A Policymaker's Guide to Smart Manufacturing

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The digitalization of manufacturing will transform how products are designed, fabricated, serviced, and used, producing tremendous economic and consumer benefits, while changing the global landscape of manufacturing competition.

Smart manufacturing—the application of information and communication technologies (ICTs) to every facet of modern manufacturing processes—is in the midst of transforming the global manufacturing economy. The digitalization of manufacturing will transform how products are designed, fabricated, used, operated, and serviced post-sale, as much as it will transform the operations, processes, and energy footprint of factories and the management of manufacturing supply chains. It will also change the global landscape of manufacturing competition, potentially reducing the relative advantage of low-cost regions. The countries—and enterprises and industries therein—that lead in embracing smart-manufacturing techniques will gain first-mover advantage over global competitors. Public policy will play a pivotal role in setting the competitive landscape affecting smart manufacturing leadership, impacting everything from how quickly countries' enterprises will be able to research, develop, adopt, and diffuse these technologies to how ready their workforces and supply chains will be to leverage them.

INTRODUCTION

Just as they have done in the media, publishing, transportation, hospitality, financial, and transportation industries, today ICTs are transforming virtually every facet of the manufacturing economy, from the way products are designed, made, and used to how the factories making those products connect, operate, and fabricate. The advent of smart manufacturing heralds a future where products are designed and produced more quickly, safely, efficiently, and inexpensively; more energy efficiently; and more customized to an individual customer's needs and demands. Moreover, as manufacturing digitalization enables increasing automation and mass customization (as opposed to mass production of largely indistinct units)—a phenomenon described as "a lot size of one"—as well as production closer to the end-user, it promises to change the economics of modern manufacturing, reducing the relative competitive advantage of low-wage nations that traditionally competed primarily via low labor costs, and thus increasing the ability of higher-wage nations to gain market share in global manufacturing industries.

This report begins by explaining the evolution of smart manufacturing, by placing smart manufacturing in the context of advanced manufacturing, and by describing how smart manufacturing touches every step of modern manufacturing value chains and production processes. It then documents the myriad benefits of smart manufacturing before reviewing the policies that leading nations are implementing to achieve smart manufacturing leadership. Finally, the report reviews the policies the United States should consider implementing to support its manufacturing sector in general, and its smart manufacturing capabilities in particular. The report makes the following policy recommendations:

Congress should:

- Enact legislation to expand federal resources for training and adoption of smart manufacturing technologies by U.S. small- to medium-size (SME) manufacturers, similar to the smart manufacturing provisions of the Senate-passed version of The Energy Policy Modernization Act of 2016 (S. 2012), which would articulate a formal definition of smart manufacturing and direct the Department of Energy's Industrial Assessment Centers program to work more closely with SME manufacturers to help them learn about and adopt smart manufacturing technologies.

- Allocate funding to build out Manufacturing USA (formerly known as the National Network for Manufacturing Innovation) from the current 9 to the envisioned 45 institutes.

- Provide a stronger tax incentive for investment in machinery and equipment, such as by enacting an investment tax credit (ITC) of 35 percent on all capital expenditures made above 75 percent of a base amount.

- As an alternative option to the above, allow firms to expense, for tax purposes, the entire cost of equipment and software in the first year, instead of having to depreciate the cost over a number of years.

- Support the Small Business R&D Act, which would require the Small Business Administration and the Internal Revenue Service to expand knowledge sharing and training on R&D tax-credit instruments and provide a report to Congress on their progress.

- Adjust the required Manufacturing Extension Partnership (MEP) cost-share ratio from 2:1 (nonfederal to federal) to 1:1.

- Increase credentialing for the manufacturing workforce by providing funding to expand the development and use of standards-based, nationally portable, industry-recognized certifications designed for specific manufacturing sectors.

- Boost support for vocational-education programs at community colleges, in part by increasing funding for Perkins vocational education and training programs.

- Reform the Workforce Investment Act system to allow more funds now going to Workforce Investment Boards to instead go to industry-led regional skills alliances.

- Pass the Manufacturing Universities Act, which would authorize and appropriate funds to create a core of at least 20 universities that brand themselves as leading manufacturing universities.

- Pass the National Fab Lab Network Act of 2015, which would create a federal charter for a nonprofit organization called "The National Fab Lab Network."

- Fund a pilot program that would integrate the maker movement and makerspaces into high schools.

- Provide sufficient funding for R&D into key underlying technological challenges relevant to the Internet of Things, such as developing standards, improving cybersecurity, and reducing power consumption.

- Fund the National Strategic Computing Initiative (NSCI) and related federal high-performance computing initiatives at a level of at least $325 million per year over the next five years.

- Recognize that trade agreements such as the Transpacific Partnership Agreement (TPP) and Trade in Services Agreement (TiSA) contain vital provisions that preclude partner nations from introducing barriers to cross-border data flows that could significantly impede the potential of smart manufacturing.

The next administration, or its agencies and departments therein, should:

- Continue the practice of articulating a national manufacturing strategy.
- Ensure that MEP centers are collaborating with and embedded within all Institutes of Manufacturing Innovation to identify emerging manufacturing process technologies and help rapidly diffuse them to SME manufacturers.
- Direct the National Institute of Standards and Technology (NIST) to continue mapping the landscape of smart manufacturing standards and leverage its convening power to facilitate industry's voluntary development and adoption of interoperable data-communication standards, as well as standards and best practices addressing cybersecurity and privacy issues.
- Negotiate (and enforce) trade agreements that preclude partner nations from imposing barriers to cross-border data flows.

WHY SMART MANUFACTURING NOW?

Several dominant manufacturing paradigms have evolved over time, with some regions being first movers and others laggards.[1] For most of human history, "manufacturing" entailed artisanal fabrication (i.e., individually skilled bronze or iron workers), a paradigm that prevailed through to the Middle Ages (approximately 700 AD), when it gave way to a craft-guild production system that was still specialized in its trade, but now evolved from the individual- to the guild-production level. This system was usurped by the so-called First Industrial Revolution, beginning at the end of the 18th century in Great Britain, which saw the introduction of water- and steam-powered mechanical production facilities (e.g., the cotton gin and textile loom) and the increased use of iron-based products.

Almost a century later, in the late 19th century, the introduction of electricity-powered mass production based on the division of labor, increased use of steel-based products and machines, and assembly-line concepts (i.e., Henry Ford and mass automobile production) heralded the so-called Second Industrial Revolution.[2] A third transformation occurred in the postwar era, when discrete goods manufacturers began to introduce automation technologies (a term coined in 1945 to describe single-purpose machines designed to produce one specific part or conduct one specific process) as well as automated, continuous-flow systems. (Continuous-flow innovations date back to 1939, when Standard Oil of New Jersey created the first fluid crackers used in industry.)[3] In these plants, raw material flowed continuously in one end and out as product at the other end. As these systems were introduced and improved in many industries over the decades following World War II, manufacturing productivity increased significantly. However, these systems were anything but flexible and, as they matured, the work could often be performed by lower-skilled labor, far from final consumer markets. At the same time, the emergence of science-based industries, including electronics and chemicals, meant that an increasing number of products became more sophisticated. It is important to note, however, that most commentators ignore this third transformation, lumping it together with the transformation at the end of the 1890s. As a result, many refer to today's transformation as the "fourth industrial revolution" or "Industry 4.0." (This report will refer to today's transformation as the fifth wave.)

The fourth transformation occurred in the 1980s and 1990s, when the first digital-electronic systems were developed, empowering ICT-enabled systems (e.g., computer-aided design and manufacturing, robotics, etc.) to further automate manufacturing, adding some flexibility but mostly enabling the better coordination of dispersed supply chains, thereby enabling the global distribution of many kinds of production.

Emerging today is a fifth wave—an era of "smart manufacturing" that integrates advanced-digital technologies more completely into production systems. These technologies include wireless communication technologies, the Internet of Things, cloud computing, easily (re)programmable robots, machine intelligence, and other next-generation digital technologies to create a direct, real-time interface between the virtual and physical world.[4]

On the advanced manufacturing floor of today, automated, intelligent equipment and systems leverage sensor data (often communicated via wireless technologies) to control flows of materials, products, and information, thus taking to the next level production processes by transforming them into modular, flexible systems that increase efficiency, enable innovation, and conserve resources. This fifth wave further includes the use of digital design technologies that facilitate design optimization not just of products themselves but also the production processes on the factory floor itself as well as the use of data analytics from products to improve their design and performance on an ongoing basis. As Robert Hardt, president and CEO of Siemens Canada, explains, smart manufacturing entails nothing less than "the availability of all relevant information in real time, through interconnection of all instances of value creation, and the capacity to derive from this data an optimal value creation flow at any point in time."[5]

As Box 1 elucidates, this era of smart manufacturing arises from the advent and maturity of a number of foundational digital technologies that enable the real-time creation, storage, communication, and analysis of data in a "digital thread" that spans across individual production machines, entire production processes, whole factories and broader enterprises, entire industrial supply chains, and the manufactured products themselves.

BOX 1: KEY TECHNOLOGIES ENABLING SMART MANUFACTURING

Sensor Technologies: Sensors embedded within devices, machines, and products themselves 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. Over the past 10 years, the cost of sensor technologies has declined a hundredfold, while the number of sensors shipped globally increased more than fivefold in the three full years from 2012 to 2014, with global sensor shipments increasing from 4.2 billion in 2012 to 23.6 billion in 2014.

Wireless Connectivity: Smart manufacturing requires wireless connectivity to join the wide variety of sensors, actuators, and robotics to analytics or control platforms. A wide variety of solutions have stepped in to fill this role, some based on unlicensed spectrum, others offered by mobile operators using licensed spectrum. Operators are looking to 5G and stopgap technologies such as narrowband Internet of Things to enable a massive influx of Internet of Things' 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. This combination of sensors and connectivity enables what is known as 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 its application in an industrial context.

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 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 an enterprise.

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, and the software algorithmically explores all possible permutations of a design solution.

Computer-Aided Design (CAD): 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.

Advanced Robotics: The next generation of industrial robots that are far cheaper and which are reprogrammable and thus not dedicated to a single specific task and as such are much more flexible and versatile. New industrial robots can mimic human movements and arms can even be physically manipulated by workers to show robots how to execute certain tasks.

SMART MANUFACTURING IN CONTEXT AND IN SPECIFIC APPLICATION

This section first articulates the broad distinction between advanced manufacturing and smart manufacturing and then describes how smart manufacturing can transform each step of manufacturing production.

The Relationship Between Advanced Manufacturing and Smart Manufacturing

There is considerable confusion over the various terms used to describe current technological changes in manufacturing.[6] Some use the term "advanced manufacturing" as interchangeable with the term "smart manufacturing." For example, the official definition of advanced manufacturing—"Advanced manufacturing technology is defined as computer-controlled or micro-electronics-based equipment used in the design, manufacture or handling of a product"—offered by the Organisation for Economic Cooperation and Development (OECD) is more or less synonymous with smart manufacturing.[7] Others use the term to describe certain manufacturing industries that make advanced-technology products.

Smart manufacturing refers to the application of information technology to every facet of modern manufacturing production process.

The President's Council of Advisors on Science and Technology (PCAST) defines advanced manufacturing as "A family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting edge materials and emerging capabilities enabled by the physical and biological sciences; for example, nanotechnology, chemistry, and biology. It involves both new ways to manufacture existing products, and the manufacture of new products emerging from new advanced technologies."[8] In essence, then, advanced manufacturing refers to two things: the production of advanced products and the adoption of advanced, ICT-based production processes. Smart manufacturing considers mainly the latter.

Indeed, smart manufacturing specifically refers to the application of information technology to every facet of modern manufacturing production process—from the way products are designed, manufactured, and consumed; to how the individual machines and equipment involved in a production process are connected and orchestrated on the factory floor; to how an intermediate product moves through entire production supply chains toward final assembly. Smart manufacturing is really about all the different ways information technologies can be applied throughout the manufacturing process to improve productivity, to save costs, to reduce energy consumption, and to deliver innovative and custom-tailored products to purchasers. In an effort to provide definitional clarity, legislation introduced in the 114th Congress proposed a useful formal definition of smart manufacturing as part of the North American Energy Security and Infrastructure Act of 2016 (S. 2012).[9] The legislation defines smart manufacturing as:

> Advanced technologies in information, automation, monitoring, computation, sensing, modeling, and networking that (A) digitally (i) simulate manufacturing production lines; (ii) operate computer-controlled manufacturing equipment; (iii) monitor and communicate production line status; and (iv) manage and optimize

> energy productivity and cost throughout production; (B) model, simulate, and optimize the energy efficiency of a factory building; (C) monitor and optimize building energy performance; (D) model, simulate, and optimize the design of energy efficient and sustainable products, including the use of digital prototyping and additive manufacturing to enhance product design; (E) connect manufactured products in networks to monitor and optimize the performance of the networks, including automated network operations; and (F) digitally connect the supply chain network.[10]

The manufacturing challenge has always been both an atom challenge and an information challenge.

Nevertheless, many people think manufacturing is only about "atoms"—i.e., about manipulating physical materials to produce physical goods. And it is that, but it is also about "bits"— information about where parts are, how effectively machines are performing, how to control machines, and how to envision what products should look like and function. In other words, the manufacturing challenge has always been an atom challenge and an information challenge. (In fact, manufacturers should strive to move bits instead of atoms as much as possible, and to a point as close to the final customer as possible.) But it is only now with the emergence of this current wave of ICTs (software, data analytics, ubiquitous wireless for information transmission, sensing, etc.) that manufacturing can begin to fully solve the information challenge. In this sense, ICT is transforming manufacturing, just as before it has other, more pure information-processing functions (e.g., travel agents, finance, accounting, etc.).

In essence, smart manufacturing is about manufacturing "with intelligence" at each step along the "Design—Make—Use" continuum. As Diego Tamburini, senior design and manufacturing industry strategist at Autodesk, argues, one can imagine an inefficiently designed, gas-guzzling, environmentally unfriendly vehicle that itself is manufactured with the most efficient production processes ever conceived.[11] Yet that alone doesn't constitute "smart manufacturing": Smart manufacturing must include the continuum of products being designed optimally (and with their energy-efficient use and operation in mind), production systems operating efficiently, and products being used intelligently and sustainably, all the way through their end-of-life.

Tim Shinbara, vice president for manufacturing technology at the Association for Manufacturing Technology (AMT), explains that policymakers should envision four levels, or layers, of smart manufacturing. At the first layer lie the intelligent machines themselves, the individual production equipment doing the work of forming, cutting, forging, and stamping products that integrate into the Industrial Internet of Things by being equipped with sensors that create information streams. At the second level, a "digital thread" consolidates information streams from those individual machines across the factory floor (and indeed across the entire enterprise-wide production system) by linking multiple "process chains" together. This represents a consolidated, ICT-enabled view of each of the individual process chains that constitute an enterprise's holistic manufacturing production system. At the third level lies applying data analytics to this broad "manufacturing intelligence" to optimize processes and to iteratively design intelligent products. At the fourth level are smart CEOs, or smart C-suite executives, who are empowered to make optimized, real-time decisions on production levels, production location, production options, etc., based on the corporate intelligence created by the smart manufacturing enterprise.[12]

But while that's the full vision, it perhaps puts the cart before the horse, so the following section details the application of "smart" at each step of the modern manufacturing system.

"Smart" at Each Step of the Modern Manufacturing System

As noted, digital technologies will transform virtually every facet of modern manufacturing, from the design of manufactured goods, to the management and execution of production processes and factory operations, to the integration of industry supply chains, to how products are used by customers once they leave the factory floor. In fact, one study estimates that manufacturers are now allocating an average of 8.1 percent of their R&D budgets to developing digital tools for these purposes.[13] The following sections analyze the application of information technologies at each stage of the manufacturing process.

Digitally Enabled Product Design

Computer-aided design (CAD) and computer-aided engineering (CAE) modeling and simulation technologies, increasingly enabled by faster computing, including high-performance computing (HPC) systems, have transformed how products get designed.[14] Computer-aided design involves creating computer models defined by geometrical parameters, whereas computer-aided manufacturing (CAM) uses geometrical design data to control automated machinery.[15] The functionality of CAD, CAE, and CAM systems has grown significantly in recent years, and they have become much cheaper, more powerful, more accessible, and easier to use.

For instance, digital simulations allow aircraft developers to improve the design and to simulate the functional operation of many critical aircraft components—such as wing and fuselage design—before a physical prototype is ever tested in a wind tunnel. Indeed, computational modeling allows aerospace designers to tackle "computational fluid dynamics multiphysics problems at scale in a virtualized environment."[16] Such application of digital-design techniques has contributed to a 50 percent reduction in the amount of wind-tunnel testing needed for a new aircraft's development.[17] Likewise, General Electric (GE) leverages HPC-powered modeling and simulation tools to "remove design cycles from jet engine component technology, doing full modeling of individual components of an engine: compressors, combustors, turbines, rotating elements, etc."[18] GE estimates its use of digital-design tools has reduced new jet-engine development timelines by at least half a year and notes that each 1 percent reduction in fuel consumption it's able to achieve from its engines saves airlines approximately $2 billion per year.[19] Likewise, Goodyear's use of CAD tools in designing its Assurance tire enabled it to reduce the product-design timeframe for new tires from three years to less than one year and to decrease tire-building and testing costs from 40 to 15 percent of the company's R&D budget.[20]

SME manufacturers also benefit from digitally enabled product-development tools. SMEs benefit because these tools (and the computing power to support them) are increasingly available in the cloud (eliminating the need for in-house ICT infrastructure to support them) and on a subscription basis (reducing the up-front, expensive perpetual licensing model of the past). For example, Zipp Speed Weaponry, a small, Indiana-based specialty manufacturer of performance-biking gear such as wheels and tires (and which is the only remaining U.S. manufacturer of advanced high-performance cycling components), leveraged HPC-enabled design software to conceive of innovative racing tires for bicycles.[21] Zipp used HPC-enabled virtual simulations to better understand computational fluid dynamics problems and to resolve turbulence challenges it was unable to solve with traditional wind-tunnel experiments, allowing Zipp to jump ahead of the global competition in its unique market niche.[22] The aerodynamic Firecast wheels Zipp introduced in 2010 based on this knowledge enabled it to double global product category revenues in just two years and to support 120 new manufacturing jobs in Indiana.[23]

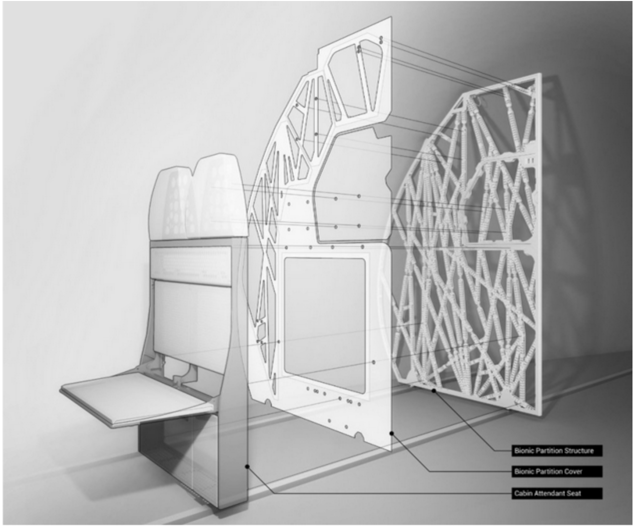
The development of generative-design tools, coupled with new production technologies, such as additive manufacturing, broadens the landscape of imagination for designers and manufacturers alike.

But such examples of impressive results from digital modeling and simulation tools represent just the beginning. Today, computer-based generative-design tools allow product designers to conceive of products with shapes, structures, and material attributes never before imaginable. The generative-design technique allows designers to tell the software what product and shape they want, what the design constraints are, and what structural and material attributes are needed; and the computer will return designs that are more efficient, optimized, strong, lightweight, and durable than designers could have foreseen.

For example, Autodesk's computer-aided design software has been effective for decades, but the company is now developing and fielding an even more data-driven approach, with an algorithmically derived initiative that allows designers to generate designs based on a list of material and performance requirements that can then be additively manufactured (e.g., 3D printed) with a high degree of precision.[24] Figure 1 shows a generatively designed aircraft bulwark, the so-called bionic partition, created through a pioneering combination of generative design, 3D printing, and advanced materials that is almost 50 percent lighter (while being far stronger) than current aircraft bulwark partition designs.[25] Incorporating such bionic partitions throughout an entire Airbus A320 could remove up to 1,100 pounds of weight per airplane. And because each 2.2-pound reduction in weight can cut fuel consumption by 233 pounds per year, the partitions could cut each airplane's CO_2 emissions by 166 metrics tons per year. If applied across an airline's entire fleet of A320s, this new design approach could save up to 465,000 metric tons of CO_2 emissions per year, the equivalent of taking 96,000 passenger cars off the road for one year.[26]

The development of generative-design tools, coupled with new production technologies such as additive manufacturing, broadens the landscape of imagination for designers and manufacturers alike. As *The Wall Street Journal's* John Koten explains, "Designers and engineers at General Electric have begun looking at ancient objects and prehistoric bird skeletons, and delving anew into topology, for inspiration on new forms of design. Their thinking: Centuries of making things under the constraints of old methods may have caused their predecessors to discard innovative structures simply because there was no practical way to produce them through milling or casting."[27]

Figure 1: Aircraft Bulwark Conceptualized Via Generative Design Techniques[28]



Put simply, information technology-enabled designed tools are transforming how products are designed, in the process speeding product-development timelines, saving money, delivering superior products to customers, and even becoming a source of competitive advantage for manufacturers. But more than just facilitating their design, information technologies are also increasingly vital to the fabrication and production of the products themselves, as the following section explains.

Additive Manufacturing (3D Printing)

Information technologies have long played a role in directing production processes and systems on the plant floor, whether it was for computer numerically controlled machines (CNCs) or the first industrial robots. But the growing capabilities of information technology in this fifth wave have unlocked new forms, not just of digitally enabled design, but also digitally enabled production.

In particular, it's digitalization that truly unlocks the potential of additive manufacturing, or 3D printing. In additive manufacturing, successive layers of material are built up to synthesize a three-dimensional solid object composed in a digital file, with each layer a thinly sliced horizontal cross-section of the eventual object.[29] Heretofore, most manufacturing processes were subtractive, that is, they started with a block of sheet metal or aluminum and were milled or stamped into desired shapes; in contrast, additive manufacturing is built up layer-by-layer, enabling fundamentally new shapes and even mechanical linkages that simply can't be achieved through traditional subtractive manufacturing techniques.

Additive manufacturing has many applications for improving speed, efficiency, reducing errors, and eliminating waste on the manufacturing line. For example, in traditional subtractive manufacturing, approximately 60 to 70 percent of an aluminum block ends up as scrap metal, depending on the complexity and shape needed.[30] Additive manufacturing allows for significantly more efficient use of materials, and a dramatic reduction in waste, producing the attendant environmental benefits. Moreover, additive manufacturing, when perfected, could drastically reduce the number of components, steps, and potential for errors in a typical manufacturing process, producing much higher levels of productivity. For these reasons, the worldwide 3D-printing industry is now expected to grow from $3.1 billion in revenue in 2013 to $12.8 billion by 2018, and exceed $21 billion in revenue by 2020.[31] Additive manufacturing is poised to impact the full range of commercial and consumer products, touching everything from shoes and prosthetics to satellites and pharmaceutical drugs.

For instance, both Nike and Under Armour are exploring how additive manufacturing can revolutionize how they manufacture footwear, ultimately allowing shoemakers to customize a sneaker to each athlete's foot.[32] For instance, Under Armour's Architect, a performance training shoe, is the first with a 3D-printed midsole designed to help athletes stay stable during strength training. For its part, Nike bills its Flyknit shoe as "the world's first mass-produced consumer product made using additive manufacturing."[33] The technique allows the tongue, sole, and upper portion of the shoe to be manufactured separately and then stitched together, with proprietary software instructing the 3D printer to switch materials to add strength or flexibility as needed. This enables Nike to produce a shoe with just a few parts instead of dozens, producing up to 80 percent less waste.[34]

The application of additive-manufacturing techniques to personalized products is just beginning. Siemens uses additive manufacturing to create in-the-ear hearing aids individually adapted to the wearer's auditory canal.[35] The prosthetics industry has been revolutionized by 3D-printed limbs tailored to patients' specific structural needs and design desires. Autodesk and the University of Toronto have teamed up to experiment with different ways of scanning limbs and creating customized 3D-prosthetic models for use in Uganda and other war-torn regions.[36] Previously, the process of securing a prosthetic limb could take anywhere from weeks to months, but new 3D-scanning and body-modeling technologies enable patients to 3D-scan their limbs and have prosthetics quickly molded specifically for them using 3D printers, making for a more-natural fit and appearance.[37]

In the industrial realm, until recently, additive manufacturing was used mainly for product prototyping. For example, Ford uses 3D printing to make prototypes of a number of auto parts, including cylinder heads, brake rotors, shift knobs, and bents.[38] While additive manufacturing will continue to play a vital role in product prototyping, today it's also increasingly being used for production runs of final products. For instance, in 2014 GE Aviation announced plans to begin mass production of its LEAP 3D-printed jet-engine fuel nozzles. GE estimates that LEAP's intricate, fuel-efficient design, which can only be manufactured by 3D printing, will produce nozzles that cut fuel costs and carbon emissions by 15 percent.[39] GE Aviation has invested $50 million in a 300,000-square-foot facility and expects to produce 40,000 3D-printed nozzles by 2019.[40] But that's just the beginning, Siemens expects that another "area of application [of additive manufacturing] is that of turbine blades, in which ventilation ducts could be integrated for cooling."[41] This could significantly improve the performance and life of aircraft engines. And in airplane manufacturing, Boeing has replaced machining with 3D printing for over 20,000 units of 300 distinct parts.[42]

Generative designs expressed through additive manufacturing make a powerful combination, affording designers and engineers new engineering freedom to craft lightweight structures, products with complex internal geometries at lower cost, and even in situ moving assemblies. For example, traditional manufacturing of a centrifuge washing machine rotor requires 32 parts, but using additive manufacturing, the same device can be constructed using just three parts, enabling small batches and customization. For its part, Lockheed Martin has significantly reduced its satellites' weight by 3D-printing lightweight parts and components and intends to "expand the process in the future to complex parts and maybe even full satellites."[43] Further, by helping create spare parts to support just-in-time (JIT) manufacturing and "on-demand equipment at the edge," 3D printing will also help eliminate outages and the need to maintain large spare-parts inventories. Moreover, additive-manufacturing's capabilities will steadily increase as its costs decrease in coming years. In fact, over the 10-year period from 2013 to 2023, Siemens estimates that the cost of additive manufacturing will decline 50 percent, even as the speed of 3D printing machines increases by over 400 percent.[44]

Ultimately, 3D printing will enable an era of "direct digital manufacturing," enabling users to literally press "print" to make parts and final products from 3D models.

Beyond industrial applications, 3D printing will become an increasingly democratized technology. Tamburini notes that "personal computing" will be joined by a new phenomenon of "personal manufacturing," with inexpensive 3D printers increasingly available at home or at "makerspaces," such as TechShop, which are spreading across the country.[45] Ultimately, 3D printing will enable an era of "direct digital manufacturing," enabling users to literally press "print" to make parts and final products from 3D models, taking users from instant concept to creation, while enabling tool-less production and dramatically reducing inventory and waste in production. Direct digital manufacturing will also enable distributed and custom manufacturing (custom manufacturing refers to "batch" quality in quantities of one), meaning it becomes possible to manufacture parts anywhere and much closer to the customer or in remote (e.g., space or battlefield) locations.[46]

However, notwithstanding the growing importance of additive manufacturing in industrial settings, it's important to also recognize its limitations. 3D printing works best when producing complex, high-value, low-volume, highly customizable products. In the near-term, additive manufacturing will likely supplement, not replace, conventional industrial-production methods. For products with long production runs (e.g., 10,000 office chairs, 50,000 cell-phone cases, etc.), additive manufacturing likely will not be used because of time and cost issues. As a NIST report, *Costs and Cost Effectiveness of Additive Manufacturing,* has shown, for items with production runs of more than several thousand units, the cost of additive production doesn't make economic sense at this time.[47] In addition, additive production times are often longer than for traditional production. However, a completely new manufacturing process called "hybrid manufacturing" is currently emerging. Hybrid manufacturing combines additive and subtractive technologies (increasingly in the same device), providing a manufacturing process combining the best of the additive and subtractive worlds: the ability to print complex shapes without wasting material provided by 3D printing, with the precision and surface finish of subtractive.

Digitally Empowered Factory Operations

Smart manufacturing is poised to provide manufacturers with a comprehensive view of what's occurring at every single point in the production system across multiple process chains and arm them accordingly with the intelligence to make real-time adjustments to optimize manufacturing processes. This includes real-time knowledge of the operational status of individual production machines and equipment and their operational environment, insight into the efficiency of production lines and work cells, and the ability to quickly reprogram or reconfigure robots and other production equipment, thus increasing manufacturers' agility and flexibility to deliver customized production runs. But much of this starts by making production equipment smart and connected through both sensors and the Internet of Things.

The McKinsey Global Institute (MGI) expects the application of the Internet of Things in the manufacturing context alone—in other words, using sensors to bring intelligence to each piece of production equipment on the factory floor to collectively optimize their use—will increase manufacturing productivity from 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.[48] Again, examples of how smart manufacturing applications—largely enabled by the Industrial Internet of Things—optimize factory operations are widespread across a wide variety of manufacturing sectors. For manufacturers, these applications produce a range of benefits: improving productivity while saving costs, reducing defects while improving quality, reducing unplanned downtime by predicting failure before it happens, reducing inventory, and minimizing waste while enhancing environmental sustainability.

For instance, smart manufacturing is transforming production processes across the automotive industry. General Motors leverages sensors to monitor humidity conditions while vehicles are being painted; if the environmental conditions are unfavorable, the vehicle or part can be moved elsewhere in the facility or the ventilation systems adjusted as necessary.[49] Likewise, Harley Davidson tracks fan speeds in its motorcycle painting areas and can algorithmically adjust the fans based on environmental fluctuations.[50] For its part, Ford has placed sensors on virtually every piece of production equipment at its River Rouge facility outside Detroit. One benefit for Ford has been that 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.[51]

Digitally empowered manufacturing processes have also transformed defense contracting. At Lockheed Martin, next-generation digital-manufacturing technologies have redefined the company's production cycle, bringing together what Lockheed calls its "digital tapestry": a seamless digital environment driven by an integrated model-based engineering (MBE) software that keeps the digital data underlying a range of products intact from conceptualization to realization.[52] In other words, Lockheed Martin can move digital information defining the part or product (e.g., the design definition file) from its design software to the downstream production machines actually fabricating parts and final products. For its part, Raytheon uses similar tools to keep track of virtually every activity in its production process. For instance, Raytheon famously keeps track of how many times a screw has been turned within each of its factories, something of great significance when the company is producing sensitive equipment such as missiles with extremely specific fault tolerances.[53]

Life sciences and ICT hardware manufacturers leverage smart manufacturing technologies to predict problems and cuts costs. Intel uses predictive modeling on data to anticipate failures, prioritize inspections, and cut monitoring costs at its chip-manufacturing plants. With so many potential variables to track, no longer should "too little information" be an excuse for waste and loss in the factory environment.[54] Merck improved one of its vaccines by conducting 15 billion calculations to determine which environmental and process factors influenced the quality of the final product.[55]

One of the most significant applications of smart manufacturing, both on the factory floor and in support of products deployed in the field, lies in the area of predictive and preventative maintenance and repair.

As several of the previous examples suggest, one of the most significant applications of smart manufacturing, both on the factory floor and in support of products deployed in the field, lies in the area of predictive and preventative maintenance and repair. This allows manufacturers to monitor the status of production equipment in real time and ideally prevent faults from occurring or else detect them immediately once they occur. Essentially, smart manufacturing transforms the maintenance model from one of repair and replace to predict and prevent.[56] MGI estimates that the use of predictive maintenance techniques will reduce factory equipment maintenance costs by up to 40 percent, while reducing equipment downtime by up to 50 percent, and reducing capital-equipment investment costs (to replace defective equipment) by up to 5 percent. As MGI explains, "once machines are interconnected and managed by IoT [Internet of Things] sensors and actuators, it is possible to improve asset utilization significantly by using auto-sensing equipment to eliminate many of the human and machine errors that reduce productivity."[57] For its part, the U.S. Department of Energy's Pacific Northwest National Laboratory estimates that predictive asset maintenance can save up to 12 percent in scheduled repair costs, reduce overall maintenance costs by up to 30 percent, and result in up to 70 percent fewer machine breakdowns.[58]

GE's Brilliant Factories initiative—which seeks to combine lean operational excellence capabilities with digital capabilities at its more than 500 plants globally—provides a compelling example. By using these digital technologies, GE's Appliances Park factory in Lexington, Kentucky, reduced by half the number of dishwashers and washing machines with production defects.[59] Manufacturers are increasingly integrating predictive-maintenance data into their enterprise resource planning (ERP) systems to improve workflow scheduling, thus optimizing repair schedules and minimizing machine downtime. For instance, Taleris, which supports airline and cargo-carrier operations, uses this technology to predict aircraft-maintenance faults and thus minimize flight delays.[60] Likewise, Germany's ThyssenKrupp AG leverages networked equipment sensors to identify and predict maintenance issues, which reduces unscheduled downtime and helps avoid unnecessary repair trips.[61] Documenting the extent to which U.S. manufacturers are deploying smarter machines to reduce production faults, a December 2013 survey by the American Society for Quality found that 82 percent of U.S. manufacturers have already begun investing in smarter machines and systems, with 49 percent reporting fewer product defects.[62]

Smart manufacturing will also help enhance inventory-optimization techniques and streamline and optimize both shop-floor processes and order fulfillment. For instance, warehouses equipped with robots can handle four times as many orders as unautomated warehouses.[63] In another example, 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. McKinsey estimates that these types of inventory-optimization measures can save 20 to 50 percent of factory-inventory carrying costs.[64]

Further, by leveraging the information produced from each device and production system on the factory floor, the Internet of Things can be applied to smart manufacturing to optimize production processes by reassigning tasks and redefining work flows. In other words, modern software and IT systems are helping optimally design the layout of factories themselves. For example, by equipping workers with badges, tags, and other sensors, companies can track activities, tasks, and interactions to better understand how each function operates. MGI estimates that the benefits from such organizational redesign on the factory floor could be worth as much as $50 billion annually.[65] Further, Internet of Things-enabled sensing technologies can be applied to alert or to halt equipment or individuals if they come too close 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.[66]

Finally, smart manufacturing techniques allow designers to rethink the traditional, location-fixed factory floor, and even to make the "factory floor" itself mobile. For instance, Pfizer is currently developing portable manufacturing platforms, allowing it to efficiently produce vaccines for children in countries where they are needed most.[67] These portable manufacturing platforms represent small-scale, modular, flexible versions of Pfizer's larger manufacturing facilities. Smart manufacturing tools allow Pfizer to develop control strategies for those technology systems so the company can effectively deploy the modules throughout the world.[68]

Digitally Linked Supply-Chain Management

Smart manufacturing will also dramatically improve companies' ability to manage their supply chains and, more broadly, to enable SMEs to integrate more seamlessly into their industrial value chains. This matters because the interconnected nature of industrial supply chains makes them hotbeds for risk, and more information can mean the difference between a recall and a successful shipment.[69] Again, virtually all manufacturing sectors are being impacted.

In the automotive sector, 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. In Germany, automotive manufacturers such as BMW have set a goal of knowing the real-time status of all the major production equipment at each company that produces key components for each of its vehicles. 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 the 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.

Of U.S. manufacturers, 82 percent have already begun investing in smarter machines and systems, with 49 percent reporting fewer product defects.

For its part, GE Oil and Gas uses a cloud-based supply-chain data platform to manage its materials, equipment, and services. The real-time system, now deployed on five continents, was created to contend with the high cost of downtime at oil fields and the need to offer increased levels of customization for clients.[70] Likewise, HP integrates network analysis into its supply-chain monitoring, leveraging data-visualization tools that have reduced the time required to complete supply-chain optimization projects by up to 50 percent.[71]

Smart Products Beyond the Factory Floor

Until recently, manufacturers had few ways to track the performance of their products once they left the loading dock. Some companies would survey consumers about product performance. Others relied on information related to warranty-based returns or replacement. But, overall, once a product left a manufacturer's hands, it entered the world of the unknown. As a result, manufacturers' ability to improve both the quality and functionality of their products was decreased.

But smart manufacturing now enables products themselves to convey information about how they are consumed and serviced, data that can be fed back into the design process to improve future versions of the product. It can even enable some products to be used as platforms for future product innovation. In essence, products are evolving into intelligent, connected devices, which are increasingly embedded within broader systems.[72] That's why companies are increasingly "selling products as a bundled package of services."

This all starts with smart products, which share three key components: 1) Physical components (e.g., mechanical and electrical parts); 2) smart components (e.g., sensors, microprocessors, data storage, embedded operating systems, and often a digital user interface); and 3) connectivity components (e.g., wireless connectivity provided by antennae or internal modems).[73] For companies, the advent of smart products means that the mindset of those who design products will have to shift from designing an individual product to designing a product that operates within systems, which also means that the domain of product development will increasingly shift from mechanical engineering to interdisciplinary systems engineering, with a heavy focus on the information-systems component.[74] In summary, information technology changes the nature of products by enabling mass customization, low-cost variability, evergreen design, and the potential for the product itself to become a platform for commerce (that is, a platform for recurring, services-based revenue streams).[75]

To start with, the software in smart, connected products can dramatically decrease the cost of variability, or customization, across a product suite. For instance, heavy-equipment manufacturer John Deere previously manufactured multiple versions of engines with different horsepower levels for its tractors, harvesters, and gins, but it can now use software to alter the horsepower level of a single, standard engine.[76] Likewise, smart products enable "evergreen design," or the continuous upgrading or updating of existing products, often through "over-the-air" updates to software operating or controlling the device. For instance, Tesla has installed autopilot software in its cars whose functionality the company can upgrade remotely. In another instance, in 2013, batteries in two Tesla Model S cars were punctured and caught fire after drivers struck metal objects in the roadway. Tesla realized the chassis on some of its vehicles was too close to the ground, and was able to send an over-the-air software update to all Model S vehicles that raised their suspension under certain conditions, significantly reducing the chances of further punctures.[77]

Information technology changes the nature of products by enabling mass customization, low-cost variability, evergreen design, and the potential for the product itself to become a platform for commerce.

