How Cloud Computing Enables Modern Manufacturing

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Cloud computing represents a key platform technology that is playing an essential and foundational role in enabling the next production revolution.

Cloud computing—the provision of infinitely scalable computing resources as a service over the Internet—is in the process of transforming virtually every facet of modern manufacturing. Whether it's how manufacturing enterprises operate, how they integrate into supply chains, or how products are designed, fabricated, and used by customers, cloud computing is helping manufacturers innovate, reduce costs, and increase their competitiveness. Critically, cloud computing allows manufacturers to use many forms of new production systems, from 3D printing and high-performance computing (HPC) to the Internet of Things (IoT) and industrial robots. Moreover, cloud computing democratizes access to and use of these technologies by small manufacturers. This report describes how cloud computing enables modern manufacturing, provides real-word case studies of this process in action, and recommends actions policymakers can take to ensure cloud computing continues to transform manufacturing and bolster America's manufacturing competitiveness.

INTRODUCTION TO CLOUD COMPUTING

Cloud computing has been described as an innovation in computing architecture whose central characteristic is the virtualization of computing resources and services.[1] Cloud computing allows computing resources to be delivered with five central attributes: as an on-demand service; with infinite and rapid elasticity and scalability; on a measured basis (meaning the service can be billed); through pooled (i.e., shared) resources; and with broad network access.[2]

Enterprises tend to implement cloud computing in one of three major formats: software as a service (SAAS), platform as a service (PAAS), or infrastructure as a service (IAAS).[3] Software as a service—think online productivity software such as Google Docs or Salesforce's online customer relationship management (CRM) software—allows users to access software applications over the Internet using personal computers, mobile devices, or instrumented machines, instead of having to store software locally on in-house devices.[4] Infrastructure as a service gives organizations access to secure, enterprise-class computing infrastructure that can be infinitely managed and scaled to meet different needs, whether for computer processing or data-storage capacity. Finally, platform as a service allows users to rent virtualized software development or production environments to efficiently develop and deploy new applications without having to invest in expensive hardware or software licenses of their own.

Cloud computing is a technology model for enabling the delivery of IT resources (i.e. servers, storage, applications, etc.) on demand. Cloud has essential characteristics such as on-demand self-service, resource pooling, and rapid elasticity—giving organizations the ability to purchase IT services in a utility-based model, paying for only the services consumed. Cloud also typically is delivered according to one of three service models, namely Software as a Service (SaaS, where the consumer uses a provider's application running on cloud infrastructure), Platform as a Service (PaaS, where the consumer can use cloud infrastructure to deploy applications) and Infrastructure as a Service (IaaS, where typically the consumer can provision IT resources and run their own systems and applications on infrastructure offered by a cloud provider). Additionally, cloud computing is usually deployed in one of four different configurations: a public cloud, a hybrid cloud, a community cloud or a private cloud.[5]

HOW CLOUD COMPUTING ENABLES MODERN MANUFACTURING

Information technology is transforming the global manufacturing economy by digitizing virtually every facet of modern manufacturing processes—a phenomenon called "smart manufacturing" in the United States and "Industry 4.0" in Europe.[6] Cloud-based computing, alongside other foundational technologies such as next-generation wireless, advanced sensors, high-performance computing, and computer-aided design, engineering, and manufacturing (CAD/CAE/CAM) software, represents an essential component of the smart manufacturing revolution.

Cloud-computing applications will impact virtually every aspect of modern manufacturing companies. At the enterprise level, cloud computing will impact how companies manage their operations, from enterprise resource planning (ERP) and financial management to data analytics and workforce training. The cloud will also prove integral to how manufacturers integrate themselves into industrial supply chains. At the manufactured-product level, cloud computing will transform everything from how products themselves are researched, designed, and developed, to how they are fabricated and manufactured, to how they are used by customers in the field. Moreover, cloud computing will play a key role toward enabling and democratizing new manufacturing production systems such as 3D printing (i.e., additive manufacturing), generative design, and the Industrial Internet of Things. In fact, digital services such as cloud computing now provide at least 25 percent of the total inputs that go into finished manufactured products.[7]

As this report will show, cloud-based solutions offer manufacturers a wide range of benefits, among the most significant of which are: scalability; operational efficiency; application and partner integration; data storage, management, and analytics; and enhanced security. In particular, cloud computing facilitates research, design, and development of new products, which powers innovation, reduces product development costs, and speeds time to market.[8] Cloud computing helps manufacturers manage their businesses with better intelligence, which is made possible through expanded use of data analytics. In fact, the cloud is fast becoming the central venue for data storage, analytics, and intelligence for most manufacturers. Cloud computing also empowers manufacturing operations, making them more productive, cost- and energy-efficient, safe, and streamlined.

Digital services such as cloud computing now account for at least 25 percent of the total inputs that go into finished manufactured products.

Cloud-based systems can be scaled up or down to manage shifting project workloads, an especially important requirement for manufacturing firms.[9] Moreover, cloud computing gives manufacturers the ability to leverage infinitely scalable computational resources on an on-demand, pay-as-you-go basis, so that manufacturers can readily access the computational resources they require without having to purchase expensive IT equipment up-front when they may only need it intermittently. This dynamic levels the playing field especially for small to medium-sized manufacturing enterprises (SMEs) that lack the financial wherewithal to purchase expensive IT equipment. This dynamic applies not only to hardware, but also to software. In the past, manufacturers of all sizes have had to purchase expensive enterprise-wide licenses for enterprise resource planning software, CRM software, product-design software, etc. But now that same CRM, ERP, or design software can be flexibly consumed as an on-demand, as-needed service, greatly improving enterprise agility while giving SMEs affordable access to global best-of-breed software.

Another key way cloud computing will impact modern manufacturing is by facilitating integration—whether of widespread supply chains or of the data streaming from IoT-enabled production equipment on the factory floor.[10] Intelligently integrating data streams from myriad partners, platforms, and devices is challenging enough, but is much more difficult to do inside companies' own data centers as opposed to in well-networked data centers operating in the cloud. Finally, cloud computing can actually make manufacturing IT systems more secure. This is because cloud-computing providers employ best-of-breed cybersecurity practices that are often far more sophisticated than what individual companies can achieve by themselves on a one-off basis.

Noting that "evidence on the productivity effects of adopting cloud applications is scarce," the economists Haug, Kretschmer, and Strobel have developed a "cloud adaptiveness measure" that captures a firm's technological and organizational readiness to adapt to cloud computing.[11] The authors find that "cloud-adaptive manufacturing firms generally exhibit higher average labor productivity compared to manufacturing firms that are not cloud adaptive."[12] Their analysis further finds that the manufacturing sector has thus far lagged the services sector in cloud adoption, but they note that this means cloud's potential in the manufacturing sector may therefore be even greater going forward.

With that introduction, this report proceeds by considering how increased investment in IT innovations such as cloud computing can bolster the competitiveness of American manufacturing and by assessing the adoption of cloud computing by manufacturers. It then explains specifically how cloud computing is being implemented at the manufacturing-enterprise and manufactured-product levels and presents several in-depth case studies of large and small manufacturers' implementations of cloud computing. It concludes by offering policy recommendations to expand use of cloud computing in the modern manufacturing economy.

AMERICAN MANUFACTURING: FAILURE OR SUCCESS?

The state of American manufacturing has become a central question for economics and politics. On the one hand, manufacturing is seen as a struggling sector of the economy. Twenty years ago, U.S. manufacturing employed approximately 17 million Americans. But today that number has fallen to just 12 million, a loss of five million jobs. The hollowing out of industry is seen as a significant economic and political problem. Pessimists point to automation and foreign trade as the culprits, and they contend that in coming years robots and artificial intelligence will only exacerbate these employment challenges.

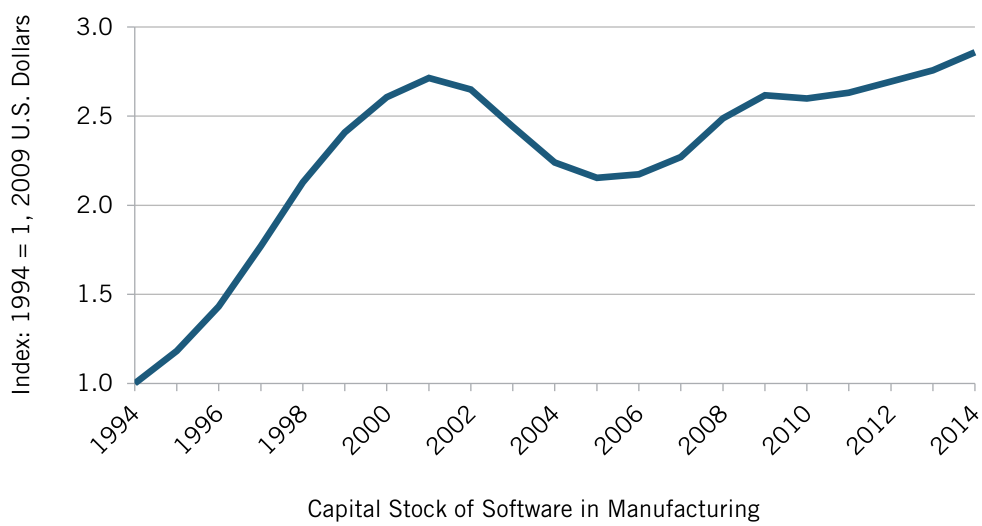
On the other hand, U.S. manufacturing output today is 40 percent greater than it was two decades ago. The notion that "America doesn't make anything anymore," the optimists argue, is simply false. Top-line data implies that America makes a lot more things, and it makes them more efficiently. On the surface, therefore, manufacturing seems like an industry enjoying rapid productivity gains—lots more output with many fewer workers.

The reality is more complex. Many of the productivity gains in manufacturing are concentrated in just a few sub-sectors, especially in computer and electronics manufacturing. Moore's Law, for example, provides a massive tailwind to manufactured computer goods, where the nature of semiconductor technology itself delivers spectacular quality gains of about 50 percent per year, regardless of labor productivity.

Remove Moore's Law from the equation, however, and the performance of non-technology manufacturing firms becomes far more mixed. Productivity growth in many manufacturing sectors over the last 15 years has flatlined, or in a few cases even declined. Outside of the manufacturing of technology itself, many manufacturing industries have been struggling. So, lumping all manufacturing together obscures important distinctions among diverse sub-sectors—food and pharmaceuticals, furniture and steel, asphalt and airplanes, etc.

One reason for the huge productivity differentials between industries and firms is the vast gulf in their use of technology. Despite slow productivity growth across the economy over the last decade, many digital industries, such as media, finance, and professional services, have demonstrated surprisingly robust productivity gains. However, most physical industries, such as transportation, health care, and many manufacturing sub-sectors, have not. Like the other physical industries, many manufacturers have been slower to exploit the power of information technology to improve design, production, and distribution. For example, the capital stock of software held by manufacturers was barely larger in 2014 than in 2001 (see figure 1). And over the last 20 years, the capital stock of total information technology deployed by non-tech manufacturers has risen just half as much as for all manufacturers (see figure 2).

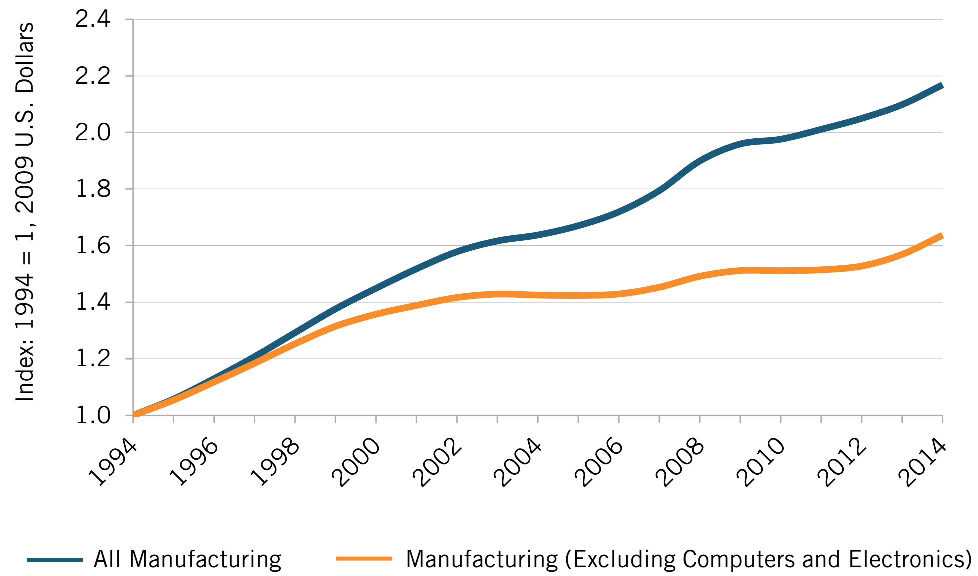
Figure 1: Manufacturing Software Investment Levels Off[13]



The "crisis of automation," which supposedly kills jobs and caps wages, is backwards. Jobs and incomes in firms and industries that use more technology inputs have, more often than not, been rising faster than in those that use less. For many manufacturing sectors, the problem is not too much technology, but too little. The physical industries in general, and many manufacturing firms in particular, have not kept pace with the more innovative digital economy.

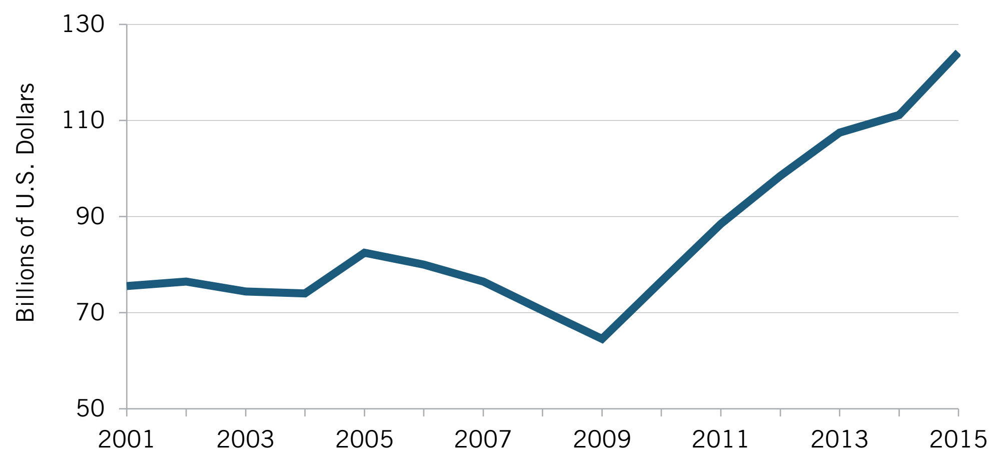
There is reason to believe, however, that this is about to change for the better. If manufacturers' investments in information technology *capital* have stagnated, they have recently begun spending far more on infotech *services*. This new focus on infotech intensity could signify the beginning of a new era of manufacturing innovation.

Figure 2: Capital Stock of IT Deployed By Non-Tech Compared to All Manufacturers[14]



Before the turn of the millennium, U.S. manufacturers were spending around $90 billion per year on information technology goods and services. A significant portion of that likely was related to fixing anticipated Y2K computer glitches. As many manufacturing sectors struggled during the 2000s, technology spending steadily declined, falling to just $64 billion at the nadir of the Great Recession.

Figure 3: Spending by U.S. Manufacturers on Technology Goods and Services[15]



Soon after, however, despite a slow economic recovery, manufacturers began spending more on technology. By 2011, IT spending reached a level not seen since 2000, and it kept going up, rapidly. In 2015, manufacturers spent $124 billion on information technology services, twice the low point of 2009. This sharp increase, seen in figure 3, is the leading edge of the digital revolution in manufacturing and is coincident with the rise of a new array of user-friendly information tools. It reflects spending on cloud computing and storage, software as a service, cloud-based design, and the non-investment components of other digital platforms like supply chains, distribution, customer support, workforce training, and the Internet of Things.

This increase is good news for productivity—and for workers. Other industries that have more fully exploited the power of information technology have enjoyed far faster productivity, employment, and income growth. These new tools should better equip U.S. firms not only to compete with global manufacturing rivals in existing markets but also to rethink the purpose and processes of manufacturing as well as to invent entirely new products and manufacturing services.

ADOPTION OF CLOUD COMPUTING BY MANUFACTURERS

Applications of cloud computing in manufacturing industries can be grouped into those that impact the manufacturing enterprise broadly and those that impact manufactured products themselves.

Over 90 percent of global enterprises report using cloud computing in some part of their business.[16] A 2015 study by market research firm IDC surveyed nearly 600 manufacturing enterprises from 17 countries and found that 66 percent of respondents reported using a public-cloud implementation for two or more applications while 68 percent were using a private cloud.[17] The study further found that these manufacturers expected to increase the cloud-services share of their annual IT budgets by 27 percent from 2015 to 2017.[18] Moreover, cloud-hosted services are expected to account for nearly half of all organization-level software usage among manufacturers by 2023.[19] The market research firm Gartner estimates that what it calls the "cloud shift"—the transition from spending on traditional IT offerings to cloud services—will be worth $111 billion in 2016 and will grow to more than $216 billion in 2020.[20]

Within the manufacturing sector itself, a study by the Economist Intelligence Unit (EIU) found that 60 percent of survey respondents believe cloud computing will be "very important" in supporting production processes, while 54 percent respond it will be "very important" for better supply chain management, 52 percent believe so for enabling design and prototyping, and 48 percent for inventory, orders, and distribution.[21]

APPLICATIONS OF CLOUD COMPUTING IN MANUFACTURING

Applications of cloud computing in manufacturing industries can be grouped into those that impact the manufacturing enterprise broadly and those that impact the manufactured product itself. For the latter, it includes how the products are researched, designed, and developed; the manufacturing processes and production systems used to manufacture them; and how the products are used, consumed, and maintained post-sale. This section describes examples of applications of cloud computing at each of these stages.

Cloud Computing at the Manufacturing-Enterprise Level

At the enterprise level, cloud computing broadly supports manufacturing enterprises' operations including through applications such as enterprise resource planning, data analysis, and workforce training and management. Cloud computing also supports manufacturers' integration into global supply, production, and value chains.

Cloud Computing Supports Manufacturing Enterprises' Operations

Manufacturers are increasingly leveraging cloud computing to manage every facet of their enterprise operations. Consider Mystery Ranch, a medium-sized manufacturer in Bozeman, Montana, that specializes in high-end backpacks and other backpacking accessories. The company leverages cloud-based software to manage virtually every aspect of its operations at five contract-manufacturing locations in the United States, Vietnam, and the Philippines, including design and engineering, production, quality control, research and testing, manufacturing, inventory management, employee management, financials, vendor relations, e-commerce, and sales and marketing.[22] Kendra Clark, Mystery Ranch's IT project manager, explains that the cloud helps the company manage the entire view of its enterprise operations, "providing visibility of consumption of raw materials, time-stamping what products have been completed, and either shipping products direct to customers or transferring them here for direct sales."[23] It's a succinct example of how manufacturers are effectively using cloud-based enterprise management resource planning solutions.

Another example in this vein is manufacturers' increasing use of cloud-based solutions to support enterprise-wide data analytics to improve their manufacturing operations and better tailor their products to customers' specific needs. For instance, large multinational manufacturers in the healthcare industry, such as Johnson and Johnson (J&J), are analyzing big data in the cloud to efficiently drive insights across the enterprise to better enable decision-making in business and operations.[24] With more than 260 operating units across 65 countries, J&J has data everywhere. As the company's director of enterprise architecture notes, this means, "It's very difficult for us to bring all the information together in order to make enterprise-wide decisions."[25] Accordingly, the company developed a hybrid-cloud architecture housing over 120 applications to explore its data on a near-real-time basis, at scale, thereby allowing it to identify patterns and relationships and garner better insights from across the enterprise for everything from maintaining inventories to forecasting new revenue opportunities.[26] "What the cloud has enabled us to do is make sense of that data," J&J's chief technology officer explained. "It's giving us the scale we need to operate and the ability to scale up and scale out. These new clouds in combination with new technologies, such as machine learning, have allowed us to flatten out the time to insight. We've decreased provisioning times from three months to under an hour, which is game changing."[27] This is a good example of how cloud computing is helping manufacturers gain a more sophisticated, enterprise-wide view of their operations, considerably enhancing their operational efficiency and speeding their time to market.

Another important enterprise-wide use of cloud computing pertains to human resource management and especially to workforce training. Manufacturers are increasingly delivering realistic, just-in-time training through cloud-enabled devices.[28] For instance, cloud-hosted resources can serve as the back end for training programs that use graphic-intensive virtual reality to simulate real-world scenarios and conditions. Elsewhere, cloud-based learning management systems can automate manufacturers' training processes from content development and course registration through to course completions, testing, assessment, and certification.[29]

For instance, Tooling U-SME, a web-based, cloud-delivered, massively open online course (MOOC) provides over 500 online classes related to manufacturing technology, breaking down the training into nine functional areas and 60 competency models to identify gaps, define requirements, and provide specific guidance for development.[30] Tooling U-SME's "Accelerate Methodology" provides a comprehensive, structured, enterprise-specific approach that helps manufacturers and their workers acquire needed skills. Similarly, in Chicago, Illinois, the Digital Manufacturing and Design Innovation Institute (DMDII), one of the 14 Institutes of Manufacturing Innovation that comprise the federally supported Manufacturing USA network, has developed a Coursera-hosted MOOC that's teaching essential skills related to digital manufacturing and design technologies.[31]

Cloud Computing Supports Manufacturing Supply Chain Integration

By elevating digital interactions above enterprises' own proprietary data centers, cloud computing plays a pivotal role in facilitating enterprises' integration into broader industrial supply chains.

By elevating digital interactions above enterprises' own proprietary data centers and into the cloud, cloud computing will play a pivotal role in facilitating enterprises' integration into broader industrial supply chains. Indeed, cloud computing platforms are becoming more pervasive in large-scale supply chains as enterprises look to gain agility and speed in resolving complex problems through more effective collaboration. (In fact, 46 percent of respondents to a 2012 SCM World Survey contended that greater supply chain collaboration leads to problems being solved twice as fast.[32]) As Accenture observes, "Cloud computing is increasingly the engine that makes supply chains talk to each other."[33] For manufacturers, cloud-based supply-chain management solutions can deliver a number of specific benefits, such as: permitting the integration of multiple IT platforms, providing an environment for collaboration, supporting integrated advanced analytics, and increasing scale and reducing costs.[34] It's expected that supply-chain management solutions delivered via software as a service will constitute a $4.4 billion market by 2018, representing more than three-fold growth since 2012.[35]

As an example, drug-maker Pfizer has leveraged cloud computing to completely reengineer its complex global supply chain, moving its supply chain fully into the cloud and introducing a new virtualized layer that delivers common information to all participants.[36] Instead of insisting that partners implement Pfizer's own ERP system, the company requested that more than 500 suppliers implement a cloud-based common-information-exchange framework, with each supplier represented as a node on a virtual supply chain.[37] Jim Cafone, Pfizer's vice president of supply network services, describes this approach as connecting "supply-neutral devices using an information architecture that includes cloud-based processes and information layers sitting above physical assets and supply chains as a way to manage the company's end-to-end networks in a 'device-dependent' fashion."[38] Cafone further notes that this supply chain virtualization has enabled Pfizer to respond much faster to unexpected events that might otherwise disrupt its complex supply chain. This has also made it possible for Pfizer to enter global markets much more efficiently. As Cafone explains, the approach enables Pfizer "to land products into portions of the world where before we and the rest of the industry were flying blind. For example, we know when a product lands [i.e., arrives] in Kenya or anywhere else in the world, because we have that traceability."[39] Cafone observed that Pfizer's cloud-based supply chain management solution has allowed it to move in 18 months from an environment of "zero shipment traceability" to a device-independent platform that has already handled more than 40,000 global shipments.[40]

Cloud Computing at the Manufactured-Product Level

Beyond the manufacturing-enterprise level, cloud computing will exert a tremendous impact on how manufactured products themselves are designed, fabricated, and used. In particular, the cloud enables a range of advanced manufacturing production systems such as 3D printing, the Internet of Things, high-performance computing, and industrial robotics.

Cloud Computing Enables Design and Development of Manufactured Products

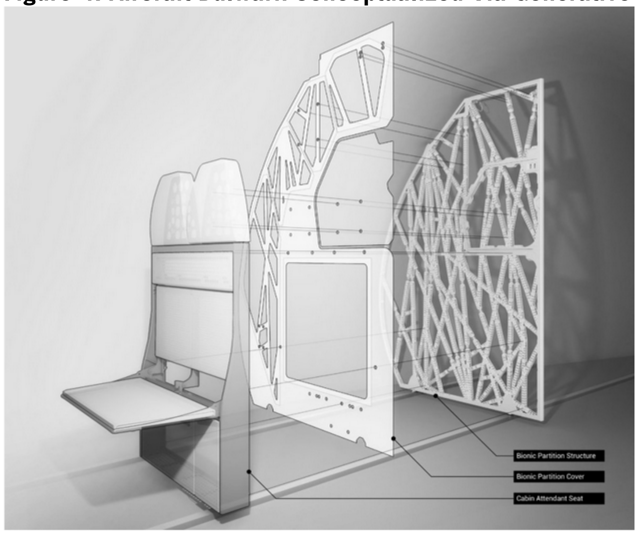
Cloud-hosted, computer-aided design tools are streamlining product-development processes, speeding innovation cycles, and accelerating time to market.

Traditionally, product design in manufacturing was all about creating physical prototypes, testing or experimenting with them, and then going through an iterative refinement process until reaching a final product. But, increasingly, cloud-hosted, computer-aided design tools are streamlining product-development processes, speeding innovation cycles, and accelerating time to market. Cloud computing allows computer-aided design, engineering, and manufacturing (CAD/CAE/CAM) to be performed on high-powered supercomputers, meaning designers and engineers no longer have to rely on powerful machines in their office or per-seat software licenses to run ground-breaking simulations or create data-intensive designs. Cloud computing provides the immense data capacity and virtualized computing power to enable this dynamic, digitally based design.[41] And by centralizing and bringing all that data into the cloud, engineers can have the same plans available to them across any device.[42]

Cloud computing is also enabling "generative design," a technique that mimics nature's evolutionary approach, in which engineers enter design goals into software, along with parameters such as materials, manufacturing methods, and cost constraints, and the software algorithmically explores all possible permutations of a solution. By leveraging cloud computing, generative-design software can quickly cycle through thousands—or even millions—of design choices, testing configurations, and learning from each iteration what works and what doesn't.[43] Generative-design software regularly returns products that are more efficient, better optimized, stronger, lighter weight, and more durable than designers could ever before have foreseen or imagined.[44] The application of generative design can be used not just for individual parts, but also multiple parts in an assembly, the manufacturing operations on individual machines making these parts, processes across several manufacturing machines, factories across several production lines, or even supply chains across multiple factories.

For instance, Airbus used generative-design techniques to design a new aircraft bulwark (see figure 4). This so-called bionic partition was developed with a pioneering combination of generative design, 3D printing, and advanced materials. It is almost 50 percent lighter than current aircraft bulwark partition designs, yet far stronger.[45]

Figure 4: Aircraft Bulwark Conceptualized Via Generative Design Techniques[46]



Cloud computing is now a sine qua non in the design shops of all major automotive manufacturers, in part because creating innovative automotive designs almost always entails a collaboration among designers, engineers, supply chain experts, and production and services organizations. Cloud-based platforms are particularly well suited to allowing such cross-functional teams to work on new designs in real time, sharing information to speed up innovation. Further, as *Forbes*' Louis Columbus explains, "the cloud helps to eliminate information silos that used to keep auto makers bogged down with delays and errors. By sharing more data, more often, automakers end up with fewer errors in initial product design and a more efficient supply chain, both of which lead directly to more profits once the vehicle model appears."[47]

For instance, Aston Martin leverages cloud-based CAD software that has reduced the time it takes the company to design components of new vehicles, such as the wheels, from as much as six months to only one or two days.[48] Moreover, from the first sketch at the start of the design process through to digital validation on the computer screen and then physical validation with a prototype part, all team members play a role in approving the design, meaning that any issues can be spotted immediately, preventing costly changes further down the line in the tooling and manufacturing stages.[49]

Similarly, automotive designers at General Motors (GM) are using a $130-million enterprise data center the company launched in 2013 to transform its global IT infrastructure.[50] The data center's private-cloud architecture serves as the computing backbone for GM's global operations, supporting activities from the design studio to the factory to the showroom.[51] For instance, GM can now conduct supercomputer-powered crash-test simulations, saving the company the $350,000 it costs each time it conducts a physical crash test.[52]

Cloud Computing Enables New Manufacturing Production Systems

Digital tools enable product design and fabrication to increasingly blend seamlessly together, with this convergence often mediated in the cloud. This means cloud computing has become a key enabler of new manufacturing production systems such as 3D printing, the Industrial Internet of Things, and even industrial robotics. This is particularly true for 3D printing, in which successive layers of material are built up to synthesize a three-dimensional solid object composed from a digital file, with each layer a thinly sliced horizontal cross-section of the eventual object.[53]

Consider Divergent 3D, maker of the Blade, the world's first 3D-printed supercar.[54] Divergent has developed a disruptive new approach to auto manufacturing that incorporates 3D-printed joints (each called a NODE™) which connect carbon-fiber structural materials, resulting in an industrial-strength chassis that can be assembled in minutes.[55] 3D printing allows Divergent to create elaborate and complex nodes which are then joined together by off-the-shelf carbon-fiber tubing. Divergent 3D has essentially developed a method of design and manufacturing that drastically reduces the footprint of manufacturing, both in terms of the machines and the materials needed to complete the manufacturing, not to mention the capital cost and complexity. (In fact, the 3D printing reduces the overall weight of the Blade's chassis by 90 percent compared to traditional vehicles.) Cloud computing has played a pivotal role in facilitating the development of these designs and linking them to the 3D printer. As Divergent 3D CEO Kevin Czinger explains, "My belief is you're going to have a replacement of an old technology base from the 20th century with a new technology base from the 21st century that combines the cloud processing with additive manufacturing and scalable, non–design-specific manufacturing using modular structures."[56] It's a textbook example of cloud-enabled 3D printing that's facilitating a dramatic rethink of traditional manufacturing processes and unlocking new value propositions.

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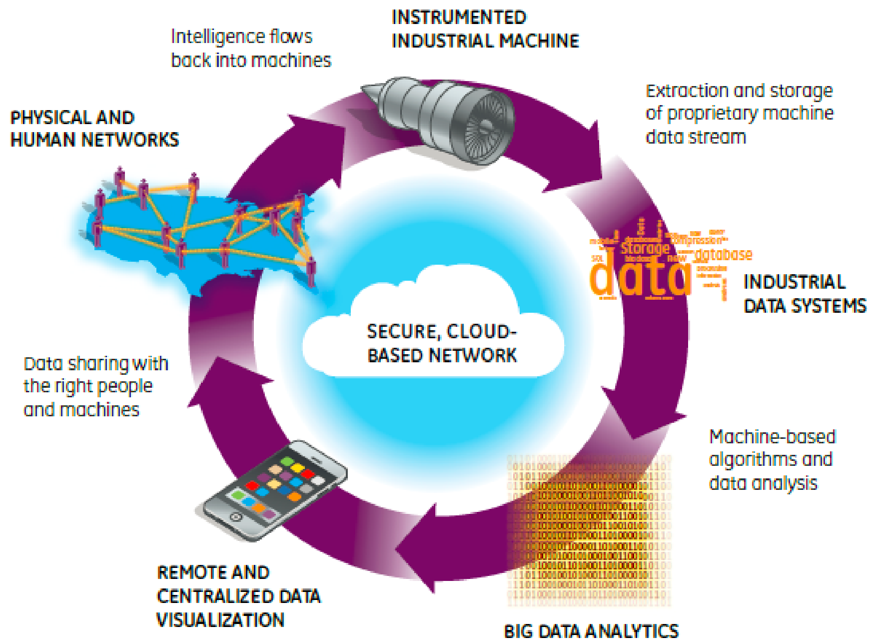
Beyond 3D printing, cloud computing platforms are proving foundational to making the Industrial Internet of Things a reality, particularly by enabling real-time, machine-to-machine, machine-to-person, and machine-to-material communications.[57] Consider "The Industrial Internet Data Loop" (figure 5, as conceptualized by General Electric) which illustrates how secure, cloud-based network computing acts as the central hub for modern industrial production systems. The cloud connects instrumented industrial machines to industrial data systems, making possible both big data analytics and data virtualization while facilitating engagement with physical and human networks. This leads to a virtuous cycle of continuous improvement, as the data being generated by industrial machines (and factories broadly) are fed through machine-based algorithms and data-analysis strategies to generate value-added insights that are then fed back into the machine and applied to the broader industrial system.[58]

Figure 5: The Industrial Internet Data Loop[59]



As GE's chief economist and executive director, global market insights, Marco Annunziata, explains, "Cloud is definitely central to many of our key technologies on the industrial Internet."[60] For instance, cloud technologies are part of the basis for Predix, GE's operating system for the industrial Internet. The cloud also enables GE's vision of the so-called "digital twin," which refers to creating software representations of machines such as individual jet engines, gas turbines, power plants, or pieces of industrial equipment. This means not just a generic software model of a pro forma jet engine or gas turbine, but an individual software model of each gas turbine or jet engine GE makes and sells, replete with full data on its history, performance, and operating conditions. Of course, these digital twins are also connected to the data streams coming off all similar devices, so the aggregated data can be used to enhance the performance of both individual machines and entire systems of devices. As Annunziata observes, "Only by leveraging the cloud can we process the gigantic volume of data being generated by these machines and also be able to communicate data with these devices scattered worldwide."[61] Annunziata also notes that cloud computing will be vital for GE's Brilliant Factories initiative, which refers to GE's vison to reshape modern manufacturing processes by combining lean operational excellence with digital capabilities at its more than 500 plants globally, with the latest Internet technologies connecting workers, industrial equipment, and the factory floor to distribution channels and supply chains.

Consider General Electric's $170 million manufacturing plant in Schenectady, New York, which makes (among other things) massive batteries for things like cellphone towers and power plants. More than 10,000 IIoT-enabled sensors spread across 180,000 square feet of manufacturing space collect temperature, humidity, air pressure, and machine operating data in real time.[62] This allows production to be monitored as it occurs and permits process adjustments to be executed on the fly, enhancing production efficiencies and conserving costs. Additionally, battery performance can be traced back to specific batches of raw material at each step of the manufacturing process. GE can thus trace a product's entire genealogy, from containers of dirt, sand and salt, to a bank of high-tech batteries supporting a nation's electric grid.[63] This is just one example of the digitally connected, cloud-enabled factory of the future.

Similarly, motorcycle manufacturer Harley-Davidson utilizes IoT connections to link every asset on the shop floor of its production facility in York, Pennsylvania. Data gleaned from these connected assets—including detailed production data—are tracked and incorporated into a real-time performance management system.[64] Harley-Davidson tracks fan speeds in its motorcycle painting areas and can algorithmically adjust the fans based on environmental fluctuations.[65] If the environmental conditions are unfavorable, a motorcycle or part can be moved elsewhere in the facility or the ventilation systems adjusted as necessary.[66] Shannon Weiss, IT asset manager at Harley-Davidson, notes that moving to the cloud has been critical for the company to "keep up with the services it needed to operate on an international scale" and that Harley's move to the cloud has enabled it to get more "bang for the buck" out of its IT assets.[67]

Cloud computing is also helping 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.[68] These portable manufacturing platforms represent small-scale, modular, flexible versions of Pfizer's larger manufacturing facilities. As Steve Hammond, Pfizer's director of process analytical support, explains, "We can put together a manufacturing process anywhere we want in the world, validate the system, put in on a boat or helicopter or truck and ship it to wherever you want to go." Hammond explains the mobile pharmaceutical factory as Pfizer's "vision of manufacturing in the future" that can help it better meet local market demand and limit distressed inventory.[69] As noted earlier, these types of mobile manufacturing platforms are linked together in part through Pfizer's cloud-connected supply chain management system.

Cloud Computing Changes Consumption of Manufactured Products

Cloud computing will play a critical role as information technologies enable products to be remotely updated, maintained, or even sold as services, as part of an increasingly common business model called "product servification."

For instance, automakers such as Ford, Tesla, and Hyundai (among others) are using the cloud to deliver over-the-air updates to vehicles' powertrain, infotainment, navigation, and safety systems. Tesla has installed autopilot software in its cars and can upgrade the functionality remotely.[70] Likewise, in 2015, Ford introduced its Ford Service Delivery Network, a cloud-based system that can remotely update vehicles' audio, infotainment, and navigation systems (among other features).[71] As Don Butler, Ford's executive director of connected vehicle and services, explained, "We couldn't do this without the cloud… It's really the only way to do it. Otherwise, we'd still need people to make a physical connection either at the dealer or through a stick."[72]

Boeing has said that it would like to be viewed as a "services company," given that services are a very important part of its operations today.[73] Cross-border data flows, in part enabled by cloud computing, represent an increasingly important enabler of the services Boeing delivers to airline customers. For instance, Boeing offers an information tool to commercial airlines called Airplane Health Management (AHM), which gathers in-flight airplane information and transmits it in real time to maintenance crews on the ground. [74] A single Boeing 737 engine produces 20 terabytes of data every hour in flight.[75] Therefore, an eight-hour flight from New York to London on an aircraft with two engines can generate 320 terabytes of data.[76] Boeing uses this data to find and diagnose problems mid-flight. The airplane uses the MyBoeingFleet.com web portal to relay any problems it identifies to maintenance personnel waiting at the next airport.[77] This is part of Boeing's effort "to connect the airplane and enable the digital airline." The service is one offering from Boeing Edge™, a suite of intelligent services Boeing provides to enable digital airline operations, including connecting the airplanes, enhancing operational efficiency, providing fleet and maintenance solutions, optimizing aviation infrastructure, and empowering and enabling the workforce.[78]

Cloud computing is facilitating a dramatic rethink of traditional manufacturing processes and unlocking new value propositions.

David Nelson, Boeing's chief cloud strategist, mentions examples of several new applications the company has developed thanks in part to cloud computing. One is an application Boeing has developed to track all of the flight paths planes take around the world. Boeing's sales staff uses this information to help sell aircraft, showing how a newer, faster one could improve the airline's operations.[79] Another cloud-based toolbox application allows mechanics to research, conduct, and verify maintenance and repairs. This "Digital Toolbox" app combines data that Boeing possesses about its own planes, but Nelson explained the truly innovative part is the work Boeing has done to integrate repair information from other aircraft manufacturers. "It's seamless to the end user, but it provides all the functionality they need," Nelson said.[80] He explained that a key reason for the application's success is that, while many large airlines work with multiple aircraft manufacturers, such as Boeing and Airbus, they can go to Boeing to get the Toolbox information from a variety of manufacturers. Nelson noted that these cloud-based solutions "run more efficiently, are less expensive, and serve Boeing's needs better" than if the company had hosted them all in-house.[81]

CASE STUDIES OF CLOUD COMPUTING ENABLING MODERN MANUFACTURING

Cloud computing is changing the manufacturing paradigm for large and small manufacturers alike, as the following case studies illustrate. This section explores how three SME manufacturers, one public-private partnership, two original equipment manufacturers (OEMs), and one broad industry sector (energy) are leveraging cloud computing to support their manufacturing activities.

Accuride

Accuride, based in Evansville, Indiana, is a leading manufacturer and supplier of wheels and wheel-end components to the North American and European commercial vehicle markets. It has leveraged cloud computing-based solutions to considerably streamline its multi-facility manufacturing operations.[82] As Paul Wright, Accuride's IT director, explains, before the advent of cloud computing, "At each plant, people on our lines were writing down things like how many parts they made, how many were scrap, what problems they had with the machines, etc." [83] Those pieces of paper were then used to write numbers onto a board every hour, and then entered once a day into an Excel spreadsheet, which was used on a daily basis to create reports for management, and transposed on a monthly basis into PowerPoint.[84]

To overhaul such a clearly inefficient process, Accuride consolidated seven separate systems running more than 200 applications into a single, cloud-based, SaaS-delivered enterprise resource planning system, enabling Accuride to centralize shared information, standardize its systems and processes, enable secure remote access, and utilize robust data collection, reporting, and other tools.[85] As Wright explains, "Using web-based tools, we're able to understand manufacturing performance in real time, directly connected to the machines… The level of visibility we have is almost like being on the factory floor." He continues, "Every time one of our machines cycles to produce a part, that signals across our ERP system that raw material has been consumed, and sends that signal through the cloud. We have full visibility, so we can measure operational performance based on that data."[86] The system also extends to Accuride's supply chain, with online portals that the company's suppliers can use to see and fulfill their material orders.[87] As Accuride President and CEO Rick Dauch concludes, cloud computing has "essentially replaced the central nervous systems of our company … positively impact[ing] nearly every aspect of our operations, from the shop floor to the top floor, while dramatically enhancing our ability to proactively address customer needs and swiftly respond to market and industry shifts."[88]

MakeTime

MakeTime, based in Lexington, Kentucky, simplifies the production of computer numerically controlled (CNC) parts. (CNC refers to the automation of machine tools by means of computers executing pre-programmed sequences of machine-control commands.) Specifically, MakeTime brokers machine-time capacity, collecting unused CNC machine time from qualified machine shops across the United States and managing the entire production process online.[89] (MakeTime has been dubbed as "the Airbnb of CNC.") MakeTime's cloud-based software helps manufacturers overcome capacity shortages, streamline procurement and operational processes, and gain insight and transparency to what has traditionally been a complicated process. MakeTime keeps all its data in the cloud and runs all its algorithms and analytics related to understanding machine utilization availability and matching it to requested demand in real time from the cloud.

As Tim Shinbara, vice president technology for the Association for Manufacturing Technology (AMT), notes, companies such as MakeTime provide a path to production for

SME manufacturers that doesn't involve waiting on requests for proposals or vetting suppliers, while helping them innovate more effectively, get to market faster, and operate more efficiently.[90] MakeTime and other firms like it significantly reduce information and expertise costs and burdens for SME manufacturers. Shinbara notes that the MakeTime model, first unveiled at AMT's 2015 MC^2 event, can thus help strengthen or reshore SMEs' supply chains without increasing capital requirements or operational expenditures.[91]

Proto Labs

Proto Labs, a fast-growing company based in Maple Plain, Minnesota, has become the world's fastest manufacturer of custom prototypes and on-demand production parts, filling orders in as little as one day with its suite of industrial 3D printing, CNC machining, and injection molding services.[92] The company offers a full suite of services from early prototyping, to fit-and-function testing, to short-run manufacturing. Proto Labs is a company truly "living the digital thread" which has leveraged software and cloud computing to shift its business model toward production of quick-turnaround, small-lot, high-value, highly customized products, enabling it to effectively compete in a hyper-competitive global marketplace. Specifically, Proto Labs has proven able to automate traditional manufacturing processes by developing complex software that communicates with a network of mills and presses, enabling plastic and metal parts to be produced in a fraction of the time it used to take.[93]

Digitalization of advanced manufacturing production systems can unlock new business models that can restore the global competitiveness of U.S. manufacturing.

As Kevin McDunn, chief technology officer of Chicago-based UI Labs, notes, Proto Labs focuses on small-volume runs because it's precisely in that prototyping phase or in the production of very high-value, small-lot parts that there's a lot of overhead, time, and labor related to back-and-forth negotiations to determine details such as design, configuration, manufacturability, etc.—yet all that overhead has a lot of impact when it comes to low-volume parts.[94] This manual, non-recurring engineering work slows down the innovation process and prevents American industry from being as productive and agile as it could be. Accordingly, Proto Labs uses software, services, and other technology to eliminate that friction as much as possible, allowing it to use virtual processes to do all the steps that previously had to be accomplished face-to-face (negotiating, discussing requirements, etc.), so it can produce high-value, highly customized products and parts at low cost with extremely rapid turn-around times.[95]

In short, Proto Labs has transformed a process that historically took traditional manufacturers four to twelve weeks to execute and reduced the turnaround time to between one day and two weeks from when the customer provides their 3D CAD model.[96] Proto Labs, which ranked number 4 on *Forbes*' 2014 list of America's best small companies, now operates eight production facilities around the world, employs over 1,000 workers, and earned $265 million in 2015.[97] Going forward, the company estimates the market for its services will exceed $7 billion, with that figure comprised of capturing $2.4 billion of the $30 billion CNC-machining market, $3.5 billion of the $55-$60 billion injection-molding market, and $800 million of the $2.5 billion 3D printing/additive services market.[98] Proto Labs provides a shining example of how the digitalization of advanced manufacturing production systems can unlock new, technically sophisticated, high-value-added, difficult-to-replicate business models that can restore the global competitiveness of American manufacturing.

Digital Manufacturing and Design Innovation Institute (DMDII)

The Digital Manufacturing and Design Innovation Institute, one of 14 Institutes of Manufacturing Innovation within Manufacturing USA, is developing new cloud-based systems that seek to democratize SME manufacturers' access to scalable computing resources and applications. DMDII envisions its Digital Manufacturing Commons (DMC) as a free, open-source software project to develop a collaboration and engineering platform that can serve as an online gateway for digital manufacturing.[99] Akin to an "app store for manufacturing," the DMC will become a digital services marketplace with a software development kit and collaboration platform at its core, essentially equipping SME manufacturers with the modeling and simulation tools they need to address technical design challenges as well as to access shared HPC resources.

The DMC will facilitate SMEs' access to a variety of productivity-enhancing applications that SME manufacturers would have difficulty assessing if they had to purchase and maintain all the requisite hardware and software in-house. As a specific example, one of the most significant manual processes involved in manufacturing is programming the measurement machine to verify the quality of parts. In fact, this step can often take many times longer than actually programming the part itself to be fabricated. Accordingly, DMC is working to streamline that effort by delivering a chain of apps developed by Metrosage, Capvidia, and Origin as a cloud-based solution that can automatically program the measurement machine from the original file. Ultimately, SME manufacturers want to review and edit data-intensive results through a cloud-provided 3D graphic interface. Because these SMEs are working with very data-intensive 3D models, this requires accessing cloud-based high-performance computing capacity that can render these in real-time with very low latency. As UI Lab's McDunn explains, "the real opportunity here is leveraging HPC to allow real-time editing and visualization of 3D-solid metal parts, which would constitute a huge leap forward in terms of democratizing the technology, meaning small companies won't have to invest nearly as much of their own hardware and software to participate in the digital thread. This can help SMEs save hours of programs per part, which decreases costs, improves speed, accelerates innovation, and quickens SMEs' time to market."[100]

Separately, DMDII is developing a real-time, data-driven "Visual Decision Support System" for manufacturers. This represents a shop-floor decision support system that will convert thousands of existing real-time data points into a collection of cloud-based dashboards to facilitate decision-making about what to produce, when to produce it, and with what components and production resources. Pilot studies of similar concepts have resulted in 98 percent reduction in line stoppages, 86 percent reduction in on-site inventory, and a 50 percent reduction in indirect material handling labor, all while increasing manufacturers' productivity by nearly 10 percent. DMDII expects to have the solution available online by early 2018.[101] Cloud applications like this will ultimately be key to connecting thousands of data inputs from logistics and production systems for the purpose of driving much more agile shop-floor decision-making.

Ford

Automotive manufacturers such as Ford have found a wide range of applications for cloud computing, which matters as today's vehicles are as much as 40 percent software, 60 percent hardware. For Ford, the cloud provides off-board computing and storage. Don Butler, Ford's executive director of connected vehicles and services, explains that this gives Ford the ability "to take that data, store it, analyze it, look at it, and figure out what value we can derive from it—[how to] more easily repair that vehicle, and analyze how people are using that vehicle."[102]

Cloud computing is exerting a tremendous impact on the life-sciences sector in terms of drug discovery, supply-chain management, and even pharmaceuticals manufacturing.

In other words, cloud computing gives manufacturers like Ford the ability to both provide services and experiences that can get better over time through interaction with remote apps because "you can change the cloud, you can update the cloud, you can deliver more services through the cloud" in addition to leveraging the cloud to send updates to the vehicle itself.[103] As Butler explains, this allows Ford to create more consumer-based, real-time interaction, services, and contextualized experiences.

Further, Ford is piloting a cloud-based solution on Google Earth to enable virtual navigation of its assembly plants, down to the level of individual workstations.[104] IntoSite™, developed by Siemens using the Google Earth infrastructure, is a cloud-based web application that allows users to share information within private virtual spaces created across Ford's plants and around the world. Ford expects the solution to help it reap benefits such as improved communication, efficiency, globalization, and standardization.[105]

Merck

Cloud computing is exerting a tremendous impact on the life-sciences sector in terms of drug discovery, supply-chain management, and even pharmaceuticals manufacturing. In fact, nearly half of all pharmaceutical manufacturers are currently using a form of cloud-based infrastructure, or are at least considering it.[106] Data—including lab, imagery, and statistical-analysis data—can all be delivered at speed thanks to cloud-based infrastructure. These productivity savings, coupled with the operational savings gained from obsolete hardware maintenance, can be reinvested into R&D efforts.[107] New medicines will be developed using an entirely new paradigm, drawing on external innovation and data from multiple sources.[108]

For instance, Merck has partnered with Numerate, a technology platform company leveraging proprietary algorithms alongside the power of cloud computing to transform the drug-design process, in order to generate novel small-molecule drug leads for an undisclosed cardiovascular disease target.[109] Numerate's algorithms provide predictive models for molecular properties with accuracies comparable to laboratory testing, enabling scientists to search through billions of compounds to rapidly and efficiently identify those with the highest probability of activity against a specific target.[110] This type of computational bioscience combines knowledge of the biocode with exploding empirical data to clear the way for scientists to design new therapies in the cloud. Such approaches could dramatically reduce the cost of pharmaceutical development and greatly expand the number of therapies that can be created and tested by moving medical research away from a "hit-and-hope" world of trial-and-error guesswork.[111]

Merck has also successfully leveraged cloud computing to improve its manufacturing process for vaccines. Vaccines often contain attenuated viruses, meaning they're altered to give a patient immunity, but not the actual disease, and thus they have to be handled under precise conditions at every step in the manufacturing process. Components might have to be stored at exactly 8 degrees below zero for a year or more, and if there is even a slight variance from regulator-approved manufacturing processes, the materials have to be discarded. As George Llado, Merck's vice president of information technology, expounds, "It might take three parts to get one part, and what we drop or discard amounts to hundreds of millions of dollars in lost revenue."[112] To tackle this challenge, Merck loaded data on sources of vaccine yield loss into the cloud, analyzing data collected from process history and maintenance systems on the manufacturing plant floor. Ultimately, Merck conducted 15 billion calculations and made over 5.5 million batch-to-batch comparisons to determine what environmental and process factors influenced the quality of the final product.[113] Merck discovered that certain characteristics in the fermentation phase of vaccine production are closely tied to yield in a final purification step. Merck received a 2014 *InformationWeek* Elite 100 Business Innovation Award for work that has enabled it to considerably improve its vaccine manufacturing operations.[114]

Nearly half of all pharmaceutical manufacturers are currently using a form of cloud-based infrastructure, or are at least considering it.

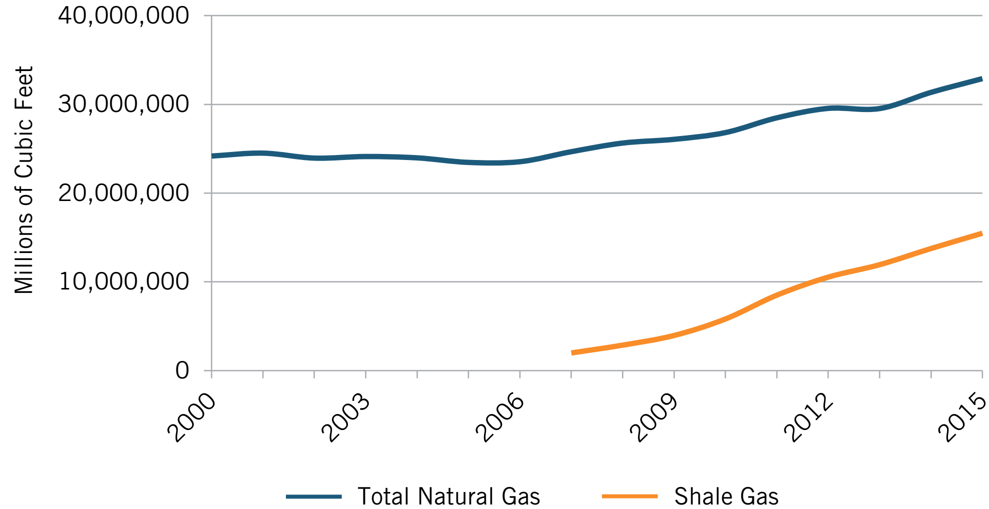
Further, in April 2017, Merck announced the launch of the Alexa Diabetes Challenge, a competition aimed at encouraging the development of cloud-based software applications using Amazon's Alexa technology to help patients with a recent diagnosis of Type 2 diabetes.[115] As Kimberly Park, Merck's vice president for customer strategy and innovation in global human health, explains, the goal is "to find innovative ways to leverage digital solutions, such as voice-activated technology, to help support better outcomes that could make a difference in the lives of those suffering from chronic conditions like diabetes."[116]

Cloud Computing in the Energy Sector

Another example of a physical industry that has begun to leverage the power of information technology is energy. A decade ago, many people believed the United States, if not the entire world, was suffering an energy crisis. The supposed arrival of "peak oil" had sent petroleum prices through the roof—topping out at nearly $140 per barrel in 2008—and many assumed prices would increase forever as supplies inevitably dwindled.

Then the American shale revolution transformed the industry and the way we think about energy. In the space of just a few years, American oil production doubled. Natural gas production grew by 50 percent (see figure 6). And nearly all the increases were due to our new ability to cost-effectively exploit previously unusable shale.

Figure 6: U.S. Output of Total Natural and Shale Gas, 2000-2015[117]



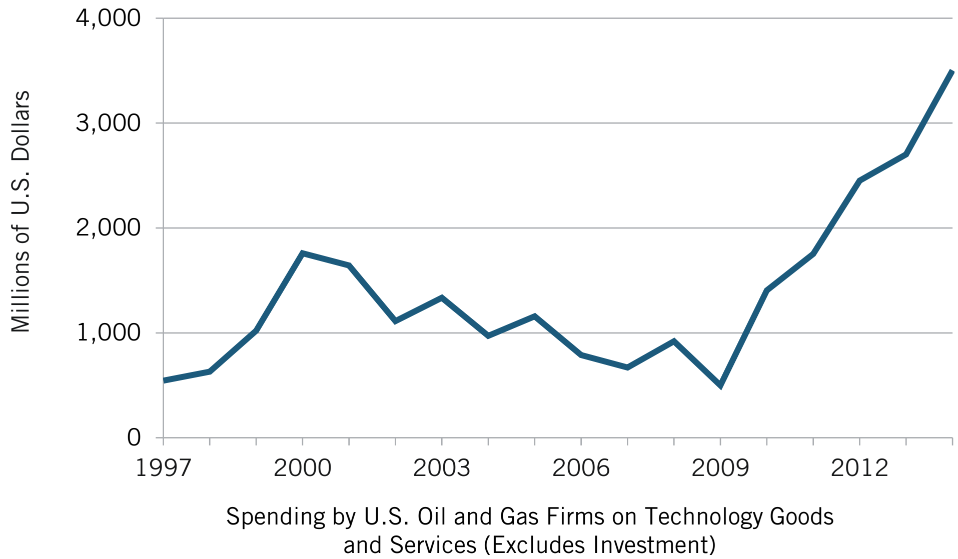
Geologists had known about petroleum-rich shale rock deposits for at least 100 years. But they couldn't figure out how to effectively and efficiently tap into those formations, abundant under U.S. soil and around the world, to produce oil and gas at competitive prices. Advances in horizontal drilling and hydraulic fracturing, however, were beginning to show promise: The idea was to drill down, and across, many miles under the earth's surface to many locations from a single, above-ground rig, then pump pressurized water into the shale rock to crack it open, releasing vast quantities of oil and gas.

In addition to the very physical processes of horizontal drilling and hydraulic fracturing, however, the surprising third technology that proved so important was digital. To find these shale formations and figure out the very best places to crack them open required highly sophisticated 3D modeling of sub-surface formations. Seismic readings and analysis of the floods of data allowed geologists and engineers to pinpoint the best places to drill and crack the rock.

Along the way, as data was collected on the success or failure of wells, formations, and techniques, the process improved at a rapid pace. "The speed of improvement has been remarkable," notes energy expert Mark Mills. "With virtually no increase in capital costs (in some cases, costs are down), the three key measures of drilling—time to drill, wells per rig, and total distance—have improved by 50-100 percent in less than five years."

As figure 7 shows, U.S. energy firms in the last decade more than tripled their spending on information technology goods and services, reaching $3.5 billion in 2014. This is the cloud effect in energy. There was an "energy recession" in 2015, capping IT spending for a year, but it is now back on the upswing. The data flowing into the cloud as oil and gas flow up to the surface will continue to improve the process in the years and decades ahead. Far from a crisis, this new combination of mechanical, chemical, and information technologies promises centuries' worth of inexpensive, reliable energy.

Figure 7: The Cloud Effect in Energy[118]



POLICY PRIORITIES FOR CLOUD COMPUTING

If the potential of cloud computing to enable modern manufacturing is to be fully realized, policymakers will need to craft a supportive policy environment. Governments around the world should consider both "domestic" and "international" policies to support greater penetration of cloud-enabled manufacturing among their industrial sectors, as the following section describes.

Domestic Policies

Domestically, U.S. policymakers should consider the following policies to support greater penetration and diffusion of cloud-enabled manufacturing:

Continue Funding the Manufacturing Extension Partnership Program

The Manufacturing Extension Program (MEP) is one of the most successful and impactful programs in the entire federal government. It is a public-private partnership with centers in all 50 states dedicated to increasing the technical and innovation capacity of America's small and medium-sized manufacturers.[119] MEP delivers a significant return on investment for U.S. taxpayers.[120] In fact, estimates find that for every dollar of federal investment, 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.[121] In 2015, MEP interacted with 29,100 SME manufacturers across the country, helping them to generate $8 billion in new and retained sales, make $3.2 million in new investments, realize $1.2 million in cost savings, and create or retain almost 70,000 jobs.[122]

And MEP is poised to play a pivotal role in helping America's more than 250,000 SME manufacturers adopt IT-enabled manufacturing technologies. In fact, according to a new report by the Michigan-based think tank Manufacturing Foresight, "Democratizing Manufacturing: Bridging the Gap between Invention and Manufacturing," the vast majority of America's SME manufacturers (over 85 percent) do not currently use digital design and manufacturing tools, typically because of expertise or cost constraints.[123] MEP thus represents a critical conduit in helping America's SME manufacturers to both understand the value of cloud-enabled manufacturing and to acquire the needed technical skills to implement it in their organizations. Congress should consider including full funding in the FY 2018 budget (at least $130 million per year) for the National Institute of Standards and Technology at the Department of Commerce to continue building upon MEP's success.

Continue Supporting the Manufacturing USA Program

Despite their significant potential benefit, the vast majority of America's SME manufacturers still aren't using digital design and manufacturing tools, typically because of expertise or cost constraints.

As noted, Manufacturing USA consists of a network of 14 Institutes of Manufacturing Innovation representing public-private partnerships designed to ensure continued U.S. leadership in advanced manufacturing product and process technologies. Institute members have made substantial joint investments in collaborative approaches to R&D and commercialization of cutting-edge manufacturing technologies.[124] As this report has described, the Digital Manufacturing and Design Innovation Institute is already playing an active and effective role in facilitating the development of cloud computing-enabled tools for HPC-aided design, parts machining and validation, enterprise decision-making support systems, etc. In addition to DMDII, several other Institutes, including America Makes (additive manufacturing), the Clean Energy Smart Manufacturing Innovation Institute (CESMII), the Institute for Advanced Composites Manufacturing Innovation (IACMI), and the Advanced Robotics Manufacturing Institute relate to cloud-enabled manufacturing in some capacity. Manufacturing USA was partially defunded in the Trump administration's FY 2018 budget request, with the five Department of Energy-led institutes, including CESMII and IACMI, targeted for elimination. Congress should consider restoring funding for these five DoE-led institutes in the FY 2018 budget, in addition to providing continued funding of $115 million for the eight Department of Defense-led institutes, as requested in the administration's budget.

Create Cloud-Neutral Tech Policies

Every technology creates new challenges. While some concerns have been raised about cloud computing, especially those relating to security and privacy, there is no need to create cloud-specific regulations. For example, cloud computing does not reduce an organization's responsibility for protecting its data. Storing data in the cloud instead of on an organization's own local servers does not reduce or limit the liability of an organization for ensuring the privacy of its data. An organization that is responsible for ensuring the privacy of its customer's data could be held liable for a breach of privacy regardless of whether it occurs in the cloud or on its own local server. Questions of responsibility for ensuring the privacy of data between the organization that owns the data and cloud-computing service providers should be resolved through applicable contract law.

This perspective should also guide policymakers' understanding of the security of data stored in the cloud. For the reality is that, because of their targeted focus and scale advantages, cloud-computing providers are able to develop expertise in secure computing that other companies cannot easily match. While cloud computing does not guarantee security, and organizations should investigate the terms of service and security practices of any particular service provider, the net result of a shift toward greater use of cloud computing will likely be a decrease in the overall security risk profile of those companies. This is particularly true for SMEs that lack the required resources and expertise to implement strong security programs. Cloud computing represents an opportunity for these organizations to realize better data security at affordable prices.[125]

As an example of the cloud's security, the U.S. Central Intelligence Agency (CIA) will be one of 17 intelligence-related agencies using a customized, secure, cloud-based solution that will replace a broad range of legacy systems. Jason Hess, cloud security manager for the National Geospatial-Intelligence Agency, explains that use of a single set of infrastructure versus multiple, older data centers actually boosts security, because consolidation means less complexity, and less complex infrastructure is easier to lock down.[126] If America's intelligence services regard cloud-based solutions to actually be more secure than existing legacy systems, it signals that manufacturers as well may be able to enhance security by integrating in the cloud.

Fund the National Strategic Computing Initiative (NSCI)

As noted, cloud-delivered, HPC-powered CAD/CAE/CAM systems that perform next-generation modeling, simulation, and design tasks are vital components of a country's leadership in the smart-manufacturing economy. 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.[127] Continued U.S. leadership in high-performance computing will require a steady, stable, robust, and predictable stream of funding.[128] The Trump administration recognizes this and has included NSCI funding in its FY 2018 budget request; Congress should appropriate these funds as requested.

Support Broadband Deployment and Investment

Cloud computing can't achieve its potential effect in the absence of robust, reliable, fast, and widespread Internet connectivity. The private sector should lead most investment in broadband Internet deployment across the United States, but there is justification for public-investment support in high-cost, rural areas (which impacts some SME manufacturers). In fact, as ITIF writes in "A Policymaker's Guide to Rural Broadband Infrastructure" private investment without public assistance will likely not be sufficient in these types of rural areas.[129] Further in this vein, federal and local governments can streamline outdated regulations to help spur private investment and help expedite the deployment of next-generation wireline and wireless infrastructure.[130] Efficient access to rights of way and municipal infrastructure to deploy wireless and wireline infrastructure will be essential to securing U.S. leadership in developing a robust Internet ecosystem around advanced wireless capabilities. In addition to robust fiber for both access and backhaul, streamlining and expediting the process requirements of new small-cell siting approvals will be required for the large-scale deployments necessitated by advanced communications technologies.

Facilitate the Commercialization of Cybersecurity Innovations

The U.S. government should not limit the commercialization of cybersecurity innovations, especially with regard to techniques companies are using to encrypt data stored in the cloud. Doing so would make the average consumer and business less secure and preclude much opportunity for advancement in information security and systems architecture. Further to this, Congress should bar the National Security Agency from intentionally weakening encryption standards, and it should strengthen transparency in the cryptographic standards-setting process.[131]

Countries that fail to put the right cloud cloud-computing policies in place are likely to fall behind in this new industrial revolution.

International Policies

U.S. policymakers should consider pursuing the following policies in the global context to support greater penetration and diffusion of cloud-enabled manufacturing.

Support the Development of Globally Interoperable, Industry-Led Standards

The development of globally interoperable technical standards as well as a common terminology to define data will be vital if cloud computing is going to serve as the platform for integrating data from production equipment, devices, and sensors made by vendors from throughout the world. Currently, there exists insufficient interoperability to pass data from design and product definition through to production equipment and processes. For example, it's 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 (not to mention different manufacturers from a variety of different countries). Accordingly, governments should work with industry to encourage the development of industry-led voluntary standards and best practices related to issues such as interoperability, privacy, and security.[132]

Negotiate Trade Agreements That Prohibit Use of Data Localization Policies

As noted, cloud computing will play an instrumental role in coordinating and connecting enterprises' far-flung global production networks and in integrating manufacturers' global supply and distribution chains. But for this vision to become reality, data must be permitted to move seamlessly over the Internet. Yet the increasing proliferation of data-localization policies throughout the world threatens to fragment and inhibit manufacturers' integrated global production chains, all connected through the cloud.[133] Whether countries' data-localization policies are predicated on supposedly enhancing data privacy or security, ensuring a government's access to data, or more often out of pure "digital protectionism," such policies do little to enhance data security, which, as noted, depends on the technical, physical, and administrative measures implemented by cloud providers to secure the data. Moreover, such data-localization policies often only harm countries' own economies. For instance, a study that Deloitte conducted for the European Commission finds that if Europe's data-localization policies were lifted, Europe's manufacturing sector could realize an additional 2.2 percent of net present value (the largest of any sector) from 2015 to 2020.[134]

Accordingly, policymakers throughout the world should eschew the use of data localization policies and commit to neither imposing measures that would ban the transfer of data nor require the local storage or processing of data or the use of local facilities. Furthermore, policymakers should pursue trade agreements that enact these norms protecting the movement, transfer, and exchange of data, as rules promulgated in text for a Trans-Pacific Partnership (TPP) and Trade in Services Agreement (TiSA) have proposed. Such rules should also become part of any renegotiated North American Free Trade Agreement (NAFTA).

CONCLUSION

Cloud computing represents a foundational, underlying platform technology that's key to enabling smart manufacturing. Cloud computing has permeated virtