, June 2007) 23, http://www.itif.org/files/ITMercantilism.pdf.

80. University of Colorado at Boulder, Institute of Behavioral Science, Research Program on Political and Economic Change, "The Costs of Complying with Foreign Product Standards for Firms in Developing Countries: An Econometric Study," Working Paper PEC2004-0004, May 19, 2004, 7, http://www.colorado.edu/ibs/pubs/pec/pec2004-0004.pdf.

81. Henning Kagermann et al., *Industrie 4.0 in a Global Context*: *Strategies for Cooperating with International Partners* (Acatech, 2016), 17, http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Projektberichte/acatech_eng_STUDIE_Industrie40_global_Web.pdf.

82. Ibid., 23.

83. Ibid., 7.

84. Ibid., 43.

85. Ibid., 9. Author's note: This risk is relatively low, however. All major IoT and M2M standards-development activities are supported by a variety of industry groups and corporations, many of which participate in multiple fora to monitor and contribute to development work. A greater risk of lock-in would arise if governments intercede in the IoT marketplace via misguided efforts to minimize business risk through "managed" innovation and competition.

86. Ibid., 8.

87. International Organization for Standardization, "ISO/IEC JTC 1 — Information Technology," https://www.iso.org/isoiec-jtc-1.html.

88. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 24.

89. Ibid., 24. Graphic developed by the European Union's Alliance for Internet of Things Innovation (AIOTI).

90. In-person interview with Ken Salaets, director, global policy, Information Technology Industry Council (ITIC), February 5, 2018.

91. Ibid.

92. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 56.

93. In-person interview with John Tuccillo, senior vice president, Industry & Government Affairs, Global Strategy, Schneider Electric, January 25, 2018.

94. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 56.

95. Smart Manufacturing Leadership Coalition, "About SMLC."

96. MT Connect Institute, "About MT Connect," http://www.mtconnect.org/.

97. Tim Shinbara, vice president, manufacturing, Association for Manufacturing Technology, phone interview by Stephen Ezell, January 29, 2018.

98. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 12.

99. Ibid.

100. American National Standards Institute, "About ANSI," https://www.ansi.org/about_ansi/overview/overview?menuid=1.

101. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 9.

102. German Federal Ministry for Economic Affairs and Energy, "The Background to Plattform Industrie 4.0," http://www.plattform-i40.de/I40/Redaktion/EN/Standardartikel/plattform.html;jsessionid=C68BD6F89AEDCC6B7C2F365A7482C9BB.

103. Plattform Industrie 4.0, "Management of the Plattform Industrie 4.0," http://www.plattform-i40.de/I40/Redaktion/EN/Downloads/Publikation-gesamt/composition-industrie-4-0.pdf?__blob=publicationFile&v=11.

104. Dr. Karsten Schweichhart, "Reference Architectural Model Industrie 4.0 (RAMI 4.0)," https://ec.europa.eu/futurium/en/system/files/ged/a2-schweichhart-reference_architectural_model_industrie_4.0_rami_4.0.pdf.

105. Ibid.

106. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 37-38.

107. Ibid., 10.

108. In-person interview with Ken Salaets, director, global policy, Information Technology Industry Council (ITIC), February 5, 2018.

109. Alliance Industrie du Futur, Plattform Industrie 4.0, and Piano Industria 4.0, "France, Germany and Italy Join Forces To Promote Digitising Manufacturing," news release, June 20, 2017, http://www.sviluppoeconomico.gov.it/images/stories/documenti/press%20release_trilateral-cooperation.pdf.

110. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 10.

111. Ibid., 40.

112. Michael Murphree, "Building Markets: The Political Economy of Technology Standards" (PhD diss., Georgia Institute of Technology, May 2014), https://smartech.gatech.edu/bitstream/handle/1853/51821/MURPHREE-DISSERTATION-2014.pdf.

113. Robert D. Atkinson, "Enough is Enough: Confronting Chinese Economic Mercantilism" (Information Technology and Innovation Foundation, February 2012), 42, http://www2.itif.org/2012-enough-enough-chinese-mercantilism.pdf.

114. Office of the United States Trade Representative (USTR), "2014 National Trade Estimate Report on Foreign Trade Barriers" (USTR, May 2014), 63, http://www.ustr.gov/sites/default/files/2014%20NTE%20Report%20on%20FTB.pdf.

115. Stephen J. Ezell and Robert D. Atkinson, "The Middle Kingdom Galapagos Island Syndrome: The Cul-De-Sac of Chinese Technology Standards" (Information Technology and Innovation Foundation, December 2014), https://itif.org/publications/2014/12/15/middle-kingdom-galapagos-island-syndrome-cul-de-sac-chinese-technology.
116. Ibid., 19.
117. U.S. Chamber of Commerce, "Made in China 2025: Global Ambitions Built on Local Protections," (U.S. Chamber of Commerce, 2017), 33, https://www.uschamber.com/sites/default/files/final_made_in_china_2025_report_full.pdf.
118. MIIT, "Notice on Launching Recommendations for Smart Manufacturing Pilot Demonstrations," http://www.miit.gov.cn/n1146295/n1652858/n1652930/n3757016/c3764217/content.html.
119. Nigel Cory, "Worst Innovation Mercantilist Policies of 2017," (Information Technology and Innovation Foundation, January 2018), 7-12, https://itif.org/publications/2018/01/22/worst-innovation-mercantilist-policies-2017.
120. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 41.
121. Ibid., 47.
122. Ibid.
123. Ibid., 48.
124. Kenji E. Kushida, "Leading Without Followers: How Politics and Market Dynamics Trapped Innovation in Japan's Domestic "Galapagos" Telecommunications Sector" *Journal of Industry, Competition, and Trade* 11, Issue 3 (June 2011): 279-307, http://link.springer.com/article/10.1007%2Fs10842-011-0104-7.
125. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 51.
126. Ibid., 50.
127. Ibid.
128. Sikich, "2017 Manufacturing Report," 7.
129. Cliff Waldman, "Automation Investment in U.S. Manufacturing: An Empirical Picture" (Manufacturers Alliance for Productivity and Innovation (MAPI), June 2016), https://mapifoundation.org/economic/2016/6/10/automation-investment-in-us-manufacturing-an-empirical-picture.
130. Ibid., 18.
131. Respondents were asked not about their experience with any specific automation technology, but rather about automation investment in general. Specifically, the survey asked: "During the past five years, has your company purchased and/or implemented one or more technologies that you have not used before, either for your U.S. or non-U.S. operations, whose purpose was to newly automate any aspect of your product-producing process through labor enhancement, labor substitution, or both?" Note: Generally, automation refers to technologies that replace humans on the factory floor: industrial robots, material handling systems, automatic guided vehicles, automated inspection, and the like. In this case, automation is *one type* of technology manufacturers invest in. Sometimes, however, some refer to automation when they really mean *digitalization* (for example, technologies such as digital prototyping, additive manufacturing, IoT, cloud, supply chain collaboration, etc.).
132. Waldman, "Automation Investment in U.S. Manufacturing: An Empirical Picture," 9.
133. Ibid.
134. Ibid., 16.
135. Ibid., 19.
136. Ibid., 14. "Credible evidence of impact on product quality" and "credible evidence of impact on workforce productivity" ranked third and fourth, respectively.

137. Sikich, "2017 Manufacturing Report," 11.

138. Ibid., 9.

139. Ibid., 8.

140. Ibid., 5, 10,

141. This typology was collaboratively developed by the authors and Diego Tamburini, principal industry lead, manufacturing, Microsoft Corporation.

142. Remarks of Elizabeth Fikes, director, product supply engineering, Proctor & Gamble, (ITIF Event: "Trade, Technology and the Future of U.S. Manufacturing," Washington, DC, December 1, 2017).

143. Ibid.

144. Douglas S. Thomas and Stanley W. Gilbert, "Costs and Cost Effectiveness of Additive Manufacturing" (U.S. Department of Commerce, National Institute of Standards and Technology, December 2014), http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1176.pdf.