Smart products also enable remote operation. For instance, ABB Robotics' industrial robots can be remotely monitored and adjusted by end users.[78] The Chilean firm Codelco, the world's largest copper miner, operates mining and excavation equipment that runs 100 percent autonomously. From a centralized control room in the Chilean capital, Santiago, technicians control excavation equipment at mining facilities throughout the world, from South America to Australia. Further, the company has recently started using robotic machinery to inspect equipment prior to its scheduled maintenance, which Codelco expects to reduce service time and minimize device management oversight.[79]

In many industries, the advent of smart products has changed the business model of the manufacturing enterprise, as an increasing number of companies embrace "servification"—that is, selling products as services—whether on a leased or monthly subscription basis. Across a range of industrial products, including jet engines, copiers, printers, and HVAC (heating, ventilation, and air conditioning) systems, companies no longer sell individual products, but rather increasingly sell products as integrated services. For example, GE's medical devices division no longer sells individual radiological equipment (e.g., MRI or X-ray machines) to hospitals; rather, it sells radiological services, where GE takes over management of a hospital's (or a larger health maintenance organization's) entire suite of radiological assets, installing the devices with remote-monitoring capabilities that allow GE to know if they are operating and functioning properly and to diagnose and detect various failure modes in advance.[80] In essence, GE owns and maintains the machines and charges customers a fee for their use of the radiological equipment instead of them having to purchasing it themselves.

Likewise, jet-engine manufacturers no longer "sell" the engine to airlines (or aircraft-leasing companies). Rather, Rolls Royce sells "power by the hour" and GE Aviation Engines sells "guaranteed thrust," removing depreciating capital assets from airline customers' balance sheets. Customers pay only for the thrust they consume, and transfer the risk of nonperformance to the leasor, so that the provider of the engine service bears the cost if an engine failure means the plane cannot fly. For jet-engine manufacturers, when they take over an airline-fleet contract, this means the airline is no longer concerned with which companies' engines power the aircraft, permitting the jet-engine leasor to, over time, surreptitiously replace any competitors' jet engines in an airline's fleet with their own. It's a subtle way to increase penetration without having to make subsequent sales to the airline's chief financial officer.

Products have evolved into intelligent, connected devices, which are increasingly embedded in broader systems that are sold as bundled services.

The data stream produced by engines and airplanes also changes the service and support offerings that jet-engine manufacturers can provide. Engines produce tremendous amounts of information. A single Boeing 737 engine produces 20 terabytes of data every hour in flight.[81] Therefore, an eight-hour flight from New York to London on an aircraft with two engines can generate 320 terabytes of data.[82] GE Aviation Engines tracks the exact conditions—temperature, humidity, altitude, particulates in the air (e.g., dust)—of each mile flown by its engines. Accordingly, when GE puts together its engine maintenance and service bid for airlines such as Emirates, Lufthansa, Southwest, or United its offer is based on knowledge of the historical use and experience of each engine in the contract. Likewise, Rolls Royce leverages the Internet of Things to collect data on real-time jet aircraft engine usage, which minimizes Rolls Royce's operations costs while increasing engine operating life and allowing the company to introduce new services such as "zero-based disruption." Analysts estimate that Rolls Royce's "Power by the Hour" business model, combined with real-time engine monitoring, produced $400 to $600 million in savings in 2014 and will generate revenue increases greater than $1 billion annually moving forward.[83]

Boeing uses the data stream created by modern aircraft to detect and diagnose potential problems mid-flight. The airplane relays any identified problems to airline-maintenance personnel waiting at the next airport using a web portal, "MyBoeingFleet.com."[84] These crews, located around the world, can then be ready with the appropriate parts to make any necessary repairs as soon as the airplane touches down. Intelligent analysis like this provides airline operators with proactive maintenance planning, helping to spot trends, eliminate inefficiencies, save money, and reduce wait times.[85] Boeing's technology, enabled by the seamless, cross-border integration of data from all over the world, allows airlines to improve their products, so passengers avoid more delayed flights, less reliable trips, higher costs, and potentially more accidents.[86]

Xerox provides another compelling example of a product company that successfully "servicized" its business model. Xerox transformed its core copier and printer business from a product to a service by introducing an offering called Managed Print Services, through which Xerox owns and oversees all of a customer's copiers and printers, and charges them by pages printed.[87] To achieve this, however, Xerox had to add sensors to all of its copiers and printers—on the photoreceptor drum, feeder output tray, and toner cartridges—to enable accurate accounting.[88] Xerox's customers have benefitted, since the service turns a fixed cost into a variable (more controllable) cost, with customers such as Proctor and Gamble finding that they have reduced paper use by 40 percent and cut company costs by 25 percent.[89]

Scania AB, a leading Swedish manufacturer of commercial vehicles, has likewise increasingly transitioned to a services-based business model focused on fleet management services including logistics, repair, and other services. In fact, Scania now generates one-sixth of its revenues through new services enabled by the wireless communication built into its vehicles.[90] Examples abound from scores of other industries, but the core insight is that smart manufacturing and smart products go hand in hand.

AGGREGATING THE BENEFITS OF SMART MANUFACTURING

The application of smart manufacturing techniques generates significant productivity benefits at the enterprise and establishment level (establishments being the multiple operating units [e.g., R&D and production facilities] of enterprises) as well as the industry and supply-chain level, and collectively these benefits aggregate to produce economy-wide benefits at the national level.

Evidence from several manufacturers that have made significant investments in smart-manufacturing technologies and principles demonstrates significant benefit. For example, a leading U.S. automaker estimates it has saved $2 billion over the past five years (2011-2015) by developing a robust Internet of Things and data-analytics capability.[91] And even a 1 percent increase in maintenance efficiency in the aviation sector could save the industry approximately $2 billion annually.[92] Again, it's IT-enabled systems that are delivering these efficiencies, explaining why 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.[93]

However, considering just the plant (e.g., factory) level, the Smart Manufacturing Leadership Coalition (SMLC) estimates that the demand-driven, efficient use of resources and supplies in highly optimized plants leveraging smart manufacturing techniques will lead to 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.[94]

In terms of quantifying the acceleration of manufacturers' product-development lifecycles and reductions in cost through the application of smart manufacturing techniques, SMLC estimates an 80 percent reduction in the cost of implementing modeling and simulation and an overall tenfold improvement in time to market in targeted industries.[95]

Aggregating this impact analysis to the broader U.S. industrial base, SMLC anticipates smart manufacturing can contribute a 25 percent increase in revenues from new products and services at firms using these techniques as well as a 25 percent increase in revenue in adjacent industries.[96] The Smart Manufacturing Leadership Council further predicts that smart manufacturing can increase the size of the addressable market for SME manufacturers and create more high-skilled jobs across small and large manufacturers alike. Here, it's worth reiterating that manufacturing jobs engender a significant employment multiplier. On average, each new manufacturing job in the U.S. economy supports four additional U.S. jobs, but when it comes to jobs created in advanced-manufacturing sectors, the employment multiplier increases to as much as 16 to 1.[97] As Nosbuch and Bernaden write, "As factories get 'smarter' and more advanced, the multiplier increases significantly. In some advanced manufacturing sectors, such as electronic computer manufacturing, the multiplier effect can be as high as 16 to one, or 16x, meaning that every manufacturing job supports 15 other jobs."[98]

Smart manufacturing can contribute to a 25 percent increase in revenues from new products and services at firms using these techniques.

At a broader level, the market-intelligence firm IDC estimates that data-driven "smart-manufacturing" processes will generate $371 billion in net global value over the next four years by 1) creating value from data; and 2) streamlining design processes, factory operations, and supply-chain risks.[99] And, as noted, the McKinsey Global Institute predicts even more significant gains, estimating that the Industrial Internet of Things will generate as much as $1.8 trillion in new value annually across the world's factories by 2025.[100]

Beyond large numbers, it's also critical to recognize how smart manufacturing will change the nature of manufacturing itself. In particular, smart manufacturing will enable shorter production runs (mass customization) to become more economical. Flexible factories and IT-optimized supply chains will change manufacturing processes to allow some manufacturers to customize more products to individual needs, such as medications with specific dosages. Just as Dell pioneered the built-to-order personal-computer revolution, Tesla is already showing how the automotive industry will be transformed by permitting customers to go online to instruct a factory on the personalized features they want built into their vehicle.[101]

Indeed, in the future, whether it comes to chocolate bars, vehicles, swim goggles, sneakers, hearing aids, prosthetics, or many other items, technology will increasingly enable the cost-effective production of more personalized products.[102] As efficient production sizes shrink and reduce the required economies of scale, this will likely have two important impacts. First, it will make it easier for smaller manufacturers to gain market share, particularly for those customers who want a more personalized product and are willing to pay a modest price premium for it. As Autodesk's Tamburini explains, this will enable entirely new kinds of innovation and means that "a startup or entrepreneur can once again compete with the big companies to bring innovations to market."[103]

Second, smart manufacturing, in part by boosting labor productivity and by reducing efficient production lot sizes, will likely enable more localized manufacturing (i.e., "on-shoring"). As the World Economic Forum observes, "With digital systems and data science, automation and adaptive processes, smart manufacturing is being used to move production closer to the markets that originate the demand."[104] In the last two manufacturing technology transitions, technology worked to enable geographically dispersed production. Mass production meant long production runs and a focus on reducing labor costs by seeking low-wage locations. But as smart manufacturing boosts productivity, labor costs relative to total costs will diminish, making at-the-margin manufacturing easier to locate in higher-cost areas. At the same time, smart manufacturing will increase needed skill levels on the shop floor, making traditional locations in low-wage nations whose workers have limited skills more problematic. Finally, by reducing efficient minimum production scale, in part through customized manufacturing, smart manufacturing will make it more economically feasible to locate some work closer to the customer base, and that will mean often in higher-income nations.

Smart manufacturing, in part by boosting labor productivity and by reducing efficient production lot sizes, will likely enable more localized manufacturing.

