Manufacturing Digitalization: Extent of Adoption and Recommendations for Increasing Penetration in Korea and the U.S.

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Manufacturing digitalization promises to transform how products are designed, fabricated, used, and serviced, but more needs to be done to facilitate the uptake of digital technologies by manufacturers in the United States, Korea, and beyond.

Whether it's called "Industry 4.0," as in Europe, the "Industrial Internet of Things (IIoT)," as in the United States, or simply "smart manufacturing," information and communication technology (ICT) is in the midst of reshaping modern manufacturing.[1] This digitalization of manufacturing will transform virtually every facet of modern manufacturing, from how products are researched, designed, fabricated and produced, distributed, and consumed to how manufacturing supply chains integrate and factory floors operate.[2] But it's still early days in the smart manufacturing revolution: for instance, 77 percent of small U.S. manufacturers still lack plans to implement Internet of Things applications over the next three years. This report examines the extent of smart manufacturing adoption by U.S. manufacturers and offers policy recommendations to increase smart manufacturing penetration in the United States, Korea, and beyond.

Smart manufacturing enables manufacturers to converge the physical and digital worlds, combining sophisticated hardware with innovative software, sensors, connectivity, and massive amounts of data and analytics to produce smarter products, more efficient processes, and more closely linked customers, suppliers, and manufacturers.[3] The digitalization of modern manufacturing holds the potential not only to restore once-robust manufacturing productivity growth, but also to reshape the landscape of global manufacturing, bolstering the competitiveness of the most innovative and most rapidly technology-adopting companies while eroding the advantage of enterprises—and nations hosting them—that have specialized in low-cost, low-tech, labor-intensive manufacturing activities. That's because digital technologies hold the potential to reduce the labor-input cost of manufacturing; to facilitate cost-competitive manufacturing closer to end users; and to place emphasis on speed, adaptability, mass customization, and the ability to orchestrate and synchronize supply chains, all of which erode the competitive advantage of the old global supply chain model premised on locating mass production in low-cost regions and shipping to the rest of the world.

To remain competitive, regardless of the sector, manufacturers will need to combine the efficiency of mass production with a buyer-oriented focus on customization; that is, the agility to cost-effectively produce in small lot sizes. This in turn means that each part or product built essentially represents a new product introduction, which thus requires an extraordinary degree of confidence and operational efficiency in every decision made across the product lifecycle—from product definition to design, manufacturing, sales, distribution, operations, and maintenance to the product's end-of-life.[4] That can be best accomplished by manufacturers leveraging smart, cyber-physical systems that combine model-based definitions (MBD), an end-to-end digital thread, modeling and simulation, the Internet of Things (IoT), artificial intelligence (AI) and machine learning, and seamless supply chain collaboration.[5] In other words, robust technology adoption and the digitalization of manufacturing processes will be required to keep manufacturers, small and large alike, competitive in this rapidly changing environment. And if governments do not want their enterprises to fall behind and lose competitive edge they will need to support their countries' manufacturing base in making the transition to the coming smart-manufacturing era.

This report first defines digital manufacturing technologies. It then assesses the potential productivity and economic benefits smart manufacturing can produce. It next examines the extent of manufacturing digitalization in the United States. It finds first that data on the topic is sporadic, incomplete, and at this point primarily survey-based. Second, it finds that, for all manufacturing digitalization's promise, U.S. manufacturers—especially small-to medium-sized enterprises (SMEs), the 250,000 of which account for 98 percent of all U.S. manufacturers—have been particularly slow to adopt digital manufacturing practices, with most companies remaining just at the initial stages of smart manufacturing technology adoption. After examining the available data on U.S. smart manufacturing adoption and investment (in both fixed and digital assets), the report turns to an analysis of how the U.S. federal government and leading states are enacting policies and programs to facilitate manufacturers' digital transformation journeys. The report concludes by proposing additional policy recommendations that go beyond the current state of practice in the United States and then focuses on how Korea can echo these.

The Digitalization of Modern Manufacturing

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; and data analytics, machine learning, and wireless connectivity that better enables machine-to-machine (M2M) communications.

Amongst the most important of these is the integration of sensors and software into the Internet of Things. 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.) so as to enable a real-time flow of information about the operational status and condition of the equipment or product.[6] With IoT, devices are essentially enriched with "embedded computing" that allows them to interact and communicate with one another.[7] 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 with regard to salient operating conditions such as temperature, humidity, and electrical flow. IoT can thus support manufacturing execution systems, warehouse management systems, warehouse control systems, and transportation management systems deployed in shop floors and warehouses.[8] 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. Sensors thus 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.[9] Such sensors will account for a significant share of the 50 billion "Things" expected to be connected to the Internet by 2020.[10]

For all smart manufacturing's promise, U.S. manufacturers, especially SMEs, have been slow to adopt digital manufacturing practices, with most companies remaining just at the initial stages of smart manufacturing technology adoption.

The application of IoT in manufacturing is projected to generate $1.2 to $3.7 trillion of value globally by 2025, across four primary forms: 1) operational efficiency; 2) predictive and preventative maintenance; 3) supply-chain management; and 4) inventories and logistics.[11] 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 aspects of manufacturing. Several case studies then follow demonstrating how manufacturers have comprehensively leveraged IoT into their manufacturing systems and go-to-market business models.

Analysts anticipate that the application of IoT toward maximizing factory-floor efficiency will have the largest impact, increasing productivity by as much as 25 percent.[12] 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.[13] 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.[14] 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 can be adjusted as necessary.[15] Similarly, Harley Davidson tracks fan speeds in its motorcycle painting areas and can algorithmically adjust the fans based on environmental fluctuations.[16]

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."[17] 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.[18] (Indeed, in the future, it's likely that even all individual parts and workpieces being 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 an entire 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 had to IoT-enable their production equipment in order to track and communicate their operational status to their original equipment manufacturer (OEM) customers.[19] 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 manufacturing competitiveness going forward will be based more and more around the strength of entire industrial supply chains (e.g., which OEM is orchestrating its supply chain most efficiently 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.[20]

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.[21] 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.[22]

Manufacturer Case Studies

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

Kaeser Kompressoren

Manufacturing competitiveness going forward will be increasingly based around the strength of entire industrial supply chains in getting innovative products to market rapidly.

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, and 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 that capture key environmental and performance data such as temperature, humidity, and vibration.[23] With equipment continuously transmitting 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.[24]

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 finds that this "air-as-a-service" business model has produced a 28.5 percent reduction in compressed air usage for a representative building supplies manufacturer and produced €30,000 in annual savings for a paint production manufacturer.[25] 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.[26] 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."[27] 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.[28] It piloted and then built out a cloud-based IoT platform. HIROTEC first IoT-enabled and then 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 generate automatic, paperless reports for the entire production line of an automobile door production facility.[29] The implementation gave HIROTEC real-time visibility into its business operations and will enable it going forward to leverage machine learning functionality to predict and prevent critical systems failures. 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."[30]

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.[31] 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.[32] 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 that manufacture 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 the 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.[33]

Rold Group

Rold Group, based near Milan, Italy, is a 250-person manufacturer of parts used in the appliance (i.e., refrigerators, washing machines, dryers, and dishwashers), lighting, and industrial sectors. In 2017, the company launched a "Rold Smartfab" initiative to digitalize the company's manufacturing operations; this included a digital-manufacturing platform, real-time monitoring of machines with sensors, display of data on touch-screens, and even mobile and wearable devices that communicate a machine's operational status in real-time down to a smart wristwatch that can instantaneously alert managers to any problems with production equipment. At its Cerro Manufacturing Plant outside Milan, Rold achieved a 7.05 percent increase in overall equipment operating efficiency (OEE) and a 6.14 percent improvement in machine performance (over the prior year). In its door lock assembly line, Rold experienced a 9.6 percent increase in OEE and production increase of almost 300,000 parts.[34] Rold has since turned its smart manufacturing platform into a service it sells to other manufacturing SMEs in Europe. It's a wonderful example of an SME that embraced digital technologies not only to transform its manufacturing operations, but also to launch an entire new line of service products.

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 on its status. 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 predict downtime more effectively and significantly decrease the extent of extra equipment needed on the production line.[35]

Defining Digital Manufacturing Technologies

While the core function of manufacturing has always been and always will be the manipulation of atoms, information is needed to assist with this. Indeed, since almost the beginning of the first industrial revolution in Great Britain, manufacturers have struggled to collect, maintain, analyze, and communicate information. And, the American innovation of "interchangeable parts" in the first half of the 19th century helped spur the development of supply chains and assembly lines, both of which needed some collection and processing of information, via paper ledgers, to manage production systems. Over the first half of the 20th century, mechanical calculators, telephones, and other electro-mechanical devices helped organize information. With the rise of the mainframe computer in the 1950s and 1960s, the mini-computer in the 1970s, the micro-computer in the 1980s, and then the Internet in the 1990s, the information functions of manufacturing became more streamlined and efficient.[36] But what is different today is not simply that the ease and costs of using information in manufacturing is improving; it is that for the first time in history it is possible to identify, track, communicate, analyze, and use information in manufacturing at an extremely granular level and on the basis of this to make changes in real time.

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To achieve this, manufacturers have a host of different technologies they can apply. Indeed, one of the challenges associated with assessing the current state of U.S. manufacturing digitalization is that the terms "Industry 4.0" or "smart manufacturing" really refer to manufacturers leveraging any number of distinct ICT applications to transform their manufacturing operations. Accordingly, the following lists the key, discrete, enabling technologies underpinning digital manufacturing. The first are technologies that have been used for several decades, but due to improvements are playing new roles in enabling smart manufacturing. These include:

- High-performance computing (HPC);
- Digital modeling, simulation, and design software tools including computer-aided design (CAD), computer-aided engineering (CAE), and computer-aided manufacturing (CAM) software, including systems that leverage generative design techniques;
- Enterprise resource planning (ERP) systems;
- Manufacturing execution systems (MES) and warehouse management systems (WMS);
- 3D printing (or "additive manufacturing");
- Robotics.

In addition, there are a set of technologies that have largely emerged within the past decade, and which in some cases are continuing to rapidly develop. These include:

- Cloud computing;
- Handheld tablets and other devices;
- Advanced sensor technologies for a wide array of applications and measurements (or "smart sensors");
- Interface of Things (e.g., Augmented Reality (AR), Virtual Reality (VR), mixed reality, and wearables);
- Artificial intelligence and machine learning;

- Big data and advanced data analytics;
- LTE and 5G wireless connectivity, enabling M2M (machine to machine communication);
- Advanced materials and nanomaterials.[37]

In particular, it is the combination of sensors and connectivity that fundamentally constitutes the Internet of Things, which refers to the technology to connect a broad scope of "things," such as machines, products, and infrastructures to the Internet through sensors and communication devices. The term Industrial Internet of Things describes IoT's application in an industrial context.

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The following describes several of these foundational ICT technologies in additional detail:

- **Computer-Aided Design**: Refers to the use of computer systems to aid in the creation, modification, analysis, or optimization of designs of parts, final products, and even entire production systems or factory environments.
- **Generative Design**: A design technique that mimics nature's evolutionary approach to design, in which designers or engineers input design goals into generative design software, along with parameters such as materials, manufacturing methods, and cost constraints, as the software algorithmically explores all possible permutations of a design solution.
- **Sensor Technologies:** Sensors embedded within devices, machines, and products themselves that measure everything from output, consumption, wear, and capacity to salient operating conditions such as temperature, humidity, and electrical flow. Sensors play a key role in creating the information streams upon which smart manufacturing techniques rely.
- **Data Analytics**: The ability to effectively analyze the massive amounts of data generated by individual plants, entire factories, whole supply chains, and the manufactured products themselves; this is vital for the vision of smart manufacturing to be realized. Accordingly, data now stands on par with people, technology, and capital as core assets of manufacturing enterprises.
- **Advanced Robotics**: The next generation of industrial robots that are far cheaper than their predecessors and that are also more flexible and versatile as they are reprogrammable and thus not dedicated to a single specific task. New industrial robots can mimic human movements and arms can even be physically manipulated by workers to show robots how to execute certain tasks.
- **Wireless Connectivity**: Smart manufacturing benefits from wireless connectivity to join the wide variety of sensors, actuators, and robotics to analytics and control platforms. A wide variety of solutions have emerged to fill this role, some based on unlicensed spectrum, others offered by mobile operators using licensed spectrum. Operators are looking both to licensed 5G systems and to technologies such as narrowband Internet of Things to enable a massive influx of IoT-connected devices. In the unlicensed sphere, a number of open and proprietary standards

have proliferated. Perhaps most notably, the Internet of Things-focused flavor of Wi-Fi, 802.11ah, will offer connectivity designed for long battery life and wide areas in the 900 MHz band.

Productivity and Economic Impacts From the Digitalization of Manufacturing

The adoption of new digital manufacturing technologies will make workers more efficient, accelerate time-to-market for innovative new products, help firms optimize inventory and processes, reduce waste and rework, and better match supply to demand, generating meaningful productivity impacts for the companies successfully integrating digital technologies into their operations. The following section examines the productivity and economic impact data available to date with regard to digital manufacturing.

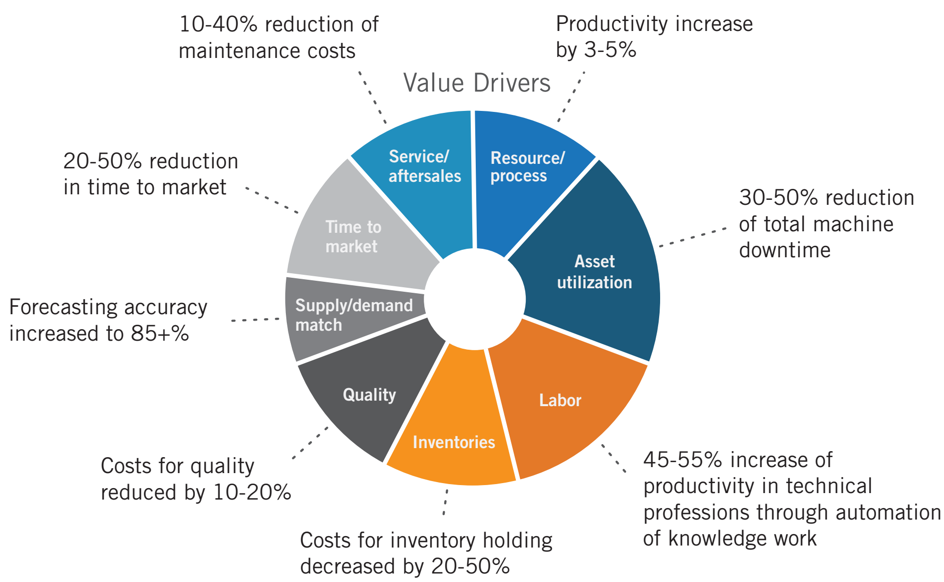
A June 2015 McKinsey Global Institute (MGI) report, "The Internet of Things: Mapping the Value Beyond the Hype," predicted that the widespread application of the Internet of Things in production processes alone—in other words, using sensors to bring intelligence to each piece of production equipment on the factory floor to collectively optimize their 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.[38] 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.[39] For individual firms, Cisco estimates that the payoff for a $20 billion manufacturing firm that digitizes as a profit upside of 12.8 percent over the ensuing three years, and 19 percent over 10 years (assuming its competitors don't also digitize).[40]

Delving into the MGI report and its analysis of the sources of those productivity gains, it becomes clear 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.[41] 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-based applications 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 of total value annually by 2025.[42] 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."[43] 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 in too close proximity to one another, which 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.[44]

Those estimates were originally reported in survey-based research from 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.[45] That report summarized the predicted productivity benefits from digital manufacturing implementations shown in figure 1.

Smart manufacturing is poised to increase the productivity of the world's factories by as much as 25 percent while adding $10 to $15 trillion to global GDP over the next 20 years.

Figure 1: Anticipated Value Drivers From Digital Manufacturing Technology Implementations (Source: McKinsey Global Institute)[46]



The United States' Smart Manufacturing Leadership Coalition (SMLC), a non-profit organization which is building America's 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 safety accidents;
- 40 percent reduction in cycle times; and
- 40 percent reduction in water usage.[47]

Similar findings are being generated throughout the world. A European Commission report estimates that Industry 4.0 will increase production by 20 percent (while reducing downtime by an estimated 50 percent) and increase total value added from manufacturing to a targeted 20 percent of all value added by 2020.[48] 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 decision-making; better customer service; consistency of delivery across markets; transparency/predictability of costs; and better performance in new markets.[49] 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.[50] 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.[51] 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."[52] 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.[53]

While the data provided above represent 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 (DMDII), one of America's 14 Manufacturing USA Institutes, located in Chicago, Illinois, to evaluate the actual returns companies are realizing from digital manufacturing implementations. A 2017 study of a refrigeration compressor value chain, which McKinsey/DMDII deemed "emblematic of companies aiming to pursue a resource productivity and efficiency strategy" found digital manufacturing implementation would drive an EBIT (earnings before interest and taxes) improvement of 20 to 35 percent.[54] Deconstructing the specific sources of value creation from digital implementation, the report found: Increased labor productivity accounted for 5 to 7 percent of the value; improved quality management accounted for 4 to 7 percent; asset utilization of factory equipment accounted for 6 to 15 percent; and efficiencies in raw materials and ordering and inventory management accounted for 4 to 5 percent of the value created.[55] In related research DMDII and McKinsey undertook in collaboration with the Product Development and Management Association (PDMA) in 2017, it was found that companies deploying digital solutions to speed time to market were improving their product innovation speeds by up to 40 percent. Specifically, they found that studied companies were accelerating their "product conception and evaluation" period from 10 weeks to 5 weeks, were reducing their "product design and 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.[56]

These 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.[57] 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 fuel efficiency.[58] 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 its internal IoT and data analytics capability to be somewhere from 300 to 470 percent.[59]

GE estimates that its "Digital Thread"—the connection of data throughout its value stream—generates approximately $700 million in annual productivity gains for the company.[60] For FY 2016, GE estimated the digital thread produced $510 million in services productivity, $90 million in its manufacturing/supply chain, $70 million from engineering, $30 million from "Cross-thread" (i.e., better connecting across the value chain), and $30 million from commercial applications.[61]

A core benefit of digital manufacturing isn't just increasing productivity on the factory floor (e.g., less machine downtime, faster production processes, etc.) but also in bolstering 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 faster than in non-using firms by approximately 5 to 10 percent.[62] The research finds 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 research and development (R&D) dollar and achieve better valuations of their innovation investments in equity markets.[63] 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).[64] 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.[65] 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.[66] Similarly for digital manufacturing, MGI estimates that "the greater adoption of Industry 4.0 technologies in the United States will boost [the country's] real labor productivity growth above the 1.5 percent annual rate posted over the past decade."[67]

It should also be noted that robotics represents a digital manufacturing technology that has exerted 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.[68] 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.[69] As the authors concluded, "For the industries in our sample, robot adoption may indeed have been the main driver of labor productivity growth."[70] They also found that robot densification is associated with increases in both total factor productivity and wages, and reductions in output prices.[71] The authors estimated 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.[72]

If U.S. manufacturers were adopting smart manufacturing technologies, organization, and practices on a reasonably deep and wide scale, we would expect to see it in the productivity statistics. Yet, we do not.

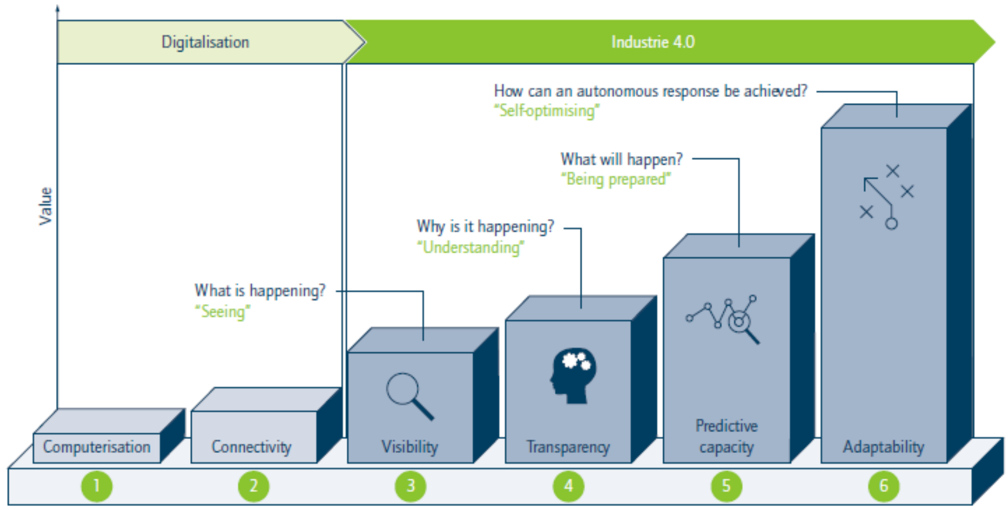
Another area where smart manufacturing can yield productivity improvements for manufacturers is in the R&D and design phase, especially as more-collaborative and higher-powered computer-aided design and computer-aided engineering software as well as web-based innovation management systems are deployed. 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.[73] 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.[74]

U.S. MANUFACTURERS' ADOPTION OF DIGITAL MANUFACTURING TECHNOLOGIES

Given all the excitement—some might even say hype—about digital manufacturing, exactly how far along are U.S. manufacturers? To date, most information about U.S. manufacturers' adoption of digital technologies has been survey-based in nature. The data shows clearly that U.S. manufacturers' adoption of digital manufacturing technologies has been sporadic and—with the exception of a small number of leading companies—remains in the initial phases.

Germany's Academy of Science and Engineering has produced an "Industrie 4.0 Maturity Index" (figure 2) that 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.[75] 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. Broadly, U.S. manufacturing in general might be said to be somewhere between Stages 2 and 3 on this development path.

Figure 2: Stages in the Industry 4.0 Development Path[76]



Courtesy: FIR e. V. at RWTH Aachen University

The first part of this section provides data addressing the extent to which U.S. manufacturers are broadly adopting smart manufacturing activities, while the second section examines data pertaining to manufacturers' adoption of specific smart-manufacturing technologies and systems. (Here, it's important to note that while the Industrial Internet of Things is a vital enabler of digital manufacturing, Industry 4.0 is about more than IIoT alone; for instance IIoT means little without effective data analytics). A third section provides some data on the cross-industry extent of digitalization, finding the extent of U.S. manufacturing industries' digitalization to be middling compared to that of other U.S. industries.

U.S. Manufacturers' Broad Implementations of Smart Manufacturing

If U.S. manufacturers were adopting smart manufacturing technologies, organization, and practices on a reasonably deep and wide scale, we would expect to see it in the productivity statistics. Yet, we do not. In fact, despite all of smart manufacturing's promise, U.S. manufacturing productivity advanced just 1 percent from 2011 to 2016, the slowest recorded rate since 1948, when the statistic was first measured.[77] So we appear to be in a position similar to what economist Robert Solow described in the 1980s, where we see digital manufacturing everywhere but in the productivity statistics. In fact, it appears worse than that: despite the improvements in the technology, the analysis of how helpful it can be, and the select case studies of firms adopting smart manufacturing, few manufacturers have made much progress.

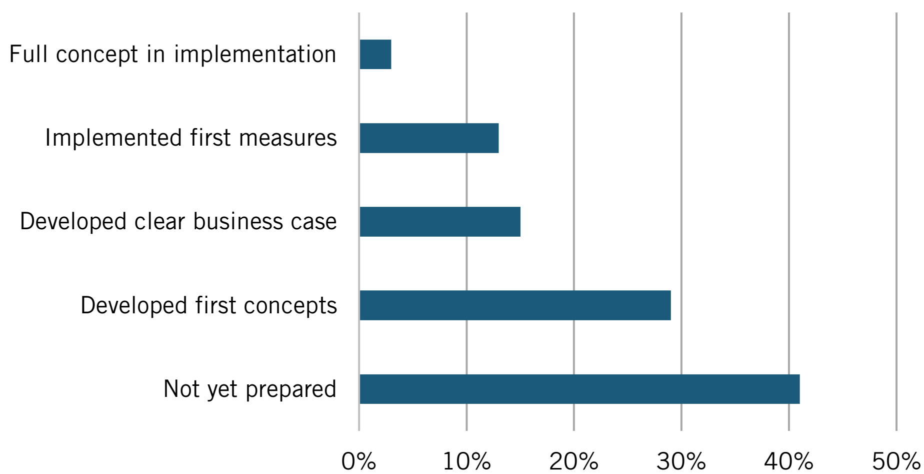
So far, digital manufacturing has thoroughly penetrated only a relatively small number of companies, most of them large multinationals. For instance, a September 2017 McKinsey survey of 400 manufacturers (mainly large firms and their suppliers, mostly from the

United States but also some from China, Germany, and Japan) found that roughly half of U.S. manufacturers in the survey had "no systematic digital roadmap or toolbox for easy rollout of digital manufacturing solutions" and that 15 percent "lacked knowledge of suitable suppliers."[78] Likewise, a 2016 Boston Consulting Group (BCG) study found that while 90 percent of U.S. manufacturing companies surveyed believed that Industry 4.0 technologies, including big data analytics, could improve productivity, "manufacturers overall are only adopting the digital processes one at a time or slowly."[79]

In March 2016, the Boston Consulting Group surveyed managers from 315 U.S. manufacturers (with revenues of at least $50 million) seeking to understand the status of their Industry 4.0 adoption plans. As figure 3 shows, as of Spring 2016, just 3 percent of U.S. manufacturers had a "full concept in implementation," 13 percent had "implemented first measures," 16 percent had "developed a clear business case," 29 percent had "developed first concepts," and 41 percent reported being "not yet prepared."[80]

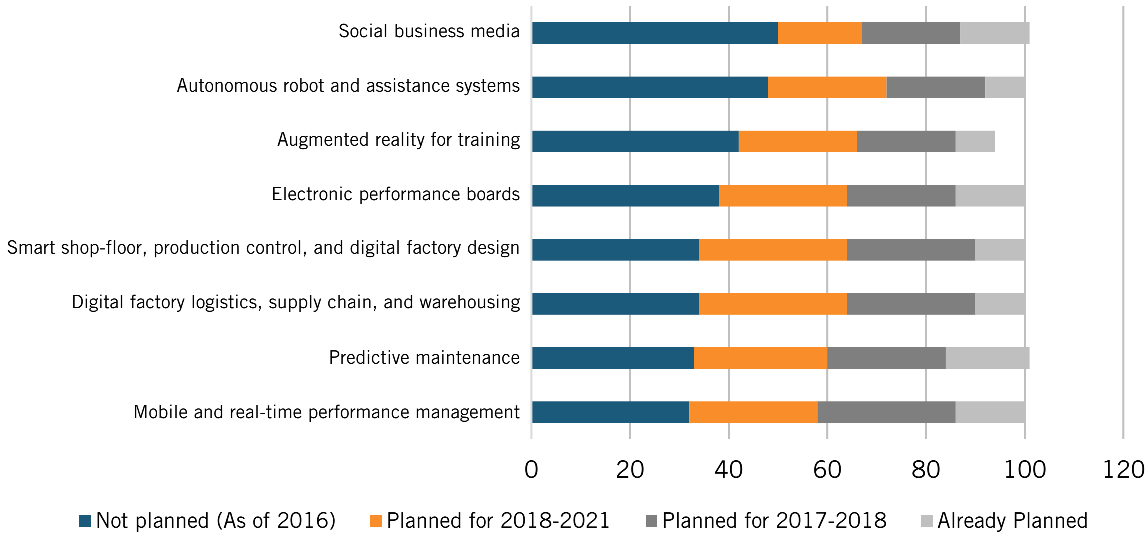
One 2016 survey found that the majority of U.S. manufacturers' Industry 4.0 implementations were planned for the years of 2018-2021, or were still not yet planned.

Figure 3: U.S. Manufacturers' Preparedness for the Introduction of New Technologies for Industry 4.0, as of March 2016[81]



That BCG report further asked about these manufacturers' anticipated Industry 4.0 implementations over the ensuing five years, from 2016 through 2021. As figure 4 shows, as of 2016, the top-five manufacturing digitalization implementations planned by surveyed U.S. manufacturers were: 1) Mobile and real-time performance management (42 percent); 2) Predictive maintenance (41 percent); 3) Digital factory logistics, Supply chain, and Warehousing (36 percent); 4) Smart shop-floor, Production control, and Digital factory design (36 percent); and 5) Electronic performance boards (36 percent).[82] By year end 2018, an additional 34 percent of surveyed manufacturers expected to have implemented "Augmented reality for training" and 28 percent to have implemented "Autonomous robot and assistance systems."[83] About three-fifths to two-thirds of U.S. manufacturers surveyed expected to have made implementations of the top-five types of Industry 4.0 implementation listed here by 2021.[84] Still, the BCG data suggested that, as of 2016, most of these manufacturers planned to implement the majority of their Industry 4.0 implementations between the years 2018-2021, or had still not yet planned any.[85]

Figure 4: U.S. Manufacturers' Anticipated Industry 4.0 Implementations, as of March 2016[86]



Also in June 2016, the Manufacturers Alliance for Productivity and Innovation (MAPI) released a report titled "Automation Investment in U.S. Manufacturing: An Empirical Picture" which surveyed (in December 2015) 402, mostly mid-size and large U.S.- and foreign-headquartered manufacturers operating in the United States to ascertain the extent of their investment in automation technology.[87] Specifically, 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."[88] In terms of size distribution, 28 percent of the surveyed manufacturers earned revenues less than $200 million, 29 percent had revenues from $200 million to $1 billion, 23 percent had revenues from $1 to $5 billion, 10 percent had revenues from $5 to $10 billion, and 10 percent had revenues greater than $10 billion.[89]

As figure 5 shows, 83 percent of MAPI-surveyed manufacturers reported they had made automation investments within the past five years, while 76 percent reported they planned to engage in automation investments over the ensuing three years. Of the companies making automation investments over the previous five years, 46 percent reported that they made their implementations "as rapidly as technology would allow" while 54 percent reported they made their investments "slowly and in stages." Among companies investing from 2015 to 2018, 76 percent reported they would do so as part of a "broader upgrade of automation" while 24 percent described their investments as a "complete asset base upgrade."[90]

Figure 5: Percent Manufacturers Engaged in Automation Investment in the Prior 5 Years and Planning to Engage in Automation Investment in the Coming 3 Years, as of December 2015[91]

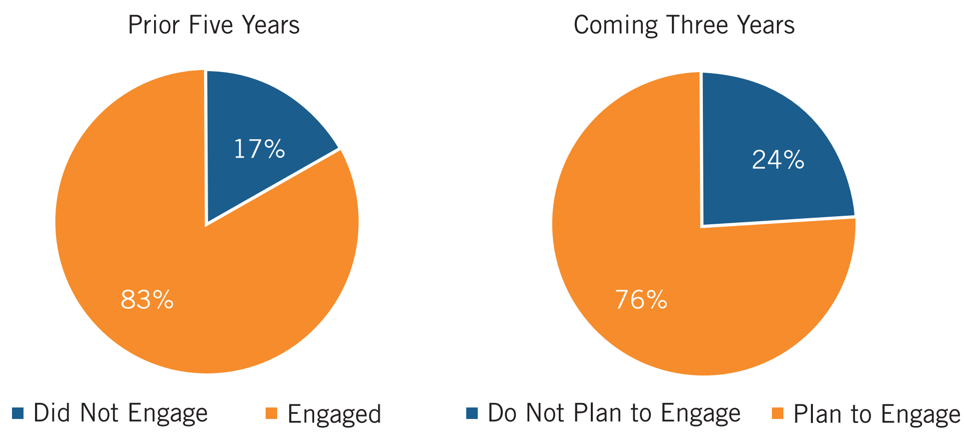
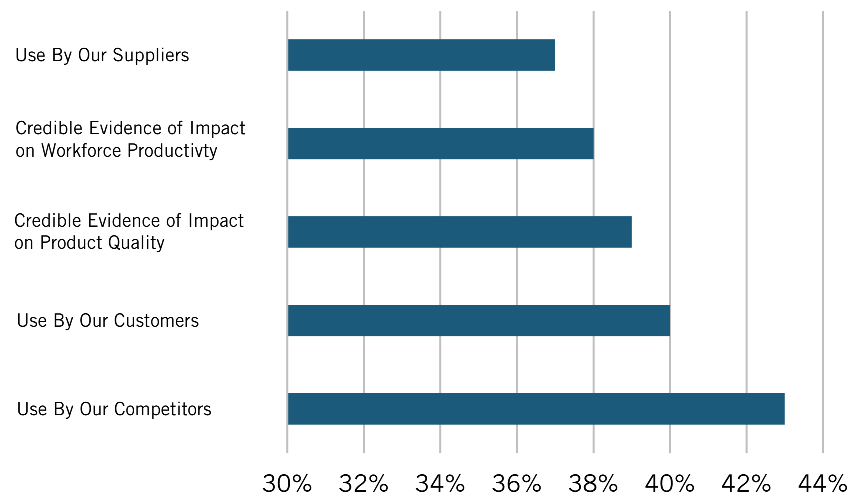


Figure 6: Top 5 Drivers of U.S. Manufacturers' Automation Investments[92]



In terms of the factors driving manufacturers' investments in automation technologies, as figure 6 shows, the top-five drivers of automation investment by surveyed U.S. manufacturers over the prior five years included: "use by our competitors"; "use by our customers"; "credible evidence of impact on product quality"; "credible evidence of impact of workforce productivity"; and "use by suppliers."[93] In other words, manufacturers' adoption of automation technologies seems principally driven by supply-chain pressures and competitive forces. Interestingly, the top five criteria manufacturers reported for evaluating the performance of new automation technologies were: 1) "whether it lowers total production costs" (56 percent); 2) "whether it improves product quality" (52 percent); 3) "whether it shortens times to market" (44 percent); 4) "whether it meets ROI requirements" (40 percent); and 5) "whether it shortens supply chains" (36 percent).[94]

Table 1: Share Within U.S. Manufacturing Industry Cohort Investing in Automation Technologies in Five Years Before or Three Years After December 2015[95]

	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%

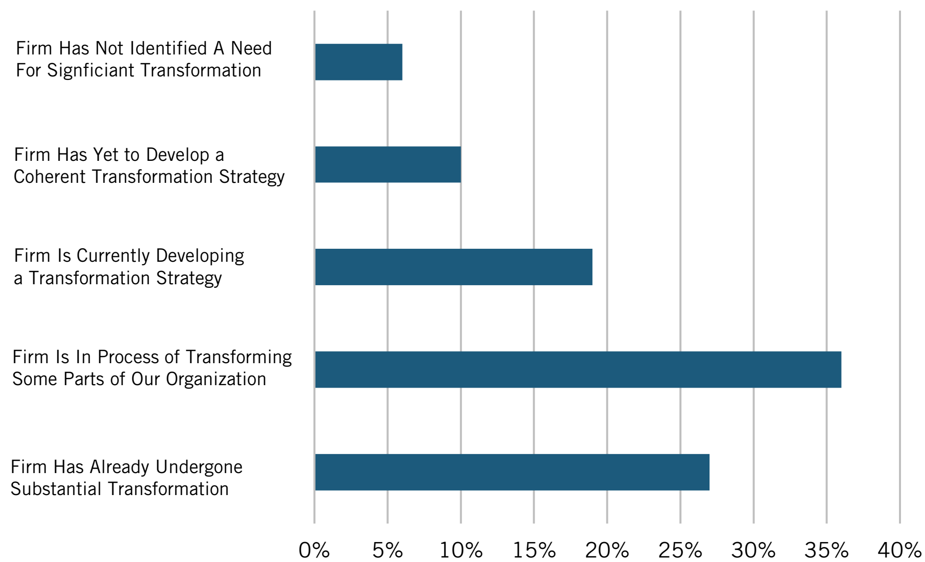
Table Courtesy: Waldman, Manufacturers Productivity and Innovation Alliance (MAPI)

The MAPI study further revealed that there's scant evidence of different levels of automation investment across major manufacturing subsectors. Indeed, as table 1 shows, U.S. manufacturers' investments in automation technologies have been roughly equivalent across manufacturing sectors. As the MAPI report explains, "Automation activity appears to be widespread across industries—neither just the high-productivity industries nor the low-productivity industries—but across all industries."[96]

To the extent there are significant automation investment differences among firms, it appears to be based more on size, rather than industry or type of production process. As the MAPI study explains, "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, just 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.[97]

Slightly more optimistic information has since emerged from a July 2017 survey conducted by The Economist Intelligence Unit (EIU) and Prudential of 537 manufacturing executives across eight U.S. industry segments, including 35 percent from large manufacturers with over 1,000 employees, 34 percent medium-sized manufacturers with 151-999 employees, and 31 percent small manufacturers with fewer than 150 employees.[98] However, this survey was not detailed about digitalization technology or specific transformations; rather it asked broadly to what extent the company was undergoing an "industrial transformation" process. As figure 7 shows, the survey found that 27 percent of companies had experienced "substantial transformation" and that 36 percent of companies were "in the process of transforming some parts of our organization," meaning that 63 percent of surveyed manufacturers reported they have experienced some degree of industrial transformation.[99] Of the remaining firms, 19 percent of their executives reported their companies to be "currently developing a transformation strategy," 10 percent that "they were aware of the need to, but have not begun developing a strategy," and 6 percent responded that they have "not identified a need for significant transformation."[100]

Figure 7: Extent of U.S. Manufacturers' "Industrial Transformations," July 2017[101]



U.S. Manufacturers' Implementation of Discrete Digital Manufacturing Technologies

Most surveys and studies have attempted to assess U.S. manufacturers' adoption of specific digital manufacturing technologies, as opposed to trying to understand the full breadth of their enterprise-wide digital transformations, as the prior section attempted to address. This section examines available data for U.S. manufacturers' implementation of specific digital manufacturing technologies, including: digital design, modeling, and simulation tools; the Industrial Internet of Things; cloud computing; data analytics; and digitalized production systems, including robotics and 3D printing.

Digital Design, Modeling, and Simulation Tools

America's largest automotive, aerospace, and heavy equipment manufacturers have used high-performance computing technologies in digital manufacturing for decades. In fact, a 2010 study by the National Center for Manufacturing Sciences found that already by then 56 percent of America's largest manufacturers (those with more than 10,000 employees) were using HPC-powered modeling and simulation tools.[102] An October 2014 Council on Competitiveness study, "Solve," reported that 72 percent of the approximately 100 large manufacturing enterprises surveyed believed that HPC is a cost-effective tool for R&D; 76 percent believed that "increasing the performance of computational models is a matter of competitive survival."[103]

But again, U.S. SMEs lag significantly in the adoption of these tools. According to Manufacturing Foresight, the vast majority, greater than 85 percent, of America's 250,000 SME manufacturers do not currently use digital design and manufacturing tools.[104] Similarly, a December 2013 study by the National Center for Manufacturing Sciences of Michigan's small manufacturers found that only 3 percent of respondents regularly use HPC for design and engineering purposes.[105] More positively, that study did find that more than 80 percent of Michigan's small machining, plastics processing, and metal-forming companies were using computer-aided design software (though not via high-performance computing platforms) and that almost 70 percent of firms were using inventory management or resource planning and scheduling (ERP/MRP) systems, although less than 70 percent were using engineering analysis software.[106] Nevertheless, it's clear that small U.S. manufacturers' use of digital design and manufacturing tools is rather underwhelming.

The vast majority, greater than 85 percent, of America's 250,000 SME manufacturers do not currently use digital design and manufacturing tools.

The Industrial Internet of Things/Sensors

In the fall of 2017, Industry of Things World USA surveyed 221 manufacturers; the survey included 24 percent of firms with fewer than 1,000 workers, 30 percent with 1,000-10,000 workers, 22 percent with 10,000-100,000 workers, and 24 percent with more than 100,000 workers.[107] As figure 8 shows, the study found that just 20 percent of U.S. manufacturers are "using IIoT to improve our production/operational processes, products, or services" and that 12 percent are investing in projects that will be live soon.[108] In other words, only about one-third of surveyed manufacturers are leveraging the Industrial Internet of Things, while about 30 percent more are evaluating the potential of IIoT. The survey further found that 37 percent of the surveyed manufacturers have "no IoT budget" within their organization (figure 9).

Similarly, a September 2017 survey by Emerson and Industry Week found middling U.S. manufacturing industry adoption rates for the Industrial Internet of Things: 60 percent of surveyed manufacturers were exploring or investing in Industrial IoT pilot projects, but only 5 percent were investing against a clear business case for how best to implement the technology.[109]

Figure 8: 2017 Industry of Things World USA Survey of U.S. Manufacturers' IIoT Adoption[110]

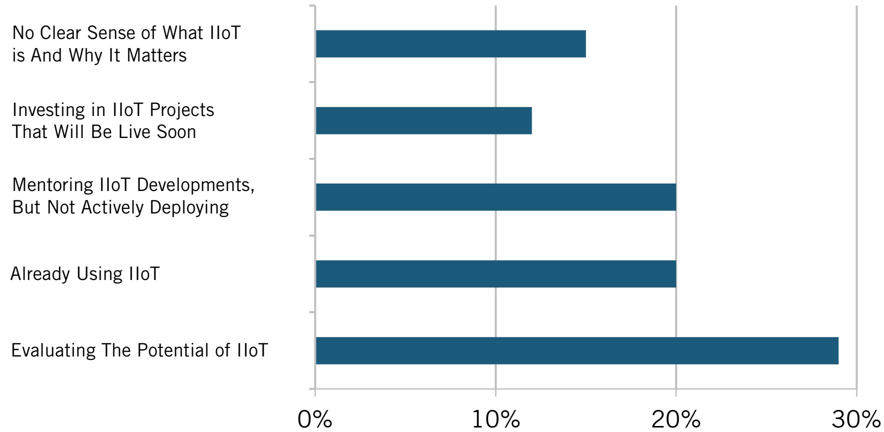
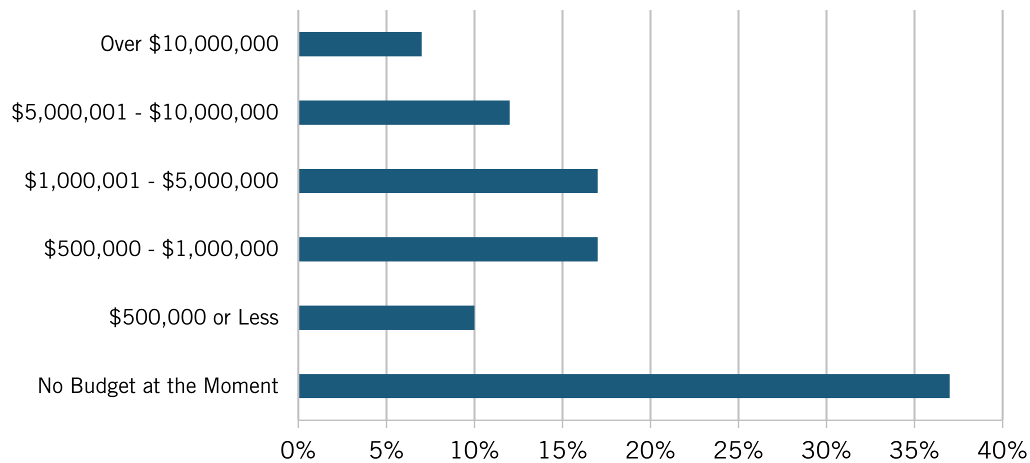


Figure 9: 2017 Industry of Things World USA Survey of U.S. Manufacturers' IIoT Investment Budgets[111]



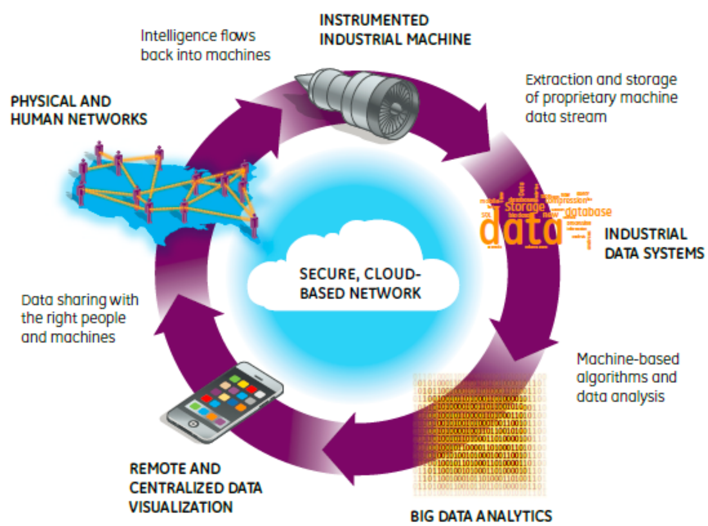
The August 2017 survey "2017 Annual IIoT Maturity Study," by BSquare (admittedly a provider of IIoT solutions), garnered 300 respondents representing firms with over $250 million in revenues operating in U.S. manufacturing, oil and gas, and transportation sectors. These reportedly had somewhat higher levels of IIoT adoption, e.g., "77 percent of manufacturing organizations are currently adopting IoT solutions" and "one-third of manufacturers surveyed established their IIoT solutions within the past year."[112] However, as Kevin Walsh, BSquare's vice president of marketing, noted, "Our study shows that while industrial organizations have enthusiastically adopted IIoT, a majority have not yet moved to more advanced analytics-driven orchestration of data insight…These later stages of IIoT maturity—analytics, orchestration, and true edge computing—tend to be where most of the ROI is realized."[113]

While the BSquare report found somewhat greater IIoT adoption among larger U.S. manufacturers, small U.S. manufacturers, in particular, are clearly lagging in IIoT adoption. 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.[114] Of these SME manufacturers, 77 percent reported they "still had no plans" to implement IIoT technologies.[115] 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.[116] 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 IIoT investment.[117]

Cloud Computing

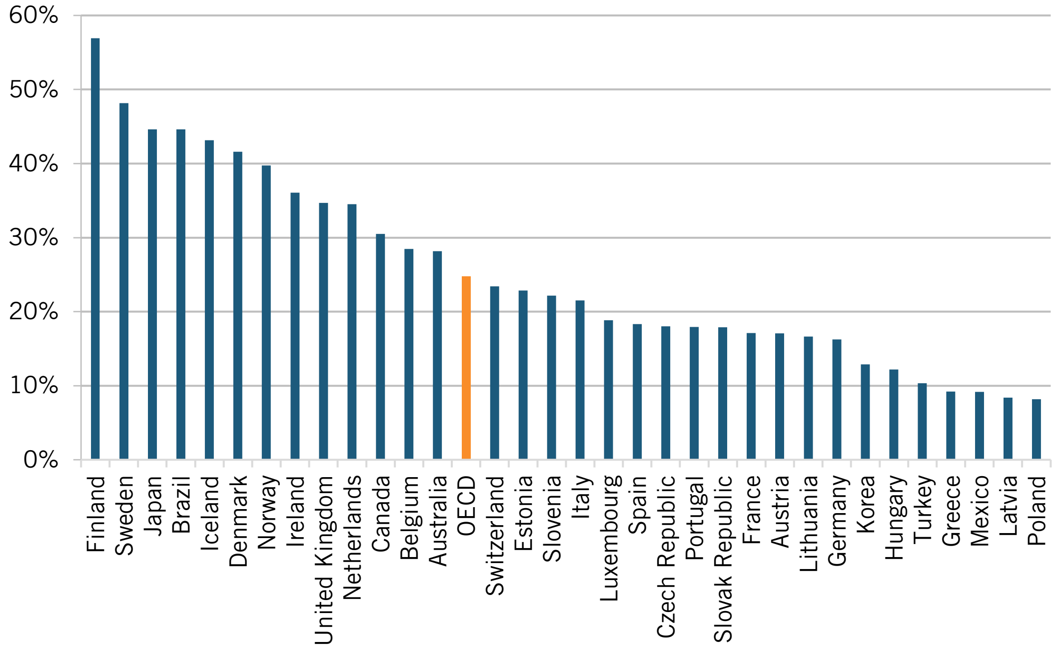
Cloud computing has become a key enabling technology for digitalized manufacturing.[118] As Marco Annunziata, GE's chief economist and executive director of global market insights, explains, "Cloud is definitely central to many of our key technologies on the industrial Internet" as shown by the company's Industrial Internet Data Loop (figure 10).[119] In other words, the cloud sits at the center, collecting and aggregating data from myriad sensors, production equipment, and end products in the field in order to facilitate big data analytics; it serves as the platform through which ERP and MES systems operate; and stores designs and sending commands to 3D printers or industrial robotics.

Figure 10: The Industrial Internet Data Loop[120]



Manufacturing initially got a later start in cloud computing (as compared to digital "pure play" sectors such as financial services), in part because it has required the embedding of network-connected devices into physical equipment—for example sensors into machine tools, or GPS-markers into an order for parts—in order to make the connection to the cloud possible.[121] In fact, in an October 2015 study by the Economist Intelligence Unit of 360 manufacturing executives, only 7 percent of respondents stated they believed cloud was exerting a pervasive presence in manufacturing industries (although even then 71 percent believed cloud computing would become a "major factor" in the industry).[122]

Figure 11: Share of Manufacturing Firms Using Cloud Computing Services by Country, 2015[123]



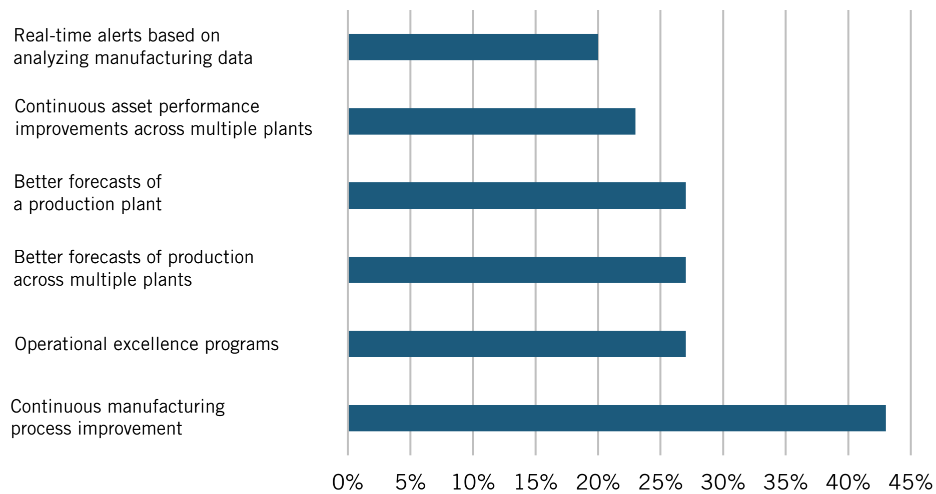
One study found that the share of U.S. manufacturers using both cloud-based productivity applications and data analytics techniques doubled between 2016 and 2017.

And, indeed, since then, U.S. manufacturers' adoption of cloud computing has accelerated rapidly. In November, 2017, Plex, a digital manufacturing cloud services provider surveyed 150 U.S.-based manufacturers (of all sizes) in industries ranging from automotive components to industrial equipment, aerospace, food and beverage, high technology, and plastics. According to its report, "2017 State of Manufacturing Technology," 90 percent were using cloud-based productivity applications, double the number in 2016.[124] In terms of benefits, 98 percent of respondents reported cloud applications were supporting continuous innovation; 96 percent reported the cloud was improving connectivity to systems, machines, suppliers, and customers; 80 percent said cloud facilitated data analytics; 71 percent said cloud helped them deal with fluctuating customer demand; and 45 percent reported that cloud applications were important contributors to new product introductions.[125] Going forward, cloud-hosted services are expected to account for nearly half of all organization-level software usage among manufacturers by 2023.[126] The OECD's "Digital Economy Outlook 2017" provided data for 33 countries (though unfortunately not for the United States) on the share of their manufacturers using cloud computing in 2015 (figure 11).[127] The "2017 State of Manufacturing Technology" report at least seems to suggest that U.S. manufacturers' use of cloud computing now exceeds that reflected in the 2015 data provided by the OECD for comparator nations, although of course the Plex data was compiled two years later. (Of course, a survey of only 150 manufacturers asking if they are using at least one cloud-based service of any type must be viewed guardedly).

Data Analytics

According to the "2017 State of Manufacturing Technology" report, twice as many U.S.-based manufacturers used data analytics in 2017 than in 2016, with data analytics applications focused foremost on improving core productivity and efficiency, followed by analytics for predictive maintenance and supply-chain risk management.[128] Nevertheless, according to the 2016 report "Manufacturing Metrics in an IoT World: Measuring the Progress of the Industrial Internet of Things," only 14 percent of the 4,000 respondents responded that their company was actively using manufacturing data in analytics.[129] The study found that the most popular data analytic uses were for "continuing manufacturing process improvement," "operational excellence programs," and "better forecasting of production," as figure 12 shows.

Figure 12: Most Popular Manufacturing Data Analytics Uses[130]



Other reports and analysts concur that the use of data analytics by U.S. manufacturers is in a fledgling stage. For instance, according to the "2017 Deloitte Global Human Capital Trends" report, just 41 percent of companies have fully implemented or made significant progress in adopting cognitive technologies within their workforce. Likewise, a 2017 study by consulting firm A.T. Kearney found that 70 percent of captured production data in manufacturing goes unused in the United States.[131]

Robotics

Robot penetration in U.S. factories has increased during this decade, yet it continues to lag behind that of other industrialized economies. According to 2017 data from the International Federation of Robotics, the United States ranks just seventh in the number of industrial robots per 10,000 workers (just 176 robots per 10,000 workers), which is just one-third of South Korea's figure of 531 robots per 10,000 workers, as figure 13 shows. The United States also trails Singapore, Japan, Germany, Sweden, Taiwan, and Denmark. Nevertheless, robot shipments to the United States increased almost 100 percent between 2010 and 2016.[132] America's automotive sector does fare better, with the United States ranking second globally with 1,261 industrial robots per 10,000 employees. However, as the McKinsey Global Institute report, "Making It In America: Revitalizing U.S. Manufacturing," notes, "while U.S. plants turning out vehicles and electronics are generally highly automated, robots have relatively little penetration in large U.S. industries such as metals and food processing."[133]

Figure 13: Number of Industrial Robots per 10,000 Workers, in 2017 by Country[134]

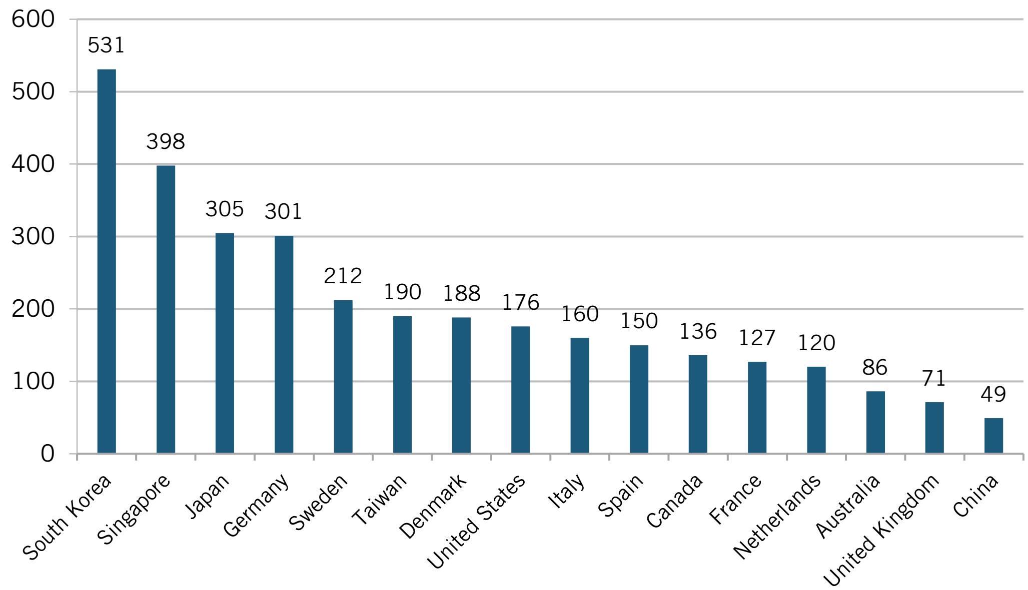
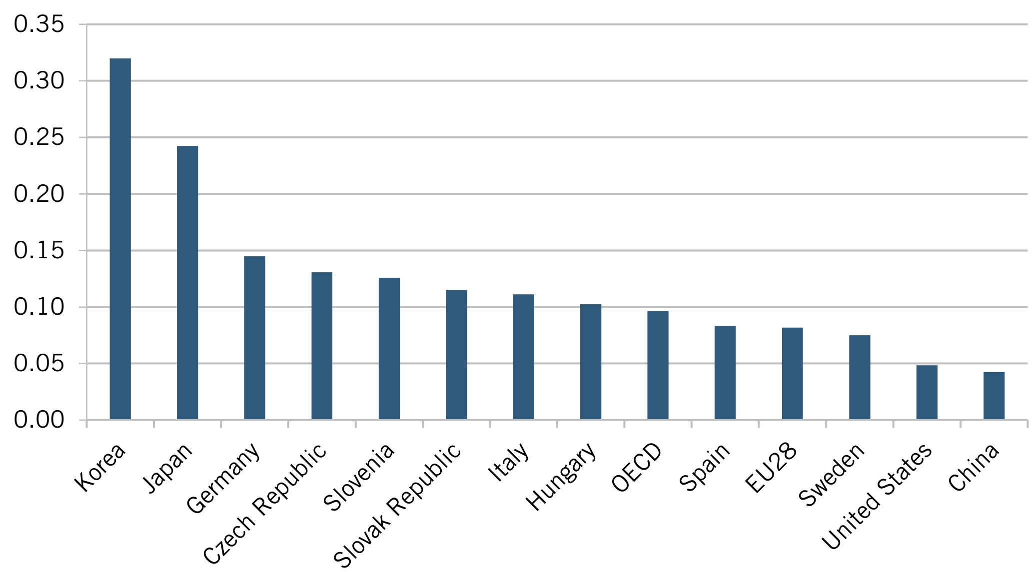


Figure 14: Top Robot-Intensive Economies, 2015[135]



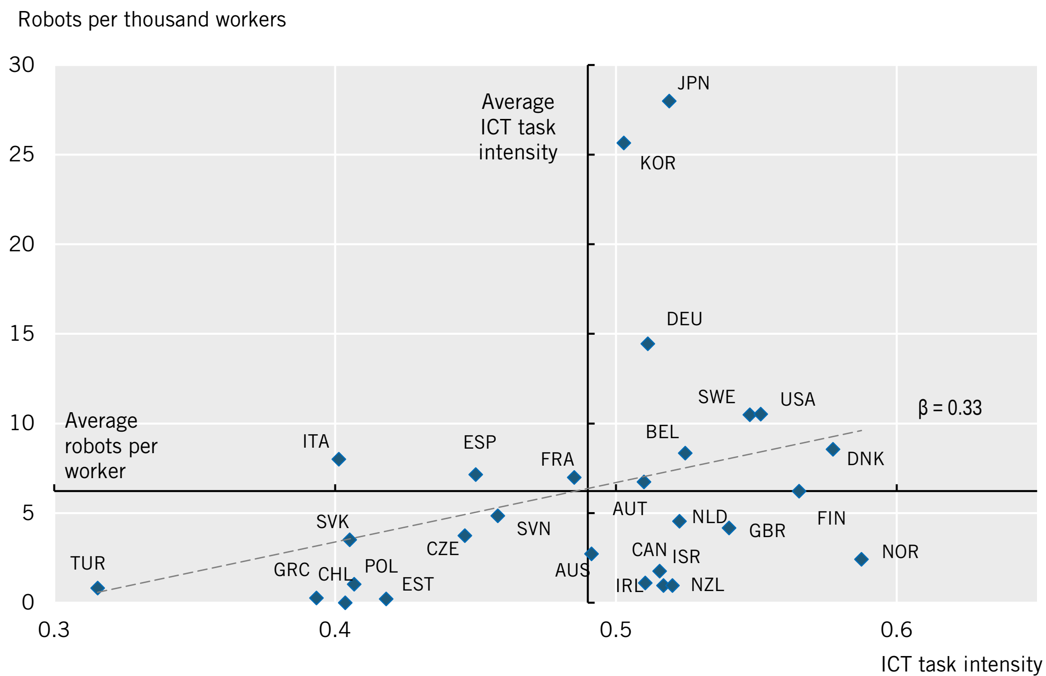
The Organization for Economic Cooperation and Development's *Science, Technology, and Industry Scoreboard 2017* report provides data on countries' "robot intensity," defined as "the industrial stock of robots over manufacturing value added."[136] As figure 14 shows, Korea and Japan clearly lead, with robot intensities about three times that of the average OECD country, while the United States clearly lags on this indicator, with an intensity actually below the OECD average. In fact, from 2005 to 2015, China's robot intensity increased from 23 percent to 88 percent that of the United States. These numbers should be seen as even more troubling given that the economic payback for robots is positively related to wage rates (and U.S. manufacturing wages are higher than in many other nations, including China, the Czech Republic, Slovenia, the Slovak Republic, and South Korea). In other words, if figure 14 controlled for how much robot adoption should occur given manufacturing workers' wages, the U.S. lag would be even greater.

As the OECD notes, the use of robots may complement the use of other technologies, because robots (although not classified as ICT tools) increasingly rely on ICT, especially software, for their functioning.[137] Robot penetration in U.S. factories has increased during this decade, yet it continues to lag behind that of other industrialized economies.

Robot penetration in U.S. factories has increased during this decade, yet it continues to lag behind that of other industrialized economies.

Figure 15 examines the correlation between ICT use on the job and robot intensity, finding it as positive (albeit not very strong) and pointing to complementarities between technological and human capital investment to implement transformative industrial processes. It shows the United States' ICT task intensity far exceeds its robot intensity.

Figure 15: Robot Intensity and ICT Task Intensity of Manufacturing Jobs, 2012 or 2015[138]



Additive Manufacturing (3D Printing)

The October 2017 "3D Printing Trends" report surveyed 303 manufacturing executives (84 percent of them from the Americas), with 40 percent of those surveyed representing firms with greater than 1,000 employees, 38 percent firms with 100 to 1,000 employees, and 22 percent firms with under 100 employees. Eighty-one percent of the executives surveyed reported that their firms were using 3D printing, with 70 percent using it for prototyping, but only 29 percent using 3D printing for producing parts; 93 percent reported they expected to increase the use of 3D printing for production parts in coming years.[139] Seventy-eight percent of the executives surveyed responded that they expect to at least double their use of 3D printing over the next two to five years;28 percent expect to increase printing by five times or more.[140]

Cross-Industry Comparisons

Collectively, the preceding statistics show that U.S. manufacturing digitalization is a work in progress. That assessment is further borne out in cross-industry evaluations of the extent of U.S. industry digitalization. For instance, in November 2017, the Brookings Foundation released a report, "Digitalization and the American Workforce" whose primary purpose was to ascertain the extent to which jobs in various U.S. industries rely on digital skills. The study leveraged data from the Occupation Information Network (O*NET) database, a project funded by the Department of Labor's Employment and Training Administration as well as historical Occupational Employment Statistics (OES) data from the Bureau of Labor Statistics.[141] Brookings identified 23 major U.S. industries and assigned them a mean digital score, based on two variables from the O*NET data. The first variable—"knowledge, computer and electronics"—measures the overall knowledge of computers and electronics required by a job, while the second—"work activity, interacting with computers"—quantifies the centrality of computers to the overall work activity of the occupation.[142] The study found "advanced manufacturing" to rank 13th out of the 23 major industry groups, with "basic goods" manufacturing ranking 15th (tied with three other industries). "ICT" (which does include some ICT manufacturing in addition to ICT services sectors) ranked seventh.[143]

Similarly, in 2015, the McKinsey Global Institute developed the MGI Industry Digitization Index, which examined 22 sectors through the lens of digital assets, digital usage, and digital workers, compiling 27 indicators to capture the many possible ways in which companies are digitizing.[144] Of the 22 U.S. industries, 4 were manufacturing-related: "Advanced manufacturing," "Oil and gas," "Chemicals and pharmaceuticals," and "Basic goods manufacturing." Of these 22 industries, "Advanced manufacturing" ranked as the sixth most-digitized, on measures including: digital spending, digital asset stock, transactions, interactions, business processes, market making, digital spending on workers, digital capital deepening, and the digitalization of work.[145] "Oil and gas" ranked seventh, while "Chemicals and pharmaceuticals" ranked ninth, and "Basic goods manufacturing" tenth. In a slightly more optimistic analysis, a November 2017 report by IHS Markit found that U.S. manufacturers have surpassed U.S. energy, maritime, agriculture, and chemicals enterprises in their adoption of IoT in business operations, moving past the "Connect" and "Collect" stages to a "Compute" stage, although not yet to the highest stage, "Create."[146]

Table 2: Industry Groups Ranked by 2016 Mean Digital Score[147]

Industry Group	Mean Digital Score 2002	Mean Digital Score 2016	Score Change 2002-2016
Professional, Scientific, and Technical Services	43	55	+12
Finance and Insurance	39	55	+16
Media	33	52	+19
Management of Companies and Enterprises	37	51	+14
Health Care services and Hospitals	35	46	+11
Real Estate and Rental and Leasing	26	45	+19
ICT	32	44	+13
Utilities	26	44	+18
Wholesale Trade	26	44	+18
Oil & Gas Extraction	25	43	+18
Educational Services	27	41	+14
Retail Trade	28	41	+12
Advanced Manufacturing	24	39	+15
Other Services (except Public Administration)	21	37	+16
Transportation and Warehousing	15	33	+18
Basic Goods Manufacturing	15	33	+18
Arts, Entertainment, and Recreation	17	33	+15
Construction	12	33	+21
Administrative and Support and Waste Management and Remediation Services	19	32	+14
Nursing and Residential Care Facilities, and Social Assistance	23	32	+9
Accommodation and Food Services	15	30	+15
Mining (Except Oil and Gas)	12	30	+18
Agriculture, Forestry, Fishing and Hunting	7	16	+8

U.S. Manufacturing Investment

This section examines U.S. manufacturers' recent investments in fixed assets broadly, and then in information technology specifically.

Fixed Asset Investment

U.S. manufacturing was hit very hard in the 2000s, losing some 6 million jobs while output declined by over one-third.[148] In fact, as late as 2017, U.S. manufacturing output had barely recovered to 2008 levels. Evidence of the drubbing U.S. manufacturing experienced can be seen in data on the percent change of the net stock of fixed assets by decade. As figure 16 shows, the net stock of U.S. manufacturing fixed assets grew very slowly in the 2000s and 2010s (2010 to 2017), both compared to total private-sector investment and to manufacturing-sector investment in previous decades.

Figure 16: Percent Change in Net Stock of Fixed Assets by Decade[149]

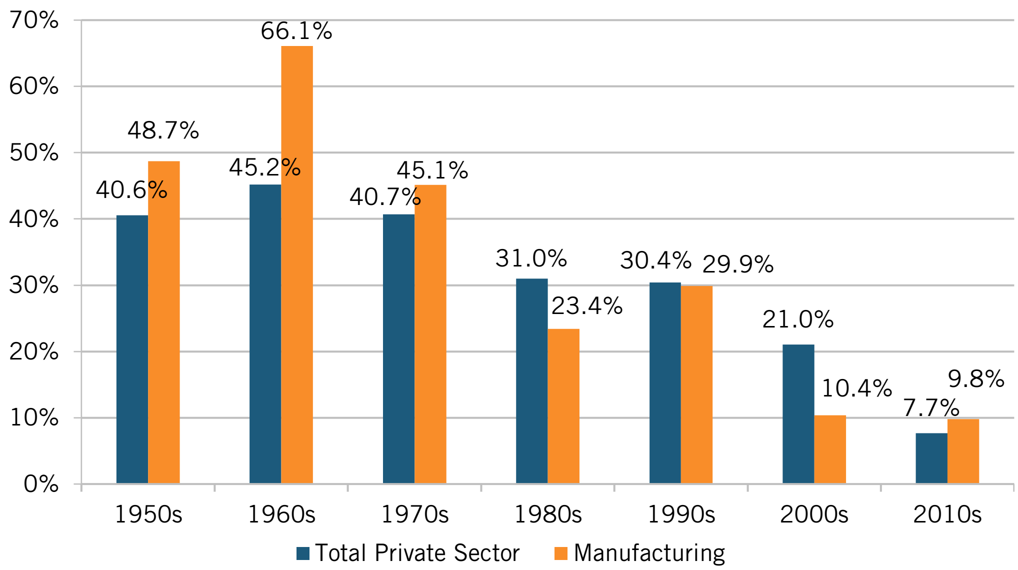


Figure 17: Average Annual Percent Change in Real Manufacturing Fixed Investment[150]

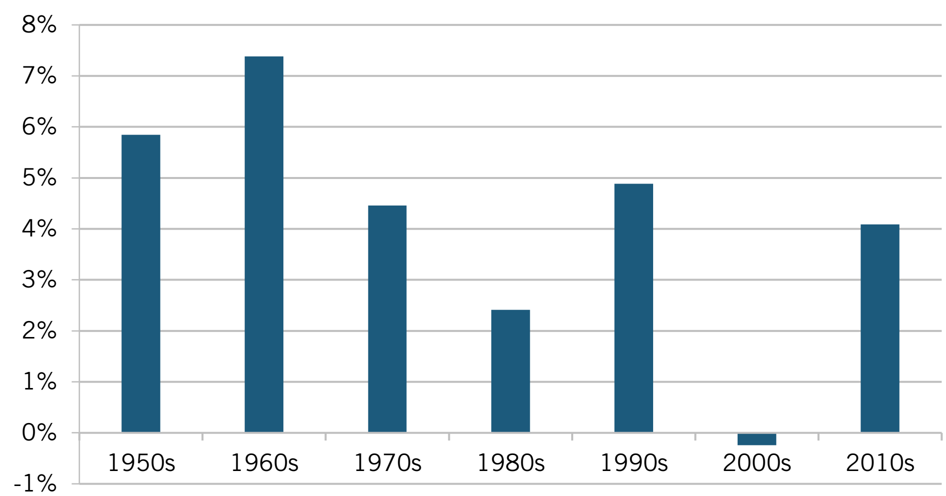
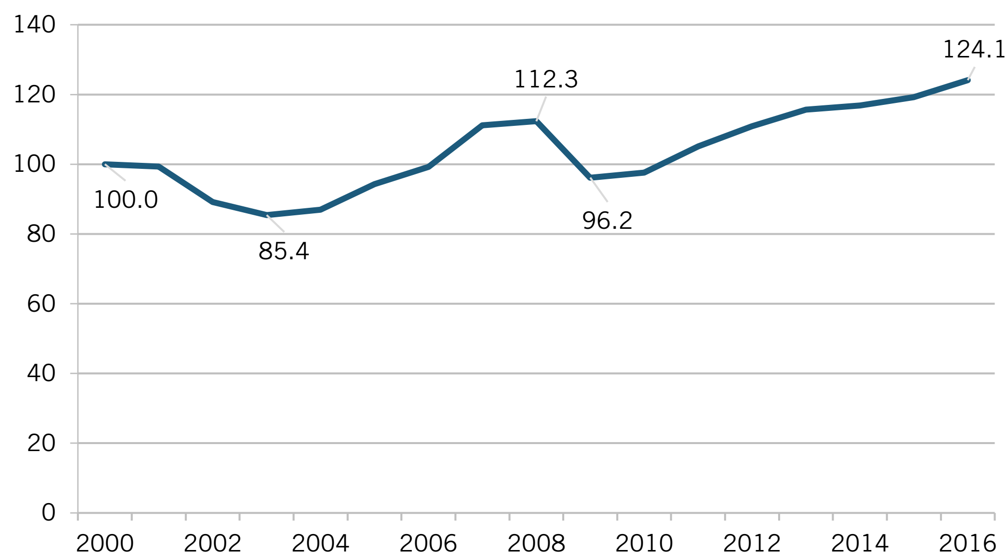


Figure 17, which depicts average annual percent change in real manufacturing fixed investment in the United States by decade from the 1950s to the 2010s, confirms this pattern, showing that in the 2010s, growth in real manufacturing fixed investment has still been below historical U.S. norms.

To be sure, as figure 18 shows, U.S. real manufacturing fixed investment has grown in absolute terms since the year 2000, beginning to recover particularly in the 2010s. Structures as a share of fixed investment has held steady at about 40 percent from 2000 to 2016.

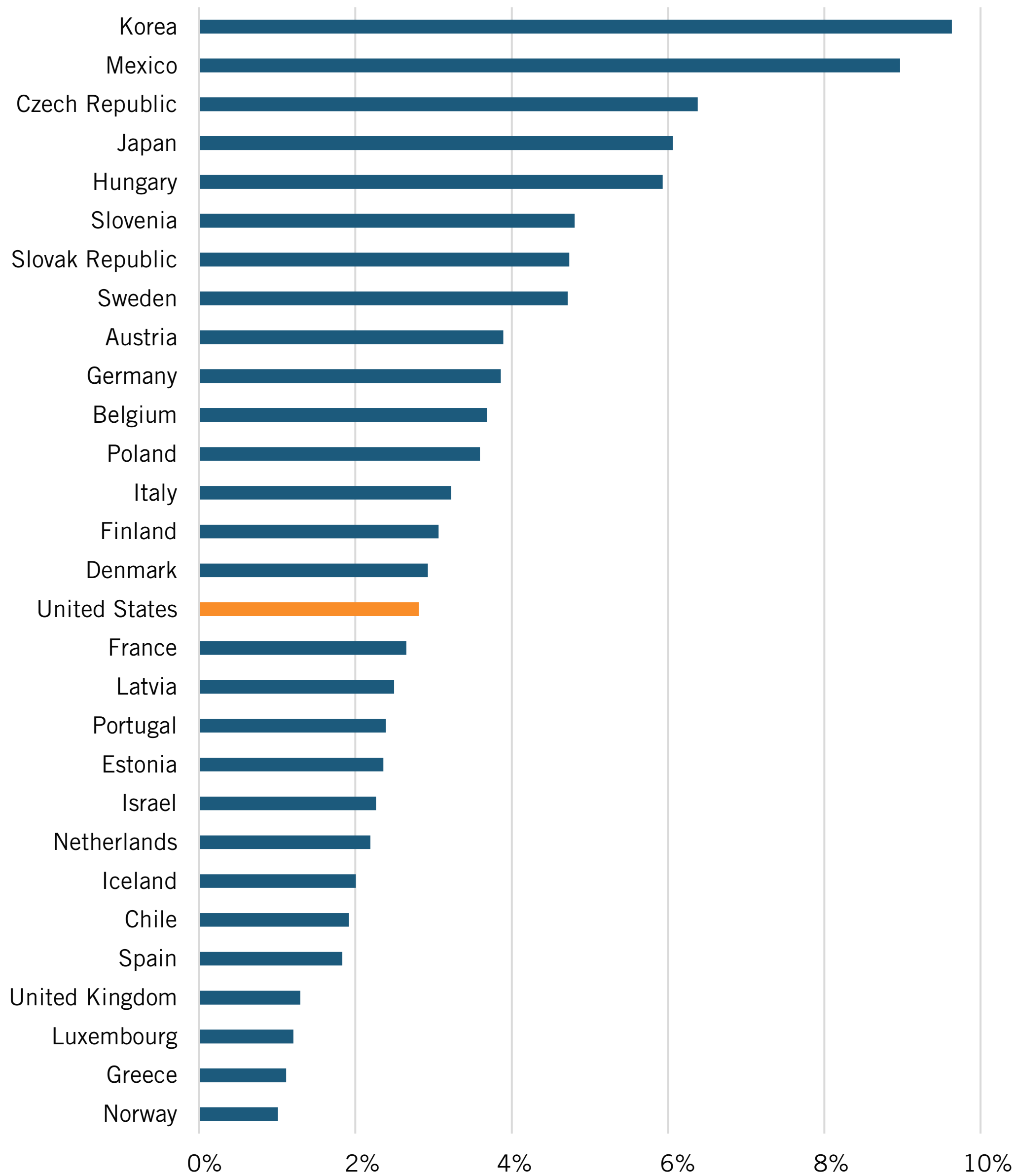
Figure 18: Real Manufacturing Fixed Investment (2000=100), 2000-2016[151]



Nevertheless, the reality, as figure 19 shows, is that U.S. manufacturing fixed investment, as a share of GDP, significantly trails that of global leaders such as Korea, Japan, and Sweden as well as up-and-comers such as Mexico, the Czech Republic, and Hungary. Collectively, these statistics are indicative of a U.S. manufacturing economy that has been sluggish in recent years and that is still trying to recover from the damage it experienced during the decade of the 2000s, including from the Great Recession.

U.S. manufacturing fixed investment, as a share of GDP, significantly trails that of global leaders such as Korea, Japan, and Sweden as well as up-and-comers such as Mexico, the Czech Republic, and Hungary.

Figure 19: Manufacturing Fixed Investment Share of GDP, (Latest Data Year Available, by Country)[152]



U.S. Manufacturers' Investments in Information Technology

U.S. manufacturers' investments in information technology have been middling in recent years, although they are showing signs of slowly accelerating. For instance, in a 2017 PWC report, just 42 percent of U.S.-based industrial-manufacturing senior executives responded that their companies were planning to increase spending on information technology in the ensuing 12 months.[153] A 2018 Infosys report, although of global manufacturers, did find a majority planning to invest in digital technologies in the coming 12 months, including 71 percent planning to invest in the Industrial Internet of Things, 68 percent planning to invest in 3D printing, and 67 percent planning to invest in cybersecurity.[154] Indeed, that's indicative of the fact that many U.S. manufacturers have been slow to exploit the power of information technology to improve design, production, and distribution. For example, the capital stock of software held by U.S. manufacturers was barely larger in 2014 than in 2001, as figure 20 shows. In fact, from 1994 to 2014, the capital stock of total information technology deployed by non-tech-based manufacturers rose just half as much as for all manufacturers (see figure 21).

Figure 20: Capital Stock of Software in U.S. Manufacturing[155]

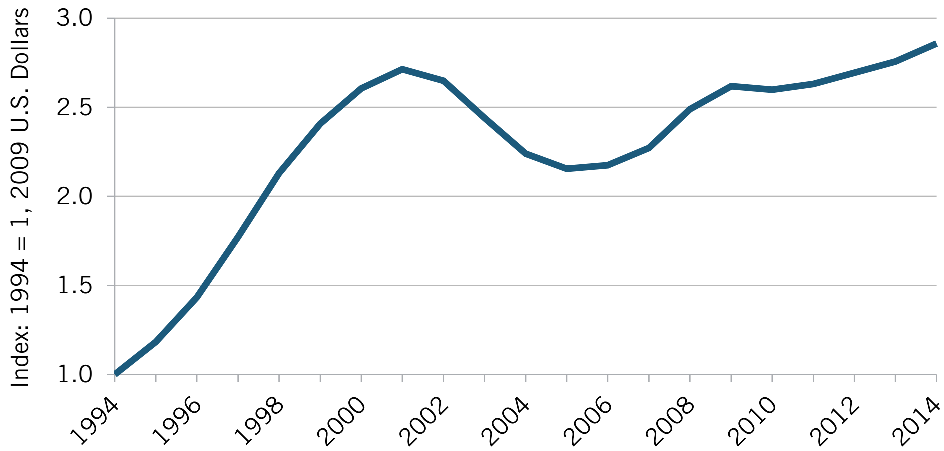
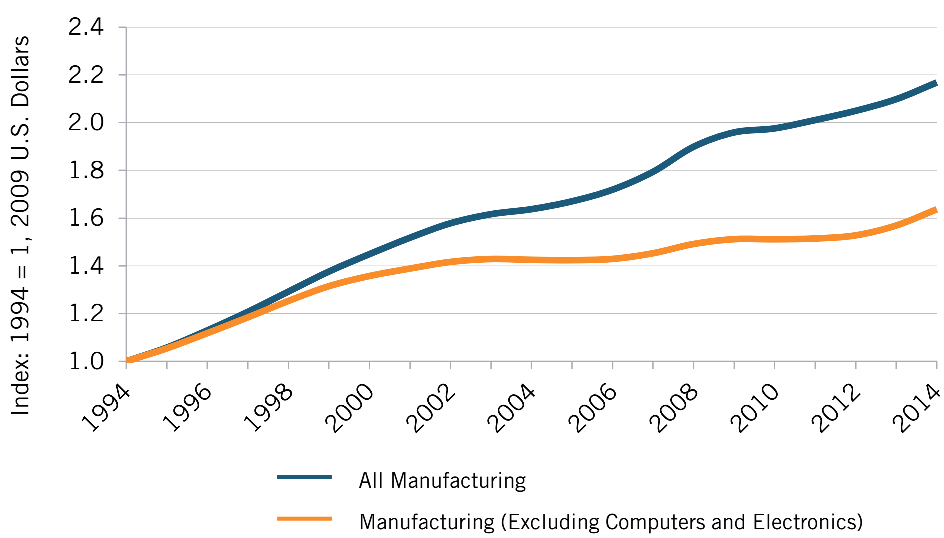
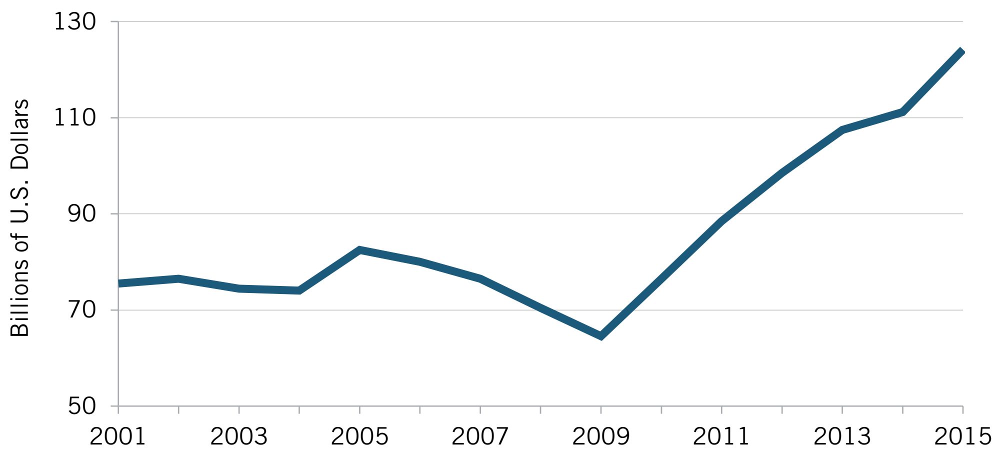


Figure 21: Capital Stock of IT Deployed by All Manufacturers Compared to All Manufacturers Minus Computers and Electronics[156]



Before the turn of the millennium, U.S. manufacturers were spending around $90 billion per year on information technology goods and services. A significant portion of that likely was related to fixing anticipated Y2K computer glitches. As many manufacturing sectors struggled during the 2000s, technology spending steadily declined, falling to just $64 billion at the nadir of the Great Recession. Soon after, however, despite a slow economic recovery, manufacturers began investing more in technology. By 2011, IT spending reached a level not seen since 2000, and it kept going up, rapidly. In 2015, manufacturers invested $124 billion on information technology services, twice the low point of 2009. This sharp increase after the nadir of the Great Recession is depicted in figure 22, and may represent the leading edge of the digital revolution in manufacturing.[157] It likely reflects manufacturers' spending on cloud computing and storage, software as a service, cloud-based design, and the non-investment components of other digital platforms like supply chains, distribution, customer support, workforce training, and the Internet of Things. In other words, U.S. manufacturers' investments in digital and information technologies may finally be showing real signs of life.

Figure 22: Spending by U.S. Manufacturers on Information Technology Goods and Services[158]



Why Has Progress Been So Slow? Challenges to the Digitalization of Manufacturing

As the previous section indicated, there remains a long way to go before the vision of smart manufacturing can be fully realized across a national (or even global) economy. This is true 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.[159] In fact, initial analyses based on an IAB-ZEW Working World 4.0 survey conducted in early 2016 found that although around half of German companies are using "technologies of the fourth industrial revolution," on average only 5 percent of all firm assets could be described as "production facilities 4.0" and only 8 percent as "electronic office and communications equipment 4.0."[160]

Put simply, it's still early, and manufacturers large and small alike face a number of hurdles in capturing the promise of smart manufacturing.[161] For instance, the SME manufacturers queried 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.[162] Moreover, as Douglas Woods, President of the Association for Manufacturing Technology (AMT), notes, "There's actually a lot of capability on production machines out there already, but it's not being used to its full extent because small companies, especially, often don't know how to leverage IIoT or digital technologies—which would allow them to reap more productivity from existing equipment.."[163] And as Sree Ramaswamy of the McKinsey Global Institute notes, "Even for companies that make a start, they seem to end up in 'pilot purgatory', endlessly piloting but not able to scale up their Industry 4.0 implementations across the enterprise."[164] There are a number of specific challenges, as the following section elaborates.

Legacy Assets

To get a sense of how much work remains to be done, the McKinsey Global Institute estimates that truly achieving Industry 4.0 will require upgrading about 40 to 50 percent of the current asset base across U.S. manufacturing industries.[165] In particular, machinery will need to be upgraded or replaced to accommodate IoT sensors and actuators and new high-performance computing platforms will be needed to support advanced modeling and simulation as well as analytics to mine data sets.[166] This imperative will become all the more pressing as existing U.S. manufacturing plant and equipment continues to age. In fact, whereas the average U.S. factory was 16 years old in 1980, today it's 25 years old. The average piece of plant equipment was seven years old in 1980, but is nine years old today.[167]

Technology Not Fully Mature

As Industry Week's Jessica Davis notes, "Implementing an Internet of Things program isn't exactly like flipping a switch. There's a lot involved, from sensors where the data is initially collected to the network the data travels, to the analytics systems that figure out what it all means."[168] And only now are analytics vendors like SAS or Splunk even launching formal divisions or product offerings to support manufacturing IoT analytics.[169] That's one reason why research firms Gartner finds that, at least through 2018, three in four IoT projects actually take up to twice as long as planned.[170] Further, some of the software and technology itself still has bugs and technical issues to be ironed out.[171]

Chicken-or-Egg Issues

One market failure that afflicts innovation in complex ecosystems stems from the fact that markets tend to be poor at coordinating action when multiple parties need to work together synergistically and simultaneously.[172] Such chicken-or-egg challenges must be overcome for innovation to occur around technology platforms such as near=field communications (NFC)-enabled contactless mobile payments, intelligent transportation systems (ITS), health IT platforms, digital signatures and electronic IDs, and the smart electric grid.[173] The same is no less true for the digitalization of manufacturing. If smart manufacturing is to work effectively, all parts of a country's manufacturing ecosystem—including OEMs and their suppliers at all levels of the value chain—need to digitize. Moreover, different industries, from aerospace and automotive to machine tools and medical devices, will have differing digital-integration challenges. Coordination among industry players will be needed to foster industry-wide manufacturing digitalization, and if a country's private-sector firms, particularly the OEMs, aren't willing to take a leading role here, then it's particularly important that public policy facilitate the development of public-private partnerships that can make digital integration happen.

Fragmented Markets and Providers and A Lack of Interoperable Standards

Smart manufacturing still faces a number of interoperability and standardization challenges. But 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.[174] 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 among them and for the overall semantics, or how data gets seamlessly passed from one device to another."[175] Thus, standardization of architectures, data-exchange formats, vocabularies, taxonomies, ontologies, and interfaces will be key to creating interoperability between different digital manufacturing technologies.

Challenges holding back greater adoption of smart manufacturing include legacy assets, lack of technological maturity, chicken-or-egg issues, fragmented markets, a lack of interoperable standards, skills gaps, and a lack of information on how to proceed.

Accordingly, the two key issues standardization must address are ensuring interoperable interfaces among 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.[176] At the same time, however, the report notes that, "whoever is first to define such internationally accepted standards will likely gain a long-term competitive advantage."[177]

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 among 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.[178]

Lack of Requisite Skills and Competencies

If American industry is to lead the smart manufacturing revolution, it will need a workforce equipped with the requisite skills.[179] A recent study by Accenture contends that 80 percent of America's manufacturing workers lack at least some essential skills needed to take full advantage of the potential of smart manufacturing.[180] Likewise, according to the Deloitte Consulting and the Manufacturing Institute report, "The Skills Gap in U.S. Manufacturing 2015 and Beyond," "Manufacturing executives report a significant gap in their ability to find talent with required skills. More troubling…the skills gap is expected to grow substantially over the next decade."[181] Specifically, that report finds that 70 percent of U.S. manufacturing employees lack necessary technology/computer skills, 69 percent lack key problem solving skills, 67 percent lack basic technical training, and 60 percent lack necessary math skills.[182] A particular challenge is that while many U.S. manufacturers, especially SMEs, have employees with the necessary mechanical engineering skills, they need to bolster their computer science skillsets. In particular, more training and firm-level skills are needed in mechatronics, a multidisciplinary field of science that includes a combination of mechanical engineering, electronics, computer engineering, telecommunications engineering, systems engineering and control engineering.[183]

Lack of Information on How to Proceed, Especially for SMEs

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 DMDII 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.[184] 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.[185] The "Industry 4.0" development path developed by Acatech (referenced in figure 2) and accompanying guidebook represent good examples of a country's efforts to help SME manufacturers navigate their digital transformation journeys.