145. Stuart F. Brown, "Toyota's Global Body Shop: The Japanese Automaker is Putting the Final Touches on a New Strategy: Being Able to Build Almost Anything, Anywhere," *Fortune*, February 9, 2004, http://archive.fortune.com/magazines/fortune/fortune_archive/2004/02/09/360102/index.htm.

146. Innosight, "The Imperative of Disruptive Innovation" (Innosight, September 2016), 2, https://www.innosight.com/wp-content/uploads/2016/09/Disruptive_Innovation_Overview_Final.pdf.

147. Ibid.

148. Cliff Waldman, "Productivity Dynamics: Decision Criteria for New Technology Investment" (Manufacturers Alliance for Productivity and Innovation, August 2016), https://static1.squarespace.com/static/58862301f7e0ab813935c244/t/58c005569de4bbc417212717/1488979287606/Rockwell_Automation_Decision_Criteria.pdf.

149. Waldman, "Automation Investment in U.S. Manufacturing: An Empirical Picture," 8.

150. Ibid.

151. Waldman, "Productivity Dynamics: Decision Criteria for New Technology Investment," 6.

152. Ibid.

153. Ibid.

154. Ibid., 7.

155. Scott Andes, Stephen Ezell, and Jesus Leal, "An Alternative to Mercantilism: Manufacturing Extension Services in Latin American and Caribbean Countries" (Information Technology and Innovation Foundation, November 2013), 3, http://www2.itif.org/2013-manufacturing-extension-services-latin-america-caribbean.pdf?_ga=2.191218986.1086856864.1516629872-1874627486.1511959405.

156. Instituto Nacional de Tecnología Industrial, "About Us," https://www.elannetwork.org/partners/inti-instituto-nacional-de-tecnolog%C3%ADa-industrial.

157. Argentina Ministerio de Producción, "Instituto Nacional de Tecnología: National Network of Innovation, Quality Support, and Technical Development for Industry," http://www.inti.gob.ar/pdf/institucional/institucional_ing.pdf.

158. Ministerio de Economía y Finanzas, "Presupuesto del Ministerio de Industria para el año 2012, Ministerio de Economía y Finanzas, Buenos Aires," (2011), 10, http://www.mecon.gov.ar/onp/html/presutexto/ley2012/jurent/pdf/D12E608.pdf.

159. Secretaría de la Pequeña y Mediana Empresa, Ministerio de Industria, http://www.sepyme.gob.ar/#.

160. Ministerio de Economía y Finanzas, "Presupuesto del Ministerio de Ciencia, Tecnología e Innovación Productiva para el año 2012", Ministerio de Economía y Finanzas, (2011), 33, http://www.mecon.gov.ar/onp/html/presutexto/ley2012/jurent/pdf/D12J71.pdf.

161. Kristian Thorn, "Science, Technology and Innovation in Argentina," *World Bank Latin American and Caribbean Region Department for Human Development Working Paper*, September, 2005, http://siteresources.worldbank.org/INTARGENTINA/Resources/ScienceTechnologyandInnovationinArgentina.pdf.

162. Ibid.

163. Andes, Ezell, and Leal, "Manufacturing Extension Services in Latin American and Caribbean Countries," 23.

164. Victoria Castillo et al. "Can SME Policies Improve Firm Performance? Evidence from an Impact Evaluation in Argentina" IDB OVE Working Paper No. 06/10 (May 2011), https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1848984.

165. Government of India, Development Commissioner Ministry of Micro, Small and Medium Enterprises (MSME), "MSE in Argentina," http://www.dcmsme.gov.in/Policies/highlights_of_internatinal_policies/Argentina.pdf.

166. Stephen J. Ezell and Robert D. Atkinson, "International Benchmarking of Countries' Policies and Programs Supporting SME Manufacturers" (Information Technology and Innovation Foundation, September 2011), 21, http://www.itif.org/files/2011-sme-manufacturing-tech-programss-new.pdf.

167. In-person interview with Anthony Murfett, minister counsellor Industry, Science and Education, Australian Embassy, Washington, DC January 10, 2018.