Indeed, smart manufacturing techniques will increasingly enable competitive manufacturing in high-cost environments. For example, 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.[105] Many companies applying the tool find that the supply-chain mismatch costs arising from increased demand-volatility exposure are frequently greater than the cost reduction offered by an offshore supplier, and that going offshore is often not a bargain. Combining this analysis with quantifying the impact of possible demand peaks also allows companies to rethink cost allocations depending on time sensitivity. In total, the tool helps manufacturers to understand volatility in order to manufacture close to their markets profitably (and without requiring subsidies).

In summary, there's an increasing economic justification in modern manufacturing for co-locating idea generation, design, systems development, production, and supply-chain management.[106] This inverts the previous manufacturing paradigm, which segregated the R&D and design from the production phase, as manufacturers sought cheaper locations offshore for what was often labor-intensive assembly or production. In short, smart manufacturing puts U.S. manufacturers in a position where they're not just pursuing low-cost, routinized, commodity manufacturing, and strengthens their ability to manufacture increasingly high-value, high-profit margin parts and products in the United States. And while a 2013 OECD report, *Interconnected Economies: Benefitting From Global Value Chains*, claimed to find "as yet little evidence that global value chains are shifting due to the wave of technological change," the reality is that fifth-wave technologies are maturing rapidly and will have significant impact on global production chains.[107]

HOW COMPETITOR NATIONS ARE SUPPORTING SMART MANUFACTURING

Recognizing the importance of smart manufacturing to their industrial future, a number of countries have launched policies and programs to support the research, development, and deployment of smart manufacturing technologies for their domestic manufacturers. The following section provides a sample of key smart-manufacturing strategies in China, the European Union, Germany, Sweden, and the United Kingdom, with a brief summary provided in Table 1.

Table 1: Summary of National Smart Manufacturing Policies/Programs by Country

Country	Smart Manufacturing Policy/Program	Investment Level
Austria	R&D projects associated with Industry 4.0	€250 million (approximately $280 million)[108]
China	Made in China 2025 Program; Implementation Plan for the 2016 Intelligent Manufacturing Pilots Special Project	Specific funding line for this pilot unavailable, but China is investing more than $3 billion in "advanced manufacturing"
European Union	"Factories of the Future" program calls for "leadership in deploying key enabling and industrial technologies"	€7 billion ($7.8 billion) (total over seven years to 2020)
Germany	Efforts to help industry associations, research institutes, and companies create Industry 4.0 implementation strategies	€500 million (approximately $550 million)
Sweden	The "Smart Industries" Strategy	163 million SEK (approximately $18 million) for various smart manufacturing support programs
United Kingdom	High-Value Manufacturing Catapult, a network of seven advanced-manufacturing technology institutes, includes a Manufacturing Technology Centre (MTC)	£140/$220 million (over the next five years)
United States	At least four related IMIs Digital Manufacturing and Design Innovation Institute (DMDII); America Makes (additive manufacturing); Clean Energy Smart Manufacturing Institute; Institute for Advanced Composites Manufacturing Innovation	Across those four institutes: public investment of $240 million; matched by $460 million from nonfederal sources, including private-sector consortium partners[109]

China

In May 2015, China's State Council issued *China Manufacturing 2025*, a 10-year plan laying out a strategy for the country to become a "world manufacturing power," especially by strengthening its intelligent manufacturing capabilities.[110] On March 31, 2016, China's Ministry of Industry and Information Technology (MIIT) announced an *Implementation Plan for the 2016 Intelligent Manufacturing Pilots Special Project*, with the plan including a detailed timeline for intelligent manufacturing pilots, in which companies are to upgrade their facilities with a range of intelligent technologies. The plan orders 60 pilot projects across a number of Chinese industrial sectors with the following directives:

- Leverage intelligent technologies to upgrade discrete manufacturing sectors (such as electronic information, machinery, aviation, aerospace, automotive);
- Leverage intelligent technologies to upgrade process-manufacturing sectors (such as oil exploration, petrochemicals);
- Promote "network-cooperative manufacturing" in integrated circuits, communication products, machinery, automobile, household appliances, and other related industries; and
- Leverage cloud computing to carry out large-scale customization for digital products and other related sectors.[111]

In April 2016, MIIT complemented the *Intelligent Manufacturing Pilots Special Project* with an *Implementation Plan for 2016 Special Project on Innovatively Promoting the Integration of Industrialization and Informatization*.[112] The plan urges Chinese manufacturers to promote the incorporation of next-generation information technologies into their manufacturing processes. The plan includes the following objectives:

- Build Internet-based service platforms to boost entrepreneurship and innovation, with the goal that over 50 percent of leading enterprises in key industries should have access to such platforms; and
- Cultivate a batch of service platforms using cloud and industry big data and achieve a 20 percent annual increase in the number of "industry cloud corporate users."[113]

To achieve the above goals, the plan for *Innovatively Promoting the Integration of Industrialization and Informatization* outlines seven priority work streams, including beginning the development of cyber-physical systems (CPS) testing and evaluation platforms and verification test beds, launching CPS application pilots, and formulating CPS-related standards.

Finally, in part to help fund these and other initiatives, in June 2016, China's National Development and Reform Commission, Ministry of Finance, and Ministry of Industry and

Information Technology announced the launch of a $3 billion (20 billion yuan) fund that will invest in the advanced-manufacturing sector, promote modernization of traditional industry, and boost high-end manufacturing.[114] The funds were contributed by China's central treasury, its State Development and Investment Corporation, and the Industrial and Commercial Bank of China.

In short, China's government has instituted several key initiatives and made significant investments toward ensuring that the country's manufacturing industries adopt and embrace smart manufacturing technologies and processes as quickly as possible. As Paul Tate, an analyst for market-research firm Frost and Sullivan, observes, "Overall, the aim of this new strategy [Made in China 2025] is to put China on par with other industrialized countries such as the U.S. and Germany … in accelerating the adoption of digital technologies and advanced production approaches."[115]

The European Union

Like China, the European Union is investing heavily to ensure its competitiveness in smart manufacturing. The European Union's (EU's) Horizon 2020 program plans to allocate €17 billion ($19 billion) for "leadership in deploying six key enabling and industrial technologies," including advanced manufacturing, through 2020. Within the seven-year (2014-2020) Horizon 2020 program, the European Commission plans to invest a total of €7 billion ($7.8 billion) in a "Factories of the Future" public-private partnership to develop the blueprints for a smarter manufacturing sector in the European Union.[116] The European Union's goal is to outline a roadmap toward high-value-added manufacturing technologies for factories of the future, which will be clean, high performing, environmentally friendly, and socially sustainable.[117] Core objectives of the Factories of the Future program include research and innovation efforts dedicated to:

Like China, the European Union is investing heavily to ensure its competitiveness in smart manufacturing.

- Integrating and demonstrating innovative technologies for advanced-manufacturing systems, culminating in development and adoption of 40 to 50 new best practices.
- Developing environmentally friendly manufacturing techniques that can reduce energy consumption in manufacturing activities by up to 30 percent; reducing waste generated from manufacturing activities by up to 20 percent; and decreasing the consumption of materials by 20 percent.
- Developing approaches to reverse the deindustrialization of Europe, including by "identifying 6-8 new types of high-skilled jobs to increase industrial commitment to stay in Europe" and to "raise European industrial investment in equipment from 6 to 9 percent by 2020."[118]

It should also be noted that Europe regards smart manufacturing as a core component of the European strategy on "smart specialization," which aims to strengthen the comparative advantage of EU regions in terms of ICT skills, R&D capability, industrial output, and infrastructure. In other words, in Europe, smart manufacturing is being pursued in part at a regional level to make European regional-manufacturing clusters more globally competitive. And it would be difficult to underestimate the importance the European Union attaches to smart manufacturing: It estimates that this fifth wave of smart manufacturing could boost the European Union's gross domestic product by €110 billion annually over the next five years, breathing new life into sectors that account for 2 million businesses, 33 million jobs, and approximately 60 percent of European economic growth.[119]

Germany

Germany refers to smart manufacturing by the term Industry 4.0. Analysts estimate that the application of advanced ICTs to German industrial manufacturing will boost the productivity of German industry by as much as 8 percent.[120] The German government has pledged more than €500 million ($550 million) to help industry associations, research institutes, and companies create implementation strategies for Industry 4.0.[121] One result of Germany's Industry 4.0 efforts is that they have identified over 300 "use cases" of how Germany's manufacturers can digitalize their production processes.[122] This also includes a range of R&D efforts to advance "smart-factory" technologies ranging from sensor-embedded systems to artificial-intelligence platforms that can help operate Internet-connected machinery. German President Angela Merkel has directly engaged in promoting Industry 4.0, noting that "We have reached a critical moment, a point where the digital agenda is fusing with industrial production." She's also identified failure to lead in smart manufacturing as a threat to Germany's industrial prowess, noting, "We have to execute quickly, otherwise those who are already leading in digital will snatch the industrial production from us" (a perhaps not-so-subtle reference to U.S. strength in digital technologies).[123]

Most evidence suggests German manufacturers intend to quickly embrace smart manufacturing. For example, a 2014 PriceWaterhouseCoopers report, *Industrie 4.0 Chancen und Herausforderungender Vierten Industriellen Revolution*, found that 85 percent of German manufacturers surveyed planned to implement Industry 4.0 solutions over the next five years.[124] Moreover, the report found that from 2015 through 2020, German industry will invest €40 billion ($50 billion) annually in Industry 4.0 applications.[125] The German industrial firms surveyed said they intended to invest, on average, 3.3 percent of their revenues in Industry 4.0 solutions over that timeframe, with those investments accounting for nearly 50 percent of their planned capital investments. The report further noted that within five years, more than 80 percent of German manufacturers will have digitalized their value chains, with those digitalized products and services expected to earn an additional €30 billion ($37 billion) annually for German industry. Likewise, a recent Deutsche Bank report, "Industry 4.0: Huge Potential for Value Creation Waiting to Be Tapped," found a similarly substantial impact, estimating that, "Thanks to Industry 4.0, German gross value added could well be boosted by a cumulative €267 billion [$332 billion] by 2025."[126] More broadly, Germany's National Academy of Science and Engineering estimates that this new technological revolution will lead to a 30 percent increase in German industrial productivity.