HOW U.S. PUBLIC POLICY IS SUPPORTING MANUFACTURING DIGITALIZATION

At least 30 nations have explicit strategies to support the digitalization of their manufacturing industries. While the United States has taken steps in this direction, it does not have close to the well-formed strategy of many of the countries depicted in figure 23.

Figure 23: Countries That Have Introduced Some Form of Industry 4.0 Support Strategy[186]

Nevertheless, the two most significant federally supported entities spearheading U.S. manufacturing digitalization are the Digital Manufacturing and Design Innovation Institute, and the U.S. Manufacturing Extension Partnership (MEP). As the following section explains, they are increasingly working in closer collaboration.

MEP represents a public-private partnership with centers in all 50 states dedicated to increasing the technical and innovation capacity of America's SME manufacturers.[187] Run by the National Institute of Standards and Technology (NIST), part of the U.S. Department of Commerce, MEP operates 580 field offices comprised of 1,200 technical experts and 2,300 allied service providers serving as trusted business advisors focused on solving manufacturers' challenges and identifying opportunities for growth.[188] MEP receives approximately $130 million in federal funding annually (although the past two Trump administration budgets have threatened to zero out program funding). States must match federal funding of the MEP centers at least dollar-for-dollar. The non-federal share is mostly met by client fees and finances provided by the states.

At least 30 nations have developed explicit strategies to support the digitalization of their manufacturing sectors.

MEP is a successful program. An April 2018 study, "The National-Level Economic Impact of the Manufacturing Extension Partnership," by the W.E. Upjohn Institute, found that MEP generates a substantial economic and financial return, nearly 14.5:1 for the $128 million annually invested by the federal government in the MEP program.[189] The study further found that total employment in the United States was over 219,000 individuals higher, that U.S. GDP is $22.01 billion larger, personal income is $13.76 billion higher, and personal income tax revenue to the federal government is $1.86 billion higher because of MEP center projects than it would be without the program.[190]

The Digital Manufacturing and Design Innovation Institute is a Chicago, Illinois-based public-private partnership representing one of America's 14 Institutes of Manufacturing Innovation comprising Manufacturing USA. It serves as the United States' central hub for the development, showcasing, access to, and transmission (especially to SMEs) of knowledge, tools, software, and expertise related to manufacturing digitalization. The Obama administration announced DMDII's formation in February 2014 with $70 million in federal funding, which has thus far received at least $140 million in 2-1 matching from companies, universities, and state and regional governments.[191] DMDII serves as a state-of-the-art proving ground for digital manufacturing and design that links information technology tools, standards, models, sensors, controls, practices and skills, and transitions these tools to America's design and manufacturing industrial base for full-scale application.[192]

DMDII works with firms of all sizes, including trying to assist SMEs. As Caralynn Collens, CEO of UI Labs (which manages DMDII), explains, "We've learned a number of lessons over the past 18 months in working more closely with SMEs on manufacturing digitalization."[193] Collens notes that DMDII has placed focus on two key areas: 1) Working with MEP Centers on promoting SMEs' awareness, assessment, and planning for manufacturing digitalization, thereby helping them to better understand solutions they can actually implement; 2) Developing SME-targeted workshops: day-long programs providing SMEs examples of tools and resources, and demonstrating how manufacturing digitalization can be implemented and add real value.[194]

In 2017, NIST announced it would embed a MEP representative in each Manufacturing USA Institute in order to facilitate transmission of the manufacturing processes, technologies, and knowledge being developed at the Institutes across America's base of small manufacturers. IMEC, Illinois's MEP Center, was designated as the embed for DMDII. In support of the first goal that Collens noted—raising SME awareness and facilitating assessment—DMDII and IMEC have teamed to develop a "Digital Manufacturing and Design" assessment tool. The tool is part of an overall "train-the-trainer" course for MEP practitioners, which includes facilitating understanding of the digital product lifecycle and digital thread, the role of technology scouting, and technology-driven market intelligence services for digital manufacturing. With these initiatives, the MEP program is doing more to support digital manufacturing among U.S. SME manufacturers, although it is only now getting these types of digital manufacturing support programs off the ground.

As IMEC President David Boulay explains, the "Digital Manufacturing and Design" assessment tool is comprised of the following five components:[195]

1. **Design and engineering.** Identifies the kinds of CAD/E (Computer Aided Design/Engineering) software that are used in the client company's day-to-day operations. This also includes a discussion regarding the kinds of CAD/E information the client exchanges with its customers and suppliers. Lastly, it helps identify possible CAD/E data-related conversion problems that may exist.

2. **Enterprise support operations.** Addresses a company's enterprise resource planning practices, with the main intent of identifying what kinds of automated sales and scheduling system integration is used in the company's day-to-day operations. It further helps evaluate the types and methods (e.g., automated, manual) of data entered and used in the company's systems.

3. **Digital factory floor.** Addresses the client's shop floor practices, with the main intent of identifying what kinds and levels of automation and system integration is used in the client's day-to-day operations. Further, it assesses the kinds of data that are generated and exchanged with the company's machines and equipment, along with any possible data-collection challenges and opportunities that may exist.

4. **Supply chain data exchange.** Focuses on a company's supplier and customer relationship practices, with the main intent of understanding the degree of supply chain system integration. This includes the kinds and frequency of information that are exchanged with suppliers, customers, and internal business systems. It also explores the kinds of data that are captured, stored, and tracked and the possible interpretation problems the client may or may not be aware of.

5. **Cybersecurity.** Practices for security of IT systems and cyber-physical systems, including manufacturing equipment (such as machine tools, inspection systems, or any device connected to some type of controller). It also inquires about which standards have been deployed, approaches used, and if any requirements or regulations are being addressed, such as DFARS (Defense Federal Acquisition Regulation Supplement).

Each section of the "Digital Manufacturing and Design" assessment tool consists of a series of questions related to these topics. The questions examine the hardware/software, processes/methods, and workforce skills of the small manufacturer. The assessment is intended to be customized based on the manufacturer. For instance, the design/engineering section may be removed if the manufacturer does not have design services. The result of each assessment will be a customized report that identifies potential strengths and areas of likely focus to advance the manufacturer's digital readiness.

DMDII, in association with IMEC, Illinois' MEP program, have co-developed a "Digital Manufacturing and Design" assessment tool to measure U.S. manufacturing SMEs' readiness for digital manufacturing.

Over 30 MEP centers have been trained on the tool thus far. Each center that completes the train-the-trainer course then conducts "lunch and learn events" and pilot company assessments in their state. However, the MEP has only started to begin rolling out the tool in recent months, so data on its impact or effectiveness is not yet available. However, further to the training objective, DMDII has collaborated with the University of Buffalo and Coursera to develop an online, 10-part "Digital Manufacturing and Design" series that has so far been viewed by over 30,000 students and manufacturing professionals.[196] It's available on Coursera under "Digital Manufacturing & Design Technology Specialization."[197]

Further to the "Awareness" objective Collens noted, DMDII has also partnered with the ManpowerGroup to develop a comprehensive taxonomy of emerging roles and skills in the digital manufacturing and design space. The report identifies 165 potential digital manufacturing and design roles, provides a comprehensive index of requisite skills and representative tasks pertaining to each role, and offers 20 success profiles for representative roles.[198] Of these "Digital Skill Set Job Roles" the taxonomy finds that: 28 percent of them will pertain to Digital Manufacturing & Processing; 21 percent to managing the Digital Thread; 16 percent to the Digital Enterprise; 11 percent to Digital Supply Chains; 10 percent to Digital Design; and 8 percent to managing Digitally Enabled Products.[199] The taxonomy helps make clear that a number of new jobs and roles will be created in the smart manufacturing economy and provides a roadmap to the training, skills, and expertise that will be required to fill them. It also provides a pathway for standardization of credentials around these skill sets.

But, as Collens continues, "We knew we'd helped SMEs assess their situation (through the Digital Assessment Tool), but we realized 'then what? How can we help SMEs actually implement real solutions?'"[200] In response, DMDII has developed a one-day "Digital Disruption Workshop" for SMEs that includes 10 different "Experiential Sessions." These sessions—covering discrete facets of manufacturing digitalization such as 3D-printing applications, smart sensor- and IoT-enabling existing machines to facilitate predictive and preventative maintenance, etc.—feature solution providers on-site demonstrating the applications as a "one-of-a-kind demonstration center" where SMEs can, as Collens explain, "see the implementations coming to life and realize practical, tangible takeaways."[201] DMDII has conducted three such workshops so far, with three more planned for 2018. Workshop surveys so far have found that: 80 percent of respondents report the workshop "changed or shaped their digital journey"; 43 percent report the workshops "advanced their thinking on manufacturing digitalization"; and 17 percent report they are "actively piloting solutions learned from the workshops" in their factory.[202]

But as Collens observes, the next step for DMDII is to "package these solutions" so they can reach U.S. manufacturers at scale. A first "packaged solution" will pertain to cybersecurity. In 2015, nearly half of cyber-attacked manufacturers globally hailed from the United States, while 35 percent of cyber-espionage attacks in the United States were directed at the manufacturing sector.[203] This means that ensuring the cybersecurity of manufacturers is paramount, especially for SMEs that enjoy only limited resources to protect their operations.

Accordingly, in March 2018, DMDII launched the National Center for Cybersecurity in Manufacturing that will serve as a "testbed for the creation and adoption of new cybersecurity technologies to secure manufacturing shop floors across the United States."[204] The Center will enable testing of cybersecurity use cases in a real-world manufacturing environment, facilitate the development of hands-on cybersecurity training programs, and create online, on-demand learning modules to reach manufacturers outside of the (Chicago, Illinois) region.[205] Specifically, DMDII has developed a "SME Cyber Assessment and Mitigation Tool" to help SMEs improve their cybersecurity practices in partnership with the Critical Infrastructure Resilience Institute at the University of Illinois. The tool includes a "user-friendly, consumer-style interface that walks users through existing cybersecurity best practices and mitigation recommendations in a series of step-by-step modules."[206] DMDII is further developing a "SME Cyber Training Program" intended to serve "as a neutral, trusted cyber-physical based test bed accessible to government, industry, and academia to evaluate existing and future manufacturing technology for cyber security."[207]

Another "packaged tool" DMDII is developing is 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 a 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.[208]

In January 2018, DMDII opened its manufacturing floor as a testbed for manufacturers and academic institutions needing to quickly test process improvements. By opening up its R&D testbed to the community, DMDII can help manufacturers avoid having to buy expensive testing equipment or to sacrifice production capacity for experimentation.[209] In addition to advanced manufacturing equipment, DMDII will also make technical experts and expertise—including in mechanical engineering, electrical engineering, systems integration engineering, manufacturing engineering, machining, and assembly—available to the community. As Thomas McDermott, chief program officer of UI Labs (which operates DMDII) explains, "We're alleviating a bottleneck in the manufacturing R&D processes…Helping companies validate a new technology in six days when it could otherwise take six months."[210] One of DMDII's partners, Rolls-Royce, reported that it was able to use DMDII's testbed facilities to test three new manufacturing tools and processes within a week. Formerly, it would have taken more than three months for them to do this internally.[211]

To further elaborate on the above, DMDII features nearly 100,000 square feet of collaboration space that serves as a demonstration center and pilot test bed where two pilot manufacturing production lines are actually running. The first is the Digital Capability Center, an innovative experiential learning facility DMDII founded in partnership with McKinsey that showcases the impact of digital manufacturing and provides training across the entire value chain on digital capabilities.[212] The Center represents a learning environment where participants can explore more than 20 experiential learning modules, leverage deep expertise to identify the technologies that are critical for their business, and access an ecosystem of over 50 technology partners providing innovative solutions across the value chain.[213] A second production line at DMDII is "the Future Factory Line," a modular factory line that actually manufactures on-site a Stanley Black & Decker impact driver to demonstrate how digital technologies can be integrated into manufacturing processes to save time and money, increase safety, and boost productivity.[214] As James Ray, global industrial president of Stanley's Engineered Fastening business, explains, "Our partnership with DMDII has been phenomenal…we get real-time data and real-time learnings and plow those right into our production facilities."[215] And, as Caralynn Collens articulates the importance of DMDII's Digital Capability Center and Future Factory lines, "America has long been a leader in innovating on the manufactured product, but it has to improve on innovating on the manufacturing process, and that's what these model production lines allow us to test and demonstrate."[216]

Building further on this, later in 2018 DMDII will launch a "Future Factory Discrete Manufacturing Testbed," followed later by a Process Manufacturing Testbed. These testbeds will integrate existing smart manufacturing technologies, identify which sensor data types can enable the biggest business impact, and enable the development of a digital twin. DMDII ultimately plans to translate these testbed learnings to a member manufacturer's operational environment.[217] (The concept of "digital twin" refers to having a pro forma software model of a product, such as a jet engine, and then maintaining virtual copies, or "images" of each instance of that product as actually deployed in the field: e.g., General

Electric has a digital model of each aircraft engine in the world, tracking its operational history, unique attributes, etc. Digital twin can also apply to a manufacturing system, such as DMDII's Discrete Testbed.)

As part of the Future Factory Testbeds, DMDII is pursuing several concrete actions, including:

- Undertaking an IoT Sensor ROI Analysis: Doing modeling, surveys, and empirical tests to determine which sensor data, if collected and leveraged, could produce the greatest return for manufacturers, particularly in predictive maintenance applications.[218]
- Developing a workshop for educating manufacturers on sensor integration and making optimal use of data analysis tools.
- Applying the digital twin modeling approach to an actual factory environment, thus "driving a business case that enables replication by others."[219]

The cost of many digital manufacturing technologies has already fallen considerably in recent years, bringing the timeframe to positive ROI closer for many manufacturers.

To be sure, DMDII plays a pivotal role in demonstrating the potential benefits of smart manufacturing, but it's the MEP centers in the states that often work hand-in-hand with small manufacturers to shepherd them through digital transformations. As Mike Coast and Bob Lyscas of the Michigan Manufacturing Technology Center (Michigan's MEP Center) explain, "We try to break down digital implementations into realistic, bite-size chunks with demonstrable positive return on investment that can build proof points for digital manufacturing's potential. We try to help small manufacturers understand that they can start with a single machine, or a work cell, and start to automate that machine or cell, and it's not going to cost you a half-million dollars."[220] Coast and Lyscas note that the cost of digital manufacturing technologies has already fallen considerably. As Lyscas explains:

> In some areas like smart sensors or robotics, the cost has been reduced by as much as 80 percent even over the past three years; what was costing in the area of $750,000 three years ago might be closer to $100,000 today. That lower cost is accelerating return on investment (ROI). For a 150-200 person-size company, we're seeing ROI 1.2-2 years and on the larger size firms (200-500 employees) we're seeing good ROI data in the two to five year timeframe. We work with SMEs to show them how to collect this data, place it in the cloud, and then drive it back across their business, and make real-time decisions on actions or equipment purchases.[221]

It should also be noted that MEP is launching a new initiative called "The Future Is Now Framework," which will "adopt guiding principles into the MEP National Network which will help to migrate the MEP Program from a Program Office and System of Centers to a National Network with value-added Program Office support, allowing a broader range of complementary services and information tailored to evolving manufacturing business owner's needs."[222] Essentially, MEP's the Future is Now (FIN) effort seeks to develop an integrated brand and network of capabilities across MEP.[223] When MEP was established in

1982 during the Reagan Administration, it made sense to have a network of state-focused centers working with manufacturers in each state. But a state-by-state focus presents difficulties when the challenges are increasingly horizontal in nature—e.g., cybersecurity, manufacturing digitalization, supply chain integration, etc.—and it makes less sense for each MEP center to develop its own capabilities in these areas independently. The challenge for MEP going forward, which FIN is trying to address, is to be able to develop and deliver expertise on these advanced manufacturing issues across each of the 50 states more consistently.

One area MEP has made progress in is recognizing that, because supply chains cross state boundaries, MEP needs more cross-state, sector-based MEP initiatives (e.g., autos in the U.S. Midwest and South). In other words, MEP is trying to take on more of a supply-chain and sector-based focus. MEP has also developed an explicit supply-chain optimization (SCO) initiative designed to help manufacturers build dynamic supply chains by developing a long-term strategy, increasing visibility throughout multiple supplier tiers, identifying and mitigating risks, identifying ERP systems that are compatible across supply chain tiers as well as appropriate and affordable for SMEs, and understanding total cost of ownership (TCO) and other best practices that encourage strategic partnerships throughout the supply chain.[224] MEP's SCO projects often begin with a two-day workshop that trains clients in specific techniques for developing a long-term vision for their company and its suppliers, and that then creates specific functional strategies to make the vision real, applicable, and executable.[225]

Some private-sector institutions, associations, and non-profits are making contributions to advancing U.S. manufacturing digitalization. For instance, the Association for Manufacturing Technology has supported the development of MT Connect, a free, open standard that enables manufacturing equipment to provide structured, contextualized data with no proprietary format.[226] 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.[227] MT Connect thus 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 worldwide.