168. Australian Government, Department of Industry, Innovation, and Science, "Industry Innovation and Competitiveness Agenda" (Australian Government, October 2014), https://www.pmc.gov.au/sites/default/files/publications/industry_innovation_competitiveness_agenda.pdf.

169. Australian Government, Department of Industry, Innovation, and Science, "Annual Report 2016-2017 Department of Industry, Innovation and Science," (Department of Industry, Innovation, and Science, 2017), https://industry.gov.au/AboutUs/CorporatePublications/AnnualReports/Pages/Annual-Report-2016-2017.aspx.

170. In-person interview with Anthony Murfett, January 10, 2018.

171. Australian Government, Department of Industry, Innovation, and Science, "Small Business Digital Taskforce," https://www.industry.gov.au/smallbusiness/Pages/Small-Business-Digital-Taskforce.aspx.

172. Ibid.

173. Kerstin Zimmerman, "Production of the Future: Advanced Manufacturing in Austria" *Bridges* vol. 42 (December 2014), http://ostaustria.org/bridges-magazine/item/8312-production-of-the-future-advanced-manufacturing-in-austria.

174. Ibid.

175. Stephen Ezell, "Industry 4.0 Holds the Key to Modern Manufacturing," *Bridges* vol. 42 (December 2014), http://ostaustria.org/bridges-magazine/item/8318-stephen-ezell-on-innovation-matters.

176. Industrie 4.0 Austria, "Fact Sheet Association Industry 4.0 Austria," http://plattformindustrie40.at/wp-content/uploads/2016/02/FlyerA4_Association-Industry-4.0-Austria.pdf.

177. Ibid., 5-6.

178. Mechatronik Cluster and Institut for Intelligent Produktion, "Maturity Modell: Making Advanced Manufacturing Measurable" (power point presentation, February 2018).

179. Phone interview with Dr. Roland Sommer, managing director of "Verein Industrie 4.0: The Platform for Intelligent Production," January 25, 2018.

180. Zimmerman, "Production of the Future: Advanced Manufacturing in Austria."

181. Ibid.

182. Industrie 4.0 Austria, "Fact Sheet Association Industry 4.0 Austria," 4.

183. OECD, "Enabling the Next Production Revolution," 82, 85.

184. National Research Council of Canada, "Mandate and Role," https://www.nrc-cnrc.gc.ca/eng/irap/about/mandate.html.
185. Ibid.
186. Ibid.
187. National Research Council of Canada, "The ITA Advantage—Industrial Technology Advisors: The Human Face of Innovation," https://www.nrc-cnrc.gc.ca/eng/irap/about/advisors.html.
188. Ezell and Atkinson, "International Benchmarking of Countries' Policies and Programs Supporting SME Manufacturers," 21.
189. KPMG, "Evaluation of the Industrial Research Assistance Program," iv.
190. Ibid., vii.
191. Jan Youtie, "Technology Extension Concepts and Impacts," (presentation, World Bank BBL Seminar Series, Washington, DC, April 23, 2015), https://www.innovationpolicyplatform.org/system/files/2015-WB-BBL-Youtie.pptx.
192. KPMG, "Evaluation of the Industrial Research Assistance Program," vii, 4.
193. Ibid., 6-7.
194. OECD, "Enabling the Next Production Revolution," 106.
195. Ibid.
196. "Canada's New Advanced Manufacturing Supercluster Expected to Create Over 13,500 Middle-Class Jobs in Ontario and Across Canada," *Cision*, February 22, 2018, https://www.newswire.ca/news-releases/canadas-new-advanced-manufacturing-supercluster-expected-to-create-over-13500-middle-class-jobs-in-ontario-and-across-canada-674846843.html.
197. OECD, "Enabling the Next Production Revolution," 399.
198. Dr. Martina Gerst, "Made in China 2025: Strategic Industries and Emerging Business Opportunities," (EU SME Center, September 3, 2016), http://www.eusmecentre.org.cn/article/made-china-2025-strategic-industries-and-emerging-business-opportunities.
199. Carrie MacGillivray et al. "Worldwide Internet of Things Forecast Update, 2016-2020: December 2016," (International Data Corporation, December 2016), https://www.idc.com/getdoc.jsp?containerId=US42082716. China's IoT market is expected to grow from $11 billion in 2015 to $121 billion by 2022, at a CAGR of 41.1 percent between 2016 and 2022.
200. Ezell and Atkinson, "International Benchmarking of Countries' Policies and Programs Supporting SME Manufacturers," 29.
201. U.S. Chamber of Commerce, "Made in China 2025: Global Ambitions Built on Local Protections" (U.S. Chamber of Commerce, 2017), 8, https://www.uschamber.com/sites/default/files/final_made_in_china_2025_report_full.pdf.
202. Ibid., 6.
203. Jonas Nahm, "China's Specialization in Innovative Manufacturing," (presentation, National Academy of Sciences NAS Innovation Policy Forum, May 23, 2017).
204. Sujai Shivakumar and Gail Cohen, *Securing Advanced Manufacturing in the United States: The Role of Manufacturing USA: Proceedings of a Workshop* (Washington, DC: National Academies Press, 2017): 16, 65.
205. Ibid., 65-67.
206. Ibid., 67.
207. Gerst, "Made in China 2025"; OECD, "Enabling the Next Production Revolution," 419.
208. Gerst, "Made in China 2025," 7, 9.