But Germany frets that a failure to lead in adoption and implementation of smart manufacturing could severely harm the country's manufacturing base. A new report by Roland Berger and the German Federation of Industries concluded that failure to adapt to the new digital landscape could cost German industry some €220 billion by 2025.[127] And despite all the hype about Industry 4.0 among Germany's largest manufacturers, there's evidence that the message is taking longer to filter to Germany's SMEs, the vaunted Mittelstand. A recent survey of 4,500 German SME manufacturers found that less than 20 percent had heard of Industry 4.0, much less taken steps to implement it.[128] This highlights the challenge that many countries will face in assisting their SME manufacturers in implementing smart-manufacturing techniques. Yet, despite such figures, there's little doubt Germany will be a leader in the global smart manufacturing revolution.

Sweden

In April 2016, Sweden introduced a new "Smart Industries" strategy which includes four core focus areas:

1. Industry 4.0: Exploiting the potential of digitalization;
2. Sustainable production: Improving the industrial sector's capacity for sustainable and resource-efficient production;
3. Industrial skills boost: Ensuring the supply of needed skills for the industrial sector;
4. Test bed Sweden: Creating test-bed environments for new technologies within Sweden.

The Industry 4.0 component of the Smart Industries strategy seeks to foster "smart industrial companies in Swedish industry that are leaders in digital development."[129] The implementation of Sweden's Smart Industries plan will seek to (i) Stimulate the development, deployment, and use of digital technologies that have the highest potential to lead industry transformation; (ii) Take advantage of digitalization opportunities regardless of company size and geographic location; (iii) Encourage new business and organizational models to utilize the potential of new technologies; (iv) Meet the needs for new knowledge that the digital revolution brings; and (v) Adapt manufacturing frameworks and infrastructure for the digital age.[130]

Sweden will invest over 160 million SEK (almost $18 million) in various efforts to support its Smart Industries initiative. These will include 60 million SEK ($6.5 million) at Vinnova (Sweden's national innovation agency) for collaborative projects for the digitalization of Sweden's manufacturing industries as well as 16 million SEK ($1.7 million) for open innovation initiatives in manufacturing firms. The Swedish Agency for Economic and Regional Growth will further invest 78 million SEK ($8.5 million) in a pilot "digitialization boost" program for Swedish manufacturing SMEs.[131]

United Kingdom

The British government will invest £140 million ($219 million) over the next six years in its High-Value Manufacturing Catapult network of seven advanced-manufacturing technology institutes, including the Manufacturing Technology Centre (MTC), which focuses on advanced-manufacturing technologies.[132] The MTC develops and proves innovative manufacturing processes and technologies in an agile, low-risk environment, in partnership with industry, academia, and other institutions.

POLICY RECOMMENDATIONS

To ensure America's continuing leadership in smart manufacturing, the Information Technology and Innovation Foundation (ITIF) offers the following policy recommendations. While several of these are more generic recommendations that would bolster the U.S. manufacturing economy broadly, by supporting U.S. manufacturing skills, technologies, and investments these policies would also bolster smart manufacturing.

First, the Obama administration broke new ground in February 2012 by releasing *A National Strategic Plan for Advanced Manufacturing*.[133] The next administration should follow suit by releasing both its own national manufacturing strategy as well as a national innovation strategy. As with the 2012 *A National Strategic Plan for Advanced Manufacturing*, policies and initiatives designed to bolster smart manufacturing should comprise a significant component of the report.

Second, the National Network for Manufacturing Innovation (NNMI), launched in 2012 by the Obama administration, and renamed in September 2016 as Manufacturing USA, is playing a pivotal role in revitalizing America's industrial commons and helping ensure U.S. leadership across a range of advanced-manufacturing process and product technologies.[134]

At least four Institutes of Manufacturing Innovation (IMIs) within Manufacturing USA address smart manufacturing-related technologies and processes. The first IMI, America Makes: The National Additive Manufacturing Innovation Institute, launched in 2011, focuses on helping the United States grow capabilities and strength in additive manufacturing (i.e., 3D printing). The Digital Manufacturing and Design Innovation Institute (DMDII) encourages factories across America to deploy digital manufacturing and design technologies, so America's factories can become more efficient and cost competitive.[135] The Institute for Advanced Composites Manufacturing Innovation (IACMI) is accelerating development and adoption of cutting-edge manufacturing technologies for low-cost, energy-efficient manufacturing of advanced polymer composites for vehicles, wind turbines, and compressed gas storage.[136] And the newest IMI, the Clean Energy Smart Manufacturing Innovation Institute, currently being stood up by the Smart Manufacturing Leadership Coalition in collaboration with the U.S. Department of Energy, will focus primarily on innovations such as smart sensors, data analytics, and controls in manufacturing that can dramatically reduce energy expenses in advanced manufacturing.[137]

Nine IMIs have currently been launched, with two more in development at the Department of Energy (Process Intensification and ReMade), two more expected to be led by the Department of Defense, and two more to be spearheaded by the Department of Commerce and focused on industry-directed challenges. This creates a pathway to reach 15 IMIs by the end of the current administration, which has also articulated a long-term vision of a network of 45 IMIs. **Congress should collaborate with the next administration to provide funding and authorization to build out a full network of 45 Manufacturing USA institutes as envisioned.**

The Manufacturing Extension Partnership (MEP) provides training, technical assistance, and other services to America's SME manufacturers. MEP centers operate in all 50 states (and Puerto Rico), managing 588 service locations with more than 1,200 field staff serving as trusted business advisors and technical experts ready and able to assist small- and mid-sized manufacturing companies.[138] Coordination between MEP and the Manufacturing USA program is vital as a key channel to diffuse the new manufacturing technologies being created by the IMIs to America's SME base. Recently, MEP and Manufacturing USA embarked on a new partnership that will embed MEP representatives within five of the IMIs, including the DMDII, with a goal of developing smart manufacturing-specific service offerings for SMEs. However, as this program was launched before the new Clean Energy Smart Manufacturing Innovation Institute, **the next administration should ensure funding for the MEP embedding program across the four remaining IMIs.**

The Manufacturing Extension Partnership represents one of the most impactful programs in the federal government, delivering significant results for taxpayers.[139] Estimates find that for every one dollar of federal investment, the MEP generates $19 in new sales growth and $21 in new client investment. This translates into $2.2 billion in new sales annually. And for every $1,978 of federal investment, MEP creates or retains one manufacturing job.[140] But MEP centers could be even more effective if the federal cost-share requirements were reduced from 2:1 (two parts nonfederal; one part federal, via NIST funding) to 1:1, as suggested in the MEP Improvement Act of 2016 (S. 2779). Adjusting MEP's cost share would enable MEP centers to become less dependent on generating fees for services provided, which would support additional work with harder-to-serve manufacturers, including very small, rural, and early-stage companies. Additional federal funding would also allow MEP centers to develop more programs helping companies scale up from lower- to higher-volume production and get innovative products to market faster. Moreover, reducing cost share would enable MEP centers to work with existing clients on projects that don't necessarily have a proven revenue stream, such as linking them to sources of new technologies (e.g., Institutes of Manufacturing Innovation, federal labs, university research) to improve production processes or foster new product development. **Congress should adjust the required MEP cost-share ratio from 2:1 (nonfederal to federal) to 1:1.**

Congress should enact legislation that expands federal resources for training and adoption of smart manufacturing technologies by U.S. SME manufacturers. **An example to follow is language in the Senate-passed version of The Energy Policy Modernization Act of 2016 (S. 2012), which would take several important steps to advance U.S. smart manufacturing leadership.** First, as noted, Congress could help establish legislative and administrative clarity with a commonly shared definition of smart manufacturing, with the Senate-passed version of S. 2012 providing a useful definition that captures the broad scope of smart manufacturing technologies. Second, S. 2012 would a**uthorize and direct the**

Department of Energy's Industrial Assessment Centers program to work more closely with SME manufacturers to help them learn about and adopt smart manufacturing technologies. The Industrial Assessment Centers program funds engineering programs at national universities to provide free assessments that can help identify significant energy savings, provide water and waste reduction recommendations, and recommend other productivity improvements at SME manufacturers.[141]

If smart manufacturing is to flourish to its fullest possible extent, America's manufacturers will need to invest in digital design tools and modernized production and plant equipment, incorporating embedded sensors and communications technology that connect them to the digital thread. In other words, America's manufacturers need to invest in new capital equipment. Unfortunately, as ITIF writes in "Restoring America's Lagging Investment in Capital Goods," American businesses' investments in new capital equipment, software, and structures have slowed significantly in recent decades. While such investment grew by 2.7 percent per year on average during the 1980s, and by 5.2 percent annually during the 1990s, from 2000 to 2011, U.S. businesses' investments in new capital equipment, software, and structures grew by just 0.5 percent. Moreover, as a share of GDP, U.S. business investment has declined by over 3 percentage points since the 1980s.[142]

To maintain a competitive edge over other nations and to restore investment growth for the sake of economic expansion, ITIF recommends that **Congress provide a stronger tax incentive for investment in machinery and equipment. Specifically, Congress should enact an investment tax credit (ITC) providing a 35 percent credit on all capital expenditures made above 75 percent of a base amount.**[143] The ITC would be modeled on the Alternative Simplified Research and Experimentation Tax Credit (ASC). The ASC provides a credit of 14 percent on R&D expenditures above 50 percent of the average of a firm's R&D expenditures over the previous three years. Similarly, the base for the ITC would be the average expenditures on qualifying capital equipment over the last three years, with the credit applying to all expenditures made above 75 percent. This would cost an estimated $45 billion per year over the next 15 years.[144] Because of the larger societal economic impact of investments in equipment and software, the credit would apply only to those investments and not to structures. Allowing for a tax credit for purchases of equipment and software would reduce the after-tax price of investment, raising the level of domestic investment and the productivity of firms.

If Congress does not elect to enact an ITC, **Congress should at least allow firms to expense, for tax purposes, the entire cost of equipment and software in the first year instead of having to depreciate the costs over a number of years.** This costs firms more because they have less capital in early years. However, in part because this does not affect the book value of firms as much as an ITC would, it may have a less-stimulating effect on investment dollar-for-dollar than an ITC.[145]

Ensuring that America's SMEs can fully take advantage of tax incentives, whether for R&D or investment in new machinery and equipment, is also important. In fact, that's why

Congress passed the PATH Act in December 2015 to expand small businesses' access to the R&D credit by permitting them to claim the credit against their employment taxes or against their Alternative Minimum Credit (AMT) tax. But not enough small businesses are aware that this legislation greatly expands their access to the credit. **Accordingly, Congress should pass the Support Small Business R&D Act, which would require the Small Business Administration and the Internal Revenue Service to expand knowledge-sharing and training on these instruments and provide a report to Congress on their progress.**

If American industry is to lead the smart manufacturing revolution, it will need a workforce equipped with the requisite skills.[146] 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.[147] Likewise, Deloitte Consulting and the Manufacturing Institute report that "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."[148] In some specific domains, even more extensive skills shortages exist. For instance, Autodesk senior director of design research Mark Davis notes that a lack of qualified workforce skills is holding back 3D printing. According to Davis, "The expertise to work with these machines [3D printers] is still in rare supply. … Even if factories did have bays of 3D printers, there'd be few qualified people to operate them."[149]

Policymakers can take several important steps that would help. First, **Congress and the administration should work to increase credentialing for the manufacturing-industry workforce by expanding the use of standards-based, nationally portable, industry-recognized certifications specially designed for specific manufacturing sectors**, such as those developed by the Manufacturing Skills Standards Council (MSSC) and supported by the National Association of Manufacturers-endorsed Manufacturing Skills Certification System.[150] In particular, the Secretaries of the Departments of Labor and Education, in conjunction with the Secretary of Commerce, should ensure that industry-approved certification standards are established and available nationwide to providers of manufacturing education and training programs by providing the funding needed to fully establish and disseminate this initiative.[151]

The community college system is a critical partner in training America's current and future workforce. Community colleges play a vital role in training job seekers with the skills to obtain a good job while simultaneously helping manufacturers obtain the workers they need to stay competitive. In fact, more than half (55 percent) of the 1,600 community colleges in the United States offer specialized training in manufacturing skills.[152] **Accordingly, Congress should boost support for vocational education programs at community colleges, in part by increasing funding for Perkins vocational education and training programs.**[153] The Obama administration has made budget requests for a "Community College to Career Fund" for community colleges to partner with businesses to train 2 million workers in a range of high-growth areas such as advanced manufacturing, while earning industry-recognized credentials.[154] Such funds should go in part toward expanding manufacturing-technology development and training programs at community colleges. **Congress should also reform the Workforce Investment Act system to allow more funds now going to Workforce Investment Boards to instead go to industry-led regional skills alliances.**

If the United States wants to win in the advanced-manufacturing economy of tomorrow, it must transform university culture away from its too-prevalent "research for the sake of research and knowledge accumulation" approach and align it much more with industry's knowledge needs. In particular, the United States needs to forge stronger industry-university research collaborations and incentivize universities to focus more on training students with the requisite skills to support U.S. engineering-based industries.

To address this, **Congress should pass The Manufacturing Universities Act of 2015, which would authorize and appropriate funds to create a core of at least 20 universities that brand themselves as leading manufacturing universities.** The Act was incorporated in the 2017 National Defense Authorization Act (NDAA) passed by the Senate in June 2016. In the House, Representatives Elizabeth Etsy (D-CT) and Chris Collins (R-NY) have introduced a companion bill, HR 1441, to the Senate Manufacturing Universities legislation. Although the House's version of the Manufacturing Universities legislation was not included in the House's version of the 2017 NDAA, policymakers could include this in the conference version of the bill and send to the next president's desk an NDAA that includes the manufacturing universities legislation.

The legislation would establish a competitive grant program managed by the National Science Foundation (NSF) to universities that propose to revamp their engineering programs and focus much more on manufacturing engineering and in particular work that is more relevant to industry. This would include more joint industry-university research projects, more student training that incorporates manufacturing experiences through co-ops or other programs, and a Ph.D. education program focused on turning out more engineering grads who work in industry. As part of this designation, academic institutions would receive an annual award from the NSF—ideally at least $5 million (for up to four years).

Makerspaces are community centers that combine manufacturing equipment and education for the purposes of enabling community members to design, prototype, and create manufactured works that wouldn't be possible to create with the resources available to individuals working alone.[155] There are several ways Congress could support the proliferation of makerspaces throughout the United States. **First, Congress should pass the National Fab Lab Network Act of 2015 (H.R. 1622), which would create a federal charter for a nonprofit organization called the National Fab Lab Network (NFLN).**[156] The NFLN would act as a public-private partnership whose purpose is to facilitate the creation of a national network of fab labs and serve as a resource to assist stakeholders with their effective operation. The network would be comprised of local digital fabrication facilities providing community access to advanced-manufacturing tools for learning skills, developing inventions, creating businesses, and producing personalized products. The labs would be workshops equipped with computer-controlled machine tools and 3-D printing, or additive manufacturing, devices which would allow students, hobbyists and those looking to start small businesses to build virtually anything.[157] Further, **Congress could fund a pilot program that would integrate the maker movement and makerspaces into high schools**. This could build off the 2012 Defense Advanced Research Projects Agency (DARPA) Manufacturing Experimentation and Outreach (MENTOR) program, which introduced new design tools and collaborative practices of making to high-school students.[158]

In "Why Countries Need National Strategies for the Internet of Things," ITIF writes that the Internet of Things represents a fundamentally transformative technology system that can unleash innovation across a wide range of sectors. Accordingly, countries should adopt national strategies to ensure that the technology develops cohesively and rapidly, that consumers and businesses do not face barriers to adoption, and that both the private and public sector take full advantage of the coming wave of smart devices.[159]

At least two Internet of Things-related policy recommendations are relevant with regard to smart manufacturing. First, substantial government investment in research and development has played a critical role in developing many vital technologies, including smartphones, search engines, genomic sequencing, and, of course, the Internet.[160] The Internet of Things should also be a high priority for government R&D investment. Accordingly, **Congress should provide sufficient funding for R&D for key underlying technological challenges relevant to the Internet of Things, such as improving cybersecurity and reducing power consumption.**[161]

Second, the development of interoperable standards will be vital both for the Internet of Things, and smart manufacturing itself, to flourish. Currently, there exists insufficient interoperability to pass data from design and product definition through to production equipment and processes. For example, it is often difficult to pass product-definition data from the controller on the machine tool to the coordinate-measuring machine that is going to inspect it, a challenge only exacerbated when machines are made by different manufacturers (and different manufacturers from different countries). **The National Institute of Standards and Technology should continue to help chart the landscape of smart manufacturing standards, and also work with industry to encourage the development of industry-led voluntary standards and best practices around issues such as interoperability, privacy, and security.**[162]

As noted, high-performance computing-empowered CAD and CAE systems performing next-generation modeling, simulation, and design tasks are vital components of a country's smart manufacturing leadership. That's why the Obama administration launched the National Strategic Computing Initiative (NSCI) in July 2015. The NSCI seeks to create a coordinated federal strategy for HPC research, development, and deployment and defines a multiagency framework for furthering U.S. economic competitiveness and scientific discovery through orchestrated HPC advances.[163] Continued U.S. leadership in high-performance computing will require a steady, stable, robust, and predictable stream of funding. **Accordingly, Congress should fund NSCI and related high-performance computing initiatives at a level of at least $325 million per year over the next five years.**[164]

To remain a leading smart manufacturing economy, policymakers must implement proactive, coordinated policies that support America's manufacturing sector in general and ability to leverage smart manufacturing in particular.

From ICT-empowered manufacturing equipment to smart products themselves, smart-manufacturing techniques will generate enormous amounts of data. But for smart manufacturing to reach its full potential, enterprises must be able to move data seamlessly across international borders. This is especially the case when about 75 percent of the value added by the Internet accrues to "traditional" industries, such as manufacturing.[165] But countries' increasing imposition of barriers to cross-border data flows, such as local data storage requirements or requirements to use local data centers in the processing of that data, could significantly impede enterprises' ability to deploy smart-manufacturing techniques in their international operations.[166] **Accordingly, U.S. trade officials should continue to negotiate trade agreements, such as the Trans-Pacific Partnership, the Trade in Services Agreement, and the Transatlantic Trade and Investment Partnership, that include strong prohibitions against barriers to cross-border data flows, and Congress should look favorably upon these provisions as some of the most significant components of these trade agreements.**

CONCLUSION

The marriage of digital and industrial is the defining aspect of the fifth wave of the industrial revolution. Information technologies are suffusing every facet of modern manufacturing, from design to fabrication to supply-chain management and the use of smart products. These technologies will fundamentally alter the landscape of global manufacturing competition. Yet the private sector will not be able to navigate this transformation alone. Around the world, nations are implementing smart manufacturing strategies and making attendant investments to ensure that their manufacturing enterprises, large and small alike, are positioned to take optimal advantage of the smart manufacturing revolution. If the United States wishes to remain a leading smart manufacturing economy, policymakers must implement robust, proactive, and coordinated public policies that support America's manufacturing sector in general and ability to leverage smart manufacturing techniques in particular.

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ACKNOWLEDGMENTS

The author wishes to thank the following individuals for providing input to this report: Rob Atkinson, Adams Nager, Daniel Castro, Joshua New, Alan McQuinn, Tim Shinbara, and Rebecca Taylor. Any errors or omissions are the author’s alone.

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