Going forward, the Association for Manufacturing Technology will host a yearly technology event called MT360, which will be held in Silicon Valley and whose intent will be to bring Fortune 500 companies together with startups and academics to create an annual signature U.S. event on manufacturing innovation and "try to find a way to get everyone on the same page."[228] AMT has also created a C-Level Manufacturing Tech Council among its members to further promote and facilitate manufacturing digitalization. As AMT President Douglas Woods explains, "We're trying to find ways to ignite U.S. manufacturers' adoption of digital manufacturing which could propel greater uptake across larger swaths of the U.S. manufacturing sector."[229] AMT is also working to build and make available an inventory of three-dimensional smart manufacturing data analytics toolsets.

America's National Science Foundation operates two forms of industry-university partnerships that have relevance for U.S. digital manufacturing: Engineering Research Centers (ERCs) and Industry/University Cooperative Research Centers (I/UCRCs). ERCs are a group of interdisciplinary centers located at universities, where academe and industry can collaborate in pursuing strategic advances in complex engineered systems and systems-level technologies that have the potential to spawn whole new industries or to radically transform the product lines, processing technologies, or service-delivery methodologies of current industries.[230] The I/UCRC program forges partnerships between universities and industry, featuring industrially relevant fundamental research, industrial support of and collaboration in research and education, and direct transfer of university-developed ideas, research results, and technology to U.S. industry to improve its competitive posture in global markets.[231]

U.S. OEMs need to take more ownership for driving digital transformation within their supply chains, including among their SME supplier base.

While no ERC or I/UCRC program currently addresses digital manufacturing directly, a number of centers are developing technologies that may have impact on facets of digital manufacturing, including the following: Advanced Electronics through Machine Learning; Center for Embedded Systems; Visual and Decision Informatics; Net-Centric & Cloud Software & Systems; Center for High-Performance Reconfigurable Computing; and Nanosystems ERC for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies.[232]

Another important program is the Department of Defense's ManTech (Manufacturing Technology) program, which anticipates and closes gaps in manufacturing capabilities for affordable, timely, and low-risk development, production, and sustainment of defense systems.[233] As Jason Jouet, deputy director of manufacturing technology in the Office of the Deputy Assistant Secretary of Defense for Manufacturing and Industrial Base policy, explains, "Our program looks to develop cross-cutting, defense-critical manufacturing needs that are beyond the ability of a single service or industry to address."[234] DoD ManTech provides a crucial link between technology invention and development and industrial applications.[235] DoD ManTech served as the source of federal funding for both the Digital Manufacturing and Design Innovation Institute as well as for other Manufacturing USA Institutes including LIFT (Lightweight Innovations for Tomorrow) and the American Institute for Manufacturing Integrated Photonics. The Defense Department annually invests about $12 billion in science and technology-related initiatives.

Activity in U.S. States

Several U.S. states have notable initiatives to support manufacturing innovation, including manufacturing digitalization. The following profiles initiatives in Virginia and Texas.

Virginia

Experts recognize Virginia's Commonwealth Center for Advanced Manufacturing (CCAM) as one of the state leaders in supporting manufacturing innovation. CCAM delivers "production-ready" manufacturing solutions at the speed of business with the intellectual rigor and innovation of universities.[236] CCAM focuses on three key technology areas: Adaptive Automation Systems, Surface Engineering, and Additive Manufacturing.[237] CCAM's physical footprint includes a 60,000-square foot facility housing computational and large-scale production labs, as well as a high bay, open-production space for heavy equipment, and surface-coating processes. CCAM seeks to spread research risks and costs among members to maximize the value of their R&D investments, conducting "generic research" on behalf of all members, although members may also sponsor "directed research" of particular interest to them. In addition to providing members with access to state-of-the-art facilities and research equipment, the center employs experts experienced in translational research who can help bridge the gap between research and commercialization. CCAM also supports workforce development by training students from Virginia universities so they can graduate with relevant industry experience, and through its creation of an Advanced Manufacturing Apprentice Academy.[238] Associated with CCAM is a new Advanced Manufacturing Laboratory at the University of Virginia that will help train students and support innovation in computer-aided design, precision milling, and 3D printing applications, particularly attuned to aerospace requirements.

Texas

The Texas A&M Engineering Experiment Station (TEES) and Texas A&M University have launched the Institute for Manufacturing Systems (IMS) as a leading center of cyber-manufacturing research, particularly for custom-parts manufacturing.[239] The North American Advanced Manufacturing Research and Education Initiative, based in McAllen, Texas, is an advanced manufacturing incubator that brings together partners from across the Rio South Texas Region to develop and recruit the skilled talent needed to grow the region's advanced manufacturing infrastructure.[240]

Policy Recommendations to Further Advance U.S. Manufacturing Digitalization

This section provides additional policy recommendations that could be undertaken by Congress or the Trump administration to further advance the digitalization of U.S. manufacturing.

Better federal tracking of data on U.S. manufacturers' implementation of digital technologies. Practically no data was available for this study from U.S. federal government agencies supporting manufacturing. Questions on the extent and types of smart manufacturing technologies U.S. manufacturers are implementing should be included in future U.S. business R&D and innovation surveys.

Introduce mechanisms to encourage OEMs to take more ownership of manufacturing supply chain digitalization. Large U.S. manufacturers have tended to keep their suppliers at arm's length, too often treating them on a transactional basis with cost as the principal concern. But as the McKinsey Global Institute notes, "this approach can affect the bottom line. One

McKinsey study found that inefficiencies in OEM-supplier interactions add up to roughly 5 percent of development, tooling, and product costs in the auto industry."[241] Put simply, U.S. OEMs need to take more ownership for driving digital transformation within their supply chains.

Accordingly, the U.S. government should provide incentives for U.S. OEMs to help 10,000 SMEs to become IoT-enabled (that is, smart-manufacturing enabled) within 10 years. The OEMs and Tier 1s (the suppliers who sell directly to original equipment manufacturers) need to press their suppliers to upgrade their equipment (otherwise it's just not on the SMEs' radar screens) and support them in these efforts. The OEMs could host workshops/seminars to guide SME suppliers in digitalization strategies and on how explicitly to integrate digitally into supply-chain management systems. Federal incentives could take the form of grants for a certain number of suppliers engaged. Also related to this, the OEMs tend to want transparency regarding the parts flowing out from the suppliers, but the suppliers may not desire this, so there are issues about who controls and secures the data. By incentivizing OEMs to collaborate with SMEs on these questions, approaches can be found that add value for both parties and frameworks set up with regard to data ownership issues.

Congress should create a competitive grant program that enables community colleges to bid to serve as digital manufacturing hubs for their regions.

Create regional digital manufacturing hubs/scale pilot digital manufacturing centers/testbeds. DMDII's Digital Capability Center and Future Factory Line represent compelling, practical, real-world exemplars of the potential of manufacturing digitalization, but they are one-offs; they need greater scale. As Collens notes, "the challenge is replicating or scaling such manufacturing demonstration centers/test-beds across the country."[242] Congress could provide funds to replicate these pilot digital manufacturing centers/testbeds to connect with smaller manufacturers across the country, such as by embedding them in national laboratories, universities, and regional community colleges.

Essentially, manufacturers need to be able to "kick the tires" of smart manufacturing systems to see how they actually work and understand what specific technologies are involved. At the same time, they need workers with new skills, including both engineers and technicians. As such, Congress should create a competitive grant program that enables community colleges to bid to serve as digital manufacturing hubs for their regions. To qualify for federal funding, community colleges would need to obtain a match from state or local governments of at least one to one; and in order to continue receiving funds to obtain at least some funding from industry partners/clients. Funding for such centers should be for at least five years, conditional on center performance. This program could be jointly operated by the Department of Labor and the National Institute of Standards and Technology.

Increase MEP funding and rethink MEP cost share requirements. MEP touches about 25,000 of America's approximately 250,000 SMEs each year, or about 10 percent. MEP could do much more if it were more robustly funded. But the reality is 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.[243] 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 overall; and Canada invests almost 10 times as much in its Industrial Research Assistance Program (IRAP).[244] Instead of zeroing out MEP, the United States should increase MEP's annual funding to closer to $200 million, putting it in line with historical norms. Additional federal funding would allow MEP centers to develop more programs helping companies scale up from lower- to higher-volume production and get innovative products to market faster.

Another challenge is that, largely because of the cost-share requirement, MEP too often has to be concerned with "fighting fires" in real-time and doesn't have the latitude to be forward-thinking about the future. Especially when SME clients are paying for MEP services, they're often interested in the here and now and near-term payoff, not on what investments they need to make (or services MEP needs to provide) to keep them competitive five years down the road.

Support SMEs' digital manufacturing investments. SMEs, in particular, need capital to invest in digital manufacturing approaches. Yet U.S. SMEs' lack of access to working capital is acute. For instance, a recent McKinsey study found that fully one-quarter of SMEs in the mid-Atlantic region lack the capital even to meet their working-capital needs.[245] In fact, access to capital has generally been tighter for SMEs in the United States than in other OECD countries since the Great Recession.[246] Moreover, studies estimate that the inability of small firms to invest in equipment and plant upgrades contributes to a stark 40 percent productivity gap with large firms.[247] Accordingly, Congress should launch a "U.S. Manufacturing Digitalization Investment Fund" that would provide repayable, low-interest loans to American SME manufacturers to help finance upfront investment in digital manufacturing technologies and solutions.

Manufacturing Foresight, an Ann Arbor, Michigan-based, independent, nonprofit, expert-driven organization focused on the future of U.S. manufacturing technology, policy, and the workforce, has likewise called for the U.S. government "to provide loan guarantees and technical assistance to accelerate the pace of modernization of SMMs, including capital equipment and implementation of smart manufacturing technologies."[248] Further, the Trump administration should direct the Small Business Administration (SBA) to identify steps to ensure that at least one-third of all SBA Section 7A loans are made to manufacturers. Right now the share is only 7.5 percent.[249]

Provide more generous tax credits for investments in new machinery and equipment. Despite the 2017 tax reform (which did constructively provide for expensing of investments for five years), Congress could provide an even stronger tax incentive for investment in machinery and equipment. Specifically, Congress should enact an investment tax credit (ITC) providing a 25 percent credit on all capital expenditures made above 75 percent of a base amount.[250]

Expand funding for Manufacturing USA Institutes and make funding permanent. The Revitalizing American Manufacturing Innovation Act (RAMI), Congressional legislation which authorized America's Manufacturing USA Institutes, specified that program funds may not be awarded to an institute more than seven years after the first award. But comparable programs in other countries, such as Germany's Fraunhofer Institutes, receive core institutional funding from the government on a permanent basis. Such funding could provide flexibility to institute managers and confidence to industry members, while limiting the influence of the largest industry members, including foreign-headquartered firms that might otherwise dominate an institute's agenda. Congress should consider a permanent program of support for the Manufacturing USA institutes, perhaps at an ultimate level of no more than 20 or 25 percent of their budgets, while maintaining incentives for them to seek industry members, ensure that they remain industry-led, and undergo evaluations for continuation on a regular basis.[251]

Congress should launch a "U.S. Manufacturing Digitalization Investment Fund" that would provide repayable, low-interest loans to American SME manufacturers to help finance upfront investment in digital manufacturing technologies and solutions.

OVERVIEW OF KOREA'S SMART MANUFACTURING POLICIES

An official visit by South Korean President Park Geun-hye to Germany in early 2014 inspired South Korea's government, through its Ministry of Trade, Industry, and Energy (MOTIE), to launch the "Manufacturing Industry Innovation 3.0" program in June 2014.[252] The initiative represented 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.[253] 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.[254]

That matters greatly because SMEs dominate South Korea's economy: South Korea has over three million in total and 99 percent of Korean manufacturers are SMEs. (Specifically, Korea's 408,659 SME manufacturers account for 99.6 percent of Korea's 410,151 total manufacturing firms, and 79 percent of manufacturing employment.)[255] This means 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 of building 10,000 Smart Factory Sites for Korean small businesses by 2020.[256] 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.[257]

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.[258] (Those investments fit 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.)[259] 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.[260]

Korea wants to have 30,000 factories operating with the latest digital and analytical technologies by 2025.

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.[261] In essence, factories participating in the Korea Smart Factory Initiative are demonstrating 25 percent productivity improvements.[262] 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.[263] 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.[264]

An especially important consideration of Korea's Manufacturing Industry Innovation 3.0 program is to enable South Korean businesses to enhance their manufacturing technology.[265] That's particularly important for two reasons. First, because, South Korea's manufacturing sector has come under growing pressure because of its low capacity (relative to China's)and the steadily improving quality of Chinese manufacturers.[266] 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.[267] 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 as a share of total business investments were just 10 percent, compared to over 30 percent in the United States.[268] It also explains why, from 2005 to 2010, IT capital contributed just 0.2 percentage points to total Korean growth, and overall 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, 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 non-ICT investments.[269] For these reasons, effectively adopting manufacturing digitalization 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 only the United States and Germany.[270] 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.[271] 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.[272]

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."[273] 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, 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 sector: "technological hardware and equipment" (i.e., smartphones). Progress is pointing in the right direction, however. In 2017, the World Economic Forum ranked Korea 13th in its global competitiveness rankings for the fourth industrial revolution, and Korea placed 14th in IMD's (the Swiss business school's) *2018 World Digital Competitiveness Rankings*, up from 19th in 2017.[274]

POLICY RECOMMENDATIONS TO FURTHER ADVANCE KOREAN MANUFACTURING DIGITALIZATION

As outlined in the previous section, Korea has already implemented many appropriate and important policies to support the country's manufacturing digitalization, including investing significantly in R&D and technology roadmap development for key Industry 4.0 technologies such as IIoT platforms, smart sensors, big data analytics, standards, etc.

Also commendable is the development of the model "smart, digitalized factories" as part of the Korea Smart Factory Initiative and the commitment to have 30,000 smart factories operating across 10 key sectors by 2025. That's the right approach because one of the most important priorities should be the diffusion of manufacturing digitalization technologies and approaches (that in many cases already exist actually) and encouraging their uptake more quickly by Korea's manufacturing base. The following provides additional policy recommendations Korea should consider.

Explicitly Support Manufacturing Digitalization by Korean Manufacturing SMEs

Korea should launch a comprehensive national program for SME manufacturing digitalization, including funding for SMEs to invest in necessary capital equipment/ technology upgrades and technical experts to facilitate this. This matters because Korean SMEs' adoption of digital technologies continues to lag, as the following three graphs show.

Figure 24: Big Data Usage by Enterprises with at Least 10 Employees, 2016[275]

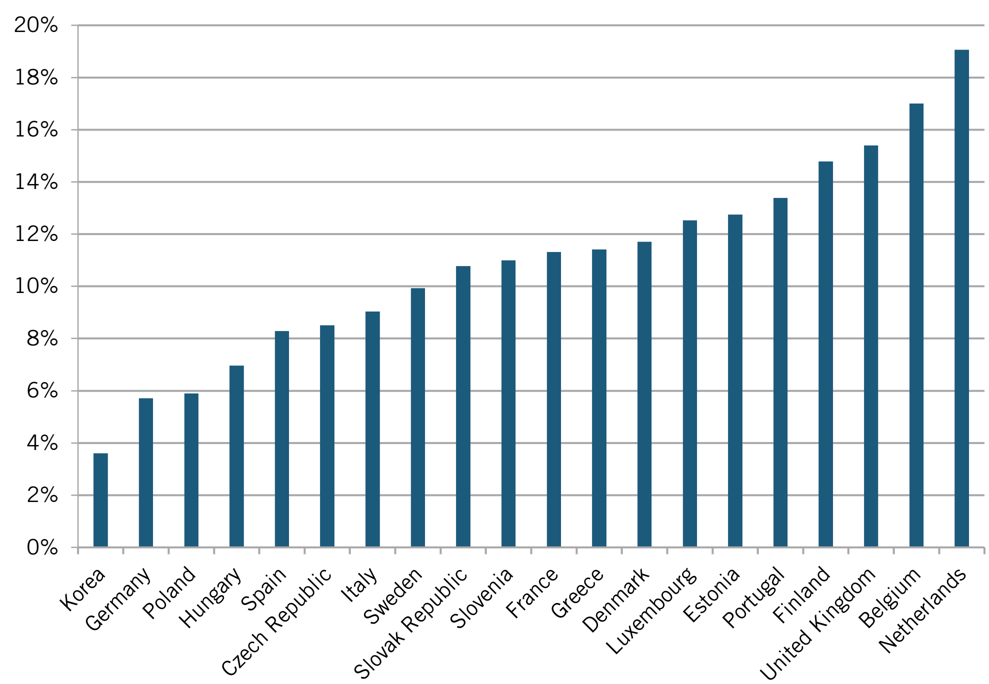


Figure 25: E-Sales Usage by Enterprises With at least 10 Employees, 2016[276]