209. Professor Jun Ni, “Future of Manufacturing: China and USA Perspective,” (presentation, Manufacture 2017, Tallinn), 14, http://manufuture2017.eu/wp-content/uploads/2017/10/pdf-Jun-Ni.pdf.

210. OECD, “Enabling the Next Production Revolution,” 418.

211. Ibid.

212. Ibid., 420.

213. Ibid., 421.

214. Ezell and Atkinson, “International Benchmarking of Countries’ Policies and Programs Supporting SME Manufacturers,” 30.

215. OECD, “Enabling the Next Production Revolution,” 422.

216. Ezell and Atkinson, “International Benchmarking of Countries’ Policies and Programs Supporting SME Manufacturers,” 22.

217. Fraunhofer Instiute, “Facts and Figures-February 2017,” https://www.fraunhofer.de/en/about-fraunhofer/profile-structure/facts-and-figures.html.

218. Philip Shapira, Jan Youtie, and Luciano Kay, “Building Capabilities for Innovation in SMEs: A Cross-Country Comparison of Technology Extension Policies and Programs” *International Journal of Innovation and Regional Development* 3-4 (2011): 254-272.

219. Fraunhofer Institute, “Fraunhofer Institutes and Research Establishments,” https://www.fraunhofer.de/en/institutes.html.

220. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 9.

221. Ibid., 6.

222. Fraunhofer Institute, “Production and Supply of Services – Industrie 4.0,” https://www.fraunhofer.de/en/research/fields-of-research/production-supply-of-services/industry-4-0.html.

223. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 9.

224. Ibid.

225. Ibid., 13.

226. Karnitsching, “Why Europe’s Largest Economy Resists New Industrial Revolution.”

227. James Temperton, “A ‘Fourth Industrial Revolution’ Is About to Begin (in Germany),” *Wired*, May 21, 2015, http://www.wired.co.uk/article/factory-of-the-future.

228. Statement by Mr. Matthias Machnig, Staatssekretär im Bundesministerium für Wirtschaft und Energie, Germany at OECD Conference on Smart Industry: Enabling the Next Production Revolution, November 18, 2016.

229. Schuh et al., “Industrie 4.0 Maturity Index: Managing the Digital Transformation of Companies.”

230. Ibid., 14.

231. *The Economist*, “Mittel-management,” November 25, 2010, http://www.economist.com/node/17572160.

232. Organization for Economic Cooperation and Development (OECD), “Enabling the Next Production Revolution: the Future of Manufacturing and Services - Interim Report” (OECD, June 1, 2016), 107, https://www.oecd.org/mcm/documents/Enabling-the-next-production-revolution-the-future-of-manufacturing-and-services-interim-report.pdf.

233. Ezell, “A Policymaker’s Guide to Smart Manufacturing,” 27.

234. OECD, “Enabling the Next Production Revolution,” 106-107.

235. Ezell and Atkinson, "International Benchmarking of Countries' Policies and Programs Supporting SME Manufacturers," 26-27.

236. Phone interview with Dr. Rainer Jäkel, then deputy director general of technology and innovation policies for Germany's Federal Ministry of Economics and Technology June 7, 2011.

237. Bundesministerium für Wirtschat und Energie, "The Central Innovation Programme for SMEs," https://www.zim-bmwi.de/zim-overview.

238. Ibid.

239. The University of Cambridge and Policy Links, "New Industrial Capabilities For New Economic Growth: A Review of International Policy Approaches to Strengthening Value Chain Capabilities," (The University of Cambridge and Policy Links, November 2017), 41.

240. Ibid.

241. Ibid.

242. German Federal Ministry of Education and Research, "German Federation of Industrial Research Associations (AiF)," https://www.research-in-germany.org/en/research-landscape/research-organisations/industrial-research-associations-aif.html.

243. The University of Cambridge and Policy Links, "New Industrial Capabilities For New Economic Growth," 38.

244. Ibid.

245. Ibid.

246. Japan Small and Medium Enterprise Agency, "Recent Policies for SMEs and Micro Businesses," (power point presentation, October 3, 2017).

247. Ibid., 4.

248. United States Government Accountability Office (GAO), "Global Manufacturing: Foreign Government Programs Differ in Some Key Respects From Those in the United States," (GAO, 2013), https://www.nist.gov/sites/default/files/documents/2017/05/09/Global.pdf.

249. Amanda Wayama, "Introducing the Iwate Industrial Research Institute," *IWATE and the ILC*, June 30, 2016, http://www.iwate-ilc.jp/eng/ktimes/introducing-the-iwate-industrial-research-institute-18/.

250. Philip Shapira, "Promoting Innovation for Mature Manufacturing SMEs: US and Japanese Policies Compared" Paper prepared for 2005 EWC/KDI Conference on Restructuring SMEs in the Age of Globalization, July 20-22, 2005, 8, http://www.cherry.gatech.edu/REFS/TRP-Ref/Shapira-JA-US-SME.pdf.

251. The University of Cambridge and Policy Links, "New Industrial Capabilities For New Economic Growth," 32.

252. Ibid., 33.

253. Ibid., 33.

254. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 46.

255. OECD, "Enabling the Next Production Revolution," 333-334.

256. Ibid., 327, 333.

257. Ibid., 333.

258. Ibid., 333-334.

259. Japan Small and Medium Enterprise Agency, "Recent Policies for SMEs and Micro Businesses."

260. Ibid.

261. The University of Cambridge and Policy Links, “New Industrial Capabilities For New Economic Growth,” 52.

262. Ibid.

263. Seokhee Han, “The Challenge of Korean Smart Factory Project in Industry 4.0 Context,” (presentation, November 3, 2016, University of Aarhus, Denmark), 8, http://icdk.um.dk/~/media/icdk/Documents/Industry%2040%20-%20Conference/2%20Seokhee%20Han%20%20Korean%20Industry%2040%20Association.pdf?la=en.

264. U.S. International Trade Administration (U.S. ITA),” Korea - Manufacturing Technology - Smart Factory,” June 30, 2017, https://www.export.gov/article?id=Korea-Manufacturing-Technology-Smart-Factory.

265. *Yonhap News Agency*, “S. Korea to Launch New Ministry Dedicated to SMEs,” July 20, 2017, http://english.yonhapnews.co.kr/news/2017/07/20/0200000000AEN20170720007700320.html.

266. Seokhee Han, “The Challenge of Korean Smart Factory Project in Industry 4.0 Context.”

267. U.S. ITA,” Korea - Manufacturing Technology - Smart Factory.”

268. Ibid.

269. Damian Felchlin, “Industry 4.0 Korea: Numerous Projects in Korea” *Swiss Business Hub South Korea*, October 25, 2017, https://www.s-ge.com/en/article/news/20174-mem-korea-industry-40-update.

270. In-person interview with Geunyoung Park, senior consultant, Deloitte Anjin LLC, November 2, 2017.

271. Han, “The Challenge of Korean Smart Factory Project in Industry 4.0 Context,” 13.

272. U.S. ITA,” Korea - Manufacturing Technology - Smart Factory.”

273. OECD, “Enabling the Next Production Revolution,” 107.

274. Henning Kagermann et al., *Industrie 4.0 in a Global Context*, 50.

275. Ibid.

276. Ibid., 51.

277. Ibid.

278. Felchlin, “Industry 4.0 Korea: Numerous Projects in Korea.”

279. Robert D. Atkinson, “The Real Korean Innovation Challenge: Services and Small Businesses” in *Korea's Economy* Vol 30 (Korea Economic Institute of America and the Korea Institute for International Economic Policy, 2015), 49-50, http://keia.org/sites/default/files/publications/kei_koreaseconomy_atkinson_0.pdf.

280. Ibid.

281. Felchlin, “Industry 4.0 Korea: Numerous Projects in Korea.”

282. Hyundai Research Institute, “The Arrival of the Fourth Industrial Revolution and Its Implications,” (Hyundai Research Institute, August 2016).

283. Felchlin, “Industry 4.0 Korea: Numerous Projects in Korea.”

284. UBS, “Extreme Automation and Connectivity: The Global, Regional, and Investment Implications of the Fourth Industrial Revolution,” (UBS, January 2016), 25, https://www.ubs.com/global/en/about_ubs/follow_ubs/highlights/davos-2016/_jcr_content/par/columncontrol/col1/actionbutton.1562449048.file/bGluay9wYXRoPS9jb250ZW50L2RhbS91YnMvZ2xvYmFsL2Fib3V0X3Vicy9mb2xsb3ctdWJzL3dlZi13aGl0ZS1wYXBlci0yMDE2LnBkZg==/wef-white-paper-2016.pdf.

285. United Kingdom Department for Business, Energy, and Industrial Strategy (BEIS), “Industrial Strategy: Building a Britain Fit for The Future,” (UK BEIS, November 2017), 205,

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/664563/industrial-strategy-white-paper-web-ready-version.pdf.

286. Phone interview with Clare Porter, head of manufacturing, Department for Business, Energy and Industrial Strategy, January 17, 2018.

287. Ibid., 19.

288. Ibid., 60-61.

289. Ibid., 192-193.

290. *The Engineer*, "Made Smarter Review Makes Recommendations for Industrial Digitalization," October 30, 2017, https://www.theengineer.co.uk/digitalisation-digital-government/.

291. Ibid.

292. UK BEIS*, Made Smarter Review, 2017*, (UK BEIS, 2017), 3-4, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/655570/20171027_MadeSmarter_FINAL_DIGITAL.pdf.

293. Ibid., 4.

294. Catapult, "About Catapult," https://catapult.org.uk/about-us/about-catapult/.

295. Catapult, "HVM Centres," https://hvm.catapult.org.uk/hvm-centres/.

296. UK BEIS, "Industrial Strategy: Building a Britain Fit for The Future," 82.

297. Phone interview with Clare Porter, January 17, 2018.

298. UK BEIS, "Industrial Strategy: Building a Britain Fit for The Future," 82.

299. Ezell and Atkinson, "International Benchmarking of Countries' Policies and Programs Supporting SME Manufacturers," 19.

300. Phone interview with Clare Porter, January 17, 2018.

301. Ibid.

302. Ibid.

303. UK BEIS, "Industrial Strategy: Building a Britain Fit for The Future," 182.

304. Ibid.

305. Ibid.

306. The World Bank, "Manufacturing, value added (% of GDP)," https://data.worldbank.org/indicator/NV.IND.MANF.ZS.

307. The White House National Economic Council (NEC), "Revitalizing American Manufacturing," (NEC, October 2016), 22, https://www.whitehouse.gov/sites/whitehouse.gov/files/images/NEC_Manufacturing_Report_October_2016.pdf. Source: Economics and Statistics Administration analysis using data from the Census Bureau's Business Dynamics Statistics (BDS).