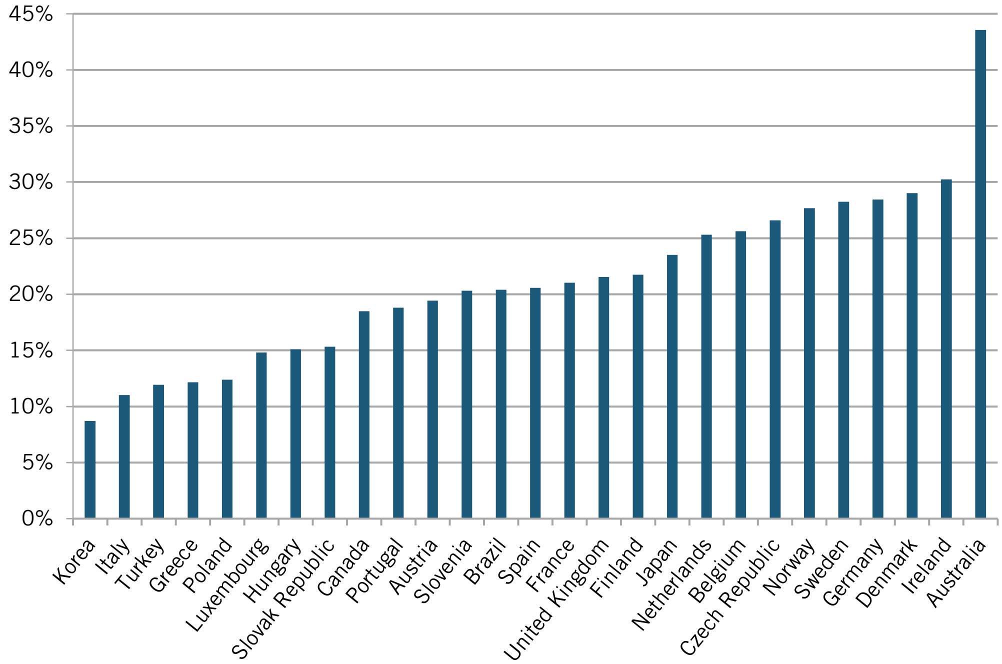
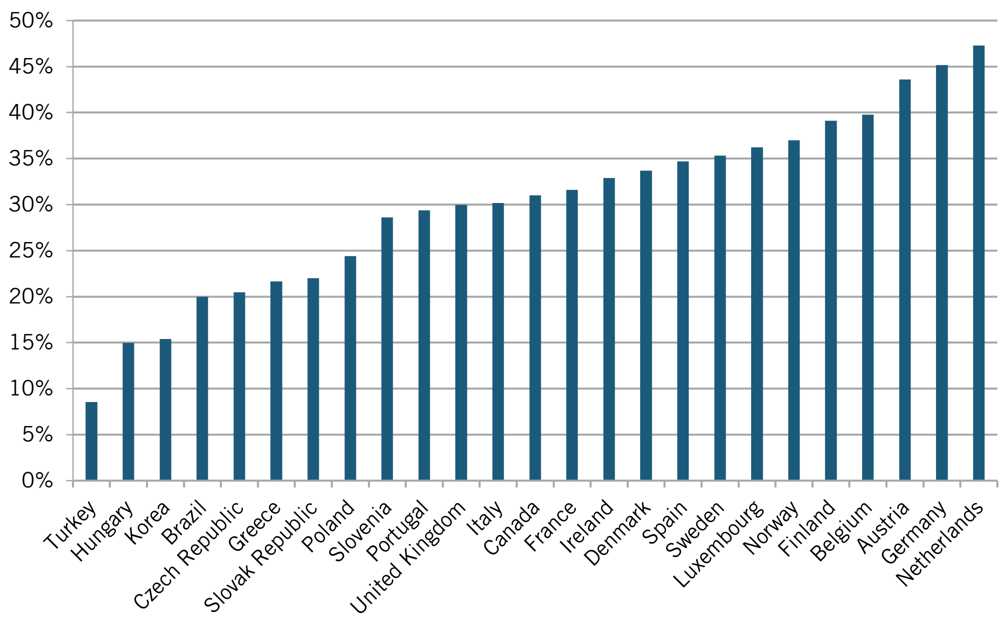


Figure 26: CRM Usage by Enterprises with at Least 10 Employees, 2016[277]



As noted, diffusion of already-existing manufacturing digitalization technologies could provide Korean manufacturing a quick boost. For instance—as showed in figure 11 on page 24—just 9 percent of Korean manufacturers (and just 12 percent of all Korean SMEs with at least 10 employees) used cloud computing in 2015. Similarly, as figure 24 shows, Korean enterprises (with at least 10 employees) exhibited the lowest rate of big data analytics out of 20 OECD countries for which data was available in 2016, with just 3.6

percent of Korean manufacturers leveraging big data analytics in their operations. Korean firms also evinced the lowest rate of e-sales usage and the third-lowest rate of customer relationship software (CRM) usage, as figure 25 and figure 26 show, respectively. Helping Korean SMEs adopt digital manufacturing practices should be a paramount policy priority.

However, Korean policy should not be targeted toward all SME manufacturers equally, but to SME manufacturers with above-average productivity and higher growth potential. That's because larger firms are on average more productive than smaller ones. For instance, studies of U.S. manufacturing firms find that the four largest firms in any manufacturing sector enjoyed labor productivity rates 37 percent higher than those in the remainder of the industry.[278] Similarly, a 1998 national survey of 10,000 manufacturers found that technology use is positively correlated with plant size.[279] The same holds true for Korea, where small firms are just 22 percent as productive as larger firms. Labor productivity in small manufacturing firms is less than one-third that of large Korean manufacturers. Closing the productivity gap between smaller and larger Korean firms will in part require some of the SMEs to achieve greater size and scale, and policy should be focused on abetting these types of firms.

Studies of U.S. manufacturing firms find that the four largest firms in any manufacturing sector enjoyed labor productivity rates 37 percent higher than those in the remainder of the industry.

However, all too often, Korean policy has focused more on keeping small firms in business rather than helping the ones who can scale up most effectively. And one way it has pursued this is through a suite of subsidies and regulatory exemptions available only to small firms. For instance, in South Korea, only small firms are eligible for a 5 percent tax credit for expenditures on industrial or advanced office equipment. Moreover, small companies pay a 10 percent corporate tax while large ones pay a 22 percent tax.[280] Public financial institutions such as the Korea Finance Corporation and the Small and Median Business Corporation provide loans directly to SMEs. Only 21 percent of loans made to SMEs were not guaranteed or collateralized by government.[281] The Korean government also operates 1,300 SME programs and 47 support measures covering taxes, marketing, and employment. The lavish benefits and regulatory exemptions SMEs enjoy mean that few firms want to grow. In fact, of the millions of SMEs in South Korea in 2002, only a paltry 696 had graduated from SME status by 2012. In other words, a more optimal approach for Korean SME manufacturing policy would be to significantly reduce the subsidies and protections they enjoy which result in significantly more small, sub-scale SMEs than is optimal, and instead focus manufacturing technical assistance and other growth-oriented programs on the most productive and innovative firms, who with some help could scale up. This doesn't mean turning eight- person firms into 8,000-person firms. It does mean helping 8 person firms grow to become 40- or even 80-person firms.

Charter a Korean Institute for Manufacturing Digitalization

Establish a Korean Institute for Manufacturing Digitalization: Korea should envision an institute similar to America's Chicago, Illinois-based Digital Manufacturing and Design Innovation Institute, a public-private partnership that serves as a central hub for the development, showcasing, access to, and transmission (especially to SMEs) of knowledge, tools, software, and expertise related to manufacturing digitalization. As noted, DMDII serves as a state-of-the-art proving ground for digital manufacturing and design that links information technology tools, standards, models, sensors, controls, practices and skills, and transitions these tools to America's design and manufacturing industrial base for full-scale application.[282] Korea could benefit from having a similar institution.

Task such an Institute with Developing A "Maturity Index" and "How-to-Playbook" That Provides SME Manufacturers Model "On-Ramps" To Digitalization: Leading digital manufacturing countries—including Austria, Germany, and the United States—have focused on building "Digital Playbooks" that provide SME manufacturers with model use cases and best practice examples in an effort to help close the awareness and knowledge gap and to help de-risk the digitalization journey. As figure 2 demonstrates, one place countries such as Austria and Germany have started is by developing a Maturity Index that helps contextualize where SMEs are situated in their digitalization journey.

Pair the Maturity Index with a "Digital Manufacturing Readiness Assessment Tool": This readiness assessment tool would include three steps: 1) Assessment/Evaluation; 2) Identification; 3) Recommendation.

Korea should focus manufacturing technical assistance and other growth-oriented programs on the most productive and innovative firms, who with some help could scale.

The Digital Manufacturing Readiness Assessment Tool evaluation phase would include items such as:

- **Assessing the depth of the enterprise's digital thread**, that is, its ability to generate a real-time stream of information regarding its production systems and physical output;
- **Inventorying existing production equipment and extent of its digitalization**, identifying the extent to which the SME manufacturer is or is not IoT-enabled and digitally connected so as to be able to generate a transmittable stream of information regarding the device's functional operating condition, ability to interface into a manufacturing execution system and warehouse management system, ability to communicate with other machines, etc.
- **Identifying data needs/requirements of upstream suppliers or downstream customers** (i.e., understanding what its data exchange needs are with partners, suppliers, customers, etc.)
- **Identifying leading challenges/obstacles in the SME's production environment or in the Internet-connectedness of the products it builds** as a starting point for understanding how digital technologies can be deployed to solve these challenges.
- **Inventorying the digital competencies** of the workforce and identifying digital-skills gaps.

The Digital Readiness Assessment Tool identification and recommendation phase would include:

- **Comparing SMEs' needs/environments against a best-practices database** that could have model digitalization implementations from similar manufacturers in other sectors.
- **Coaching** SMEs on organizational changes needed to implement digitalized manufacturing process innovations.

- **Recommendations on key performance indicators** SME should use to evaluate progress/success.

Provide an online benchmarking tool for manufacturing digitalization for SMEs: In 2015, the United Kingdom launched the Mayfield Commission study, assigned to find the causes of, and propose solutions to, the "large and widening productivity gap that exists between the UK and leading advanced economies."[283] One of the outcomes of the study has been the launch of the UK's BetheBusiness website, an online repository of inspiration, tools, and resources for businesses to get started on their improvement journey.[284] The website includes an online productivity benchmarking tool that allows UK SMEs (of at least 10 employees) to assess where they stand vis-à-vis peers, on a sector-specific basis, in terms of challenges such as Digitalization; Future Planning; Employee Engagement; and Leadership.[285] It's one example to draw from, but the suggestion is that Korea develop such a Digital Manufacturing Readiness Assessment Tool and in part make it available online, with the ability to benchmark a firm's results against anonymized data from similar peers in the manufacturing sectors in which they compete. This would give Korean SMEs the ability to make real-time assessments about how well they are progressing toward manufacturing digitalization and suggest useful routes toward improvement.

Learn From Other "Future Factory" Programs: As noted, Korea is appropriately building a number of future factories. In this process, it should be sure to always look to be learning best practices from others, where applicable. In this regard, worth considering is DMDII's "Future Factory Testbeds" that will integrate existing smart manufacturing technologies, identify which sensor data types can enable the biggest business impact, and enable a digital twin pilot involving a member manufacturer's operational environment.[286]

As part of the Future Factory Testbed, DMDII is pursuing several concrete actions, including:

- Undertaking an IoT Sensor ROI Analysis: Conducting modeling, surveys, and empirical tests to determine which sensor data, if collected and leveraged, could produce the greatest return for manufacturers, particularly in predictive maintenance applications.[287]
- Developing a workshop for educating manufacturers on sensor integration and making optimal use of data analysis tools.
- Applying the digital twin modeling approach to an actual factory environment, thus "driving a business case that enables replication by others."[288]

Provide SMEs and Other Manufacturers with Total Cost of Ownership Tools: Smart manufacturing techniques will increasingly enable competitive manufacturing in high-cost environments. Even then, U.S. companies have found that they've missed about 20 percent of the costs entailed in offshoring.[289] To help manufacturers understand the true costs of offshoring, the U.S. Department of Commerce developed the Access Costs Everywhere (ACE) Total Cost of Ownership (TCO) evaluation tool to help manufacturers understand their true costs of production.[290] Similarly, Professor Suzanne de Treville of the University of Lausanne has developed supply-chain analytics tools that help companies quantify and price the advantages they have in manufacturing locally, making it easier to show that the apparent cost reduction offered by a competitor in a low-wage country might not be as compelling as it seems. By applying quantitative finance tools to demand dynamics, Treville' s freely available Cost-Differential Frontier (CDF) price calculator allows manufacturers to price the increase in exposure to demand volatility that comes from increases in lead time, which often reveals that going offshore is not a bargain.[291] Similar tools for Korean manufacturers might surface unrecognized outsourcing costs and encourage more local manufacturing.

Manufacturing Cybersecurity

In the United States, 35 percent of cyber-espionage attacks have been directed at the manufacturing sector, meaning ensuring the cybersecurity of manufacturers is paramount, especially for SMEs that have the most limited resources to protect their operations.[292] To facilitate this, America's DMDII is developing a SME Cyber Assessment and Mitigation Tool that will help SMEs improve their cybersecurity practices. This will include a "user-friendly, consumer-style interface that walks users through existing cyber security best practices and mitigation recommendations in a series of step-by-step modules."[293] DMDII has also launched a National Center for Cybersecurity in Manufacturing and proposed creating an online and in-person SME Cyber Training Program that would serve "as a neutral, trusted cyber-physical based test bed accessible to government, industry, and academia to evaluate existing and future manufacturing technology for cyber security."[294] **Korea should similarly develop a cybersecurity assessment program for its manufacturers that helps them diagnose their situation and suggest tangible steps manufacturers can take to enhance their cybersecurity environment.**

Supporting Digital Manufacturing Supply Chains

Support the Digitalized Integration of Korean Manufacturing Supply Chains: As this report articulates, countries' manufacturing competitiveness increasingly will be determined by the agility and synchronization of entire supply chains: that is, the ability of Original Equipment Manufacturers to orchestrate complex supply chains so that innovative, even mass-customized, products can get to market quickly. However, too often the OEM-supplier relationship is characterized by OEMs just beating suppliers up on costs, even though they should be bolstering suppliers' innovation capacity because it can boost the cost-quality attributes of an OEM's finished product. In other words, there's a market failure here.

Accordingly, Korea's government should provide incentives for Korean OEMs to help 10,000 SMEs become IoT-enabled (or smart manufacturing-enabled) within 10 years. OEMs and Tier 1s need to press suppliers to upgrade their equipment (otherwise too often it's just not on the SMEs' radar screens) and support them in their efforts. The OEMs could host workshops/seminars to guide SME suppliers in digitalization strategies and how explicitly to integrate digitally into supply chain management systems. These incentives could take the form of block grants for a certain number of suppliers engaged. Also related to this, the

OEMs tend to want transparency regarding the parts flowing out from the suppliers, but the suppliers may not desire this, so there are issues about who controls and secures the data. By incentivizing OEMs to collaborate with SMEs on these questions, approaches can be found that add value for both parties and frameworks set up with regard to data ownership issues.

Expanding Access to Capital for Innovative SME Manufacturers

Provide grants or vouchers to SMEs wishing to develop new or to significantly improve existing products, processes, or technical services. This could take the form of a national program offering innovation vouchers, as used in some U.S. states such as Connecticut and Rhode Island (and countries like Austria, Canada, and Holland) which offer grants ranging in value from $25,000 to $50,000; these enable SMEs to "buy" expertise from universities, national laboratories, or public research institutes regarding preparatory studies, analysis of technology transfer, analysis of the innovation potential of a new technology, etc. The intent of the vouchers is both to spur innovation in SMEs and to stimulate knowledge transfer from universities and research institutions to SMEs. They also have an added benefit of more closely aligning the interests of industry and academia and giving universities and labs an incentive to be more responsive to industry needs.

Countries will need to introduce a comprehensive national manufacturing digitalization strategy and make the requisite investments if they wish to keep pace in the race for smart manufacturing leadership.

Create Manufacturing Reinvestment Accounts. To help SME manufacturers bootstrap themselves, Korea could establish a "deferred-tax investment" program for SME manufacturers, allowing them to make tax-deferred investments into manufacturing reinvestment accounts, where the funds can be subsequently withdrawn tax-free if used for research and development, workforce training, or capital equipment investments. In 2011, Connecticut put such a program in place for its SME manufacturers.

Digital Manufacturing Skills/Education

Ensuring that a country's manufacturing workforce is equipped with the digital competencies required to enable enterprises and industries to take advantage of smart manufacturing's promise appears to be a challenge everywhere. The following offers several policy recommendations.

Leverage Massively Open Online Courses (MOOCs) for Manufacturing Skills Education: For instance, Tooling U-SME, a web-based, cloud-delivered, massively open online course provides over 500 online classes related to manufacturing technology, breaking down the training into nine functional areas and 60 competency models to identify gaps, define requirements, and provide specific guidance for development.[295] Tooling U-SME's "Accelerate Methodology" provides a comprehensive, structured, enterprise-specific approach that helps manufacturers and their workers acquire needed skills. Similarly, DMDII has developed a Coursera-hosted MOOC that's teaching essential skills related to digital manufacturing and design technologies.[296] Korea should ensure that similar online courses are available to teach key digital manufacturing skills.

Develop a Digital Manufacturing and Design Roles Inventory: As noted, America's DMDII partnered with ManpowerGroup to develop a comprehensive taxonomy of emerging roles and skills in the digital manufacturing and design space. The report identifies 165 potential digital manufacturing and design roles, providing a comprehensive index of requisite skills and representative tasks pertaining to each role, and offers 20 success profiles for representative roles.[297] Korea could develop a similar taxonomy.

Ensure that national technology high schools and colleges embrace hands-on and problem-solving based learning approaches. For instance, Japans' National Institute of Technology organizes 51 Colleges of Technology, called Kosen, which provide unique five-year engineering education (from age 15) with an additional two years of advanced courses, all under close cooperation with industry with the goal of fostering top-level practical and creative engineers.[298] The Kosen schools offer a unique blend of classroom-based as well hands-on, project-based learning, which is both cross-curricular and student-centered, and teachers are mainly coaches, mentors, facilitators and evaluators.[299] More than 80 percent of faculty members hold the highest degree in their research field. Over 99 percent of Kosen graduates get jobs in their field of study, and in fact graduates receive an average of 20 job offers from Japan's most sought-after innovators and engineers.[300] The Kosen approach recognizes that, as the OECD's Andreas Schleicher writes, "Innovation and problem solving depend increasingly on the ability to synthesize disparate elements to create something different and unexpected. This involves curiosity, open-mindedness and making connections between ideas that previously seemed unrelated. It also requires knowledge across a broad range of fields."[301] Japan's Kosen schools, very similar to the Olin College of Engineering outside Boston, Massachusetts in the United States, recognize this and emphasize creative and flexible problem-solving approaches, as opposed to the rote-learning approach that has for too long been the focus of many Asian educational systems (in both Korea and Japan in particular).[302] Korea should work to foster more industry project-based, hands-on learning approaches at its high schools, colleges, and universities.

CONCLUSION

Nations are competing fiercely for advanced manufacturing leadership.[303] 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 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.

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