308. National Association for Manufacturing, "Top 20 Facts About Manufacturing," http://www.nam.org/Newsroom/Top-20-Facts-About-Manufacturing/.

309. Small Business and Entrepreneurship Council, "Small Business Facts and Data," http://sbecouncil.org/about-us/facts-and-data/.

310. Ezell and Atkinson, "International Benchmarking of Countries' Policies and Programs Supporting SME Manufacturers," 17.

311. National Institute of Standards and Technology (NIST), "Manufacturing Extension Partnership (MEP)," https://www.nist.gov/mep.

312. NIST MEP, "2015 NIST MEP Annual Report," (NIST MEP, 2015), 2, https://www.nist.gov/sites/default/files/documents/2016/11/14/annual-report-2015-final.pdf.

313. Ezell and Atkinson, "International Benchmarking of Countries' Policies and Programs Supporting SME Manufacturers," 17.

314. NIST MEP, "MEP National Network Strategic Plan 2017-2022," (NIST MEP, 2017), https://www.nist.gov/sites/default/files/documents/2017/12/20/mep_national_network_plan_2017to2022final.pdf.

315. Ezell and Atkinson, "International Benchmarking of Countries' SME Support Programs."

316. National Institutes of Standards and Technology (NIST) Manufacturing Extension Partnership, "2013 Economic Impact Summary" (NIST MEP, 2014), 2, https://www.nist.gov/sites/default/files/documents/mep/MEP-PARTNERING-IMPACTS-2014-Final.pdf.

317. NIST, "Manufacturing Extension Partnership National Network," https://www.nist.gov/mep/mep-national-network.

318. NIST MEP, "NIST Awards $12 Million to MEP Centers in 11 States," news release, January 13, 2017, https://www.nist.gov/news-events/news/2017/01/nist-awards-12-million-mep-centers-11-states.

319. Author's analysis; Wendy H. Schacht, "Manufacturing Extension Partnership Program: An Overview," (Congressional Research Service, June 2009), http://digital.library.unt.edu/ark:/67531/metadc26113/m1/1/high_res_d/97-104_2009Jun29.pdf.

320. Ezell and Atkinson, "International Benchmarking of Countries' SME Support Programs," 8.

321. NIST MEP, "MEP National Network Strategic Plan 2017-2022," 8.

322. Manufacturing USA, "How We Work," https://www.manufacturingusa.com/pages/how-we-work.

323. David M. Hart, Stephen J. Ezell, and Robert D. Atkinson, "Why America Needs a National Network for Manufacturing Innovation" (Information Technology and Innovation Foundation, December 11, 2012), https://itif.org/publications/2012/12/11/why-america-needs-national-network-manufacturing-innovation.

324. "The Institute," Digital Manufacturing and Design Innovation Institute, accessed October 4, 2016, http://dmdii.uilabs.org/the-institute/technology.

325. "About," The Institute for Advanced Composites Manufacturing Innovation, accessed October 30, 2016, http://iacmi.org/about-us/.

326. The White House, "FACT SHEET: President Obama Announces Winner of New Smart Manufacturing Innovation Institute and New Manufacturing Hub Competitions" news release, June 20, 2016, https://www.whitehouse.gov/the-press-office/2016/06/20/fact-sheet-president-obama-announces-winner-new-smart-manufacturing.

327. UI Labs, "Manufacturing Focus Areas," http://www.uilabs.org/innovation-platforms/manufacturing/focus-areas/.

328. James Barkley, then Director, Digital Manufacturing Commons, Digital Manufacturing and Design Innovation Institute, phone interview by Stephen Ezell, ITIF, March 4, 2016.

329. Stephen J. Ezell and Bret Swanson, "How Cloud Computing Enables Modern Manufacturing," (AEI and Information Technology and Innovation Foundation, June 2017), 18, http://www2.itif.org/2017-cloud-computing-enables-manufacturing.pdf.

330. Caralynn Collens, CEO, UI Labs, in-person interview by Stephen Ezell, February 14, 2017.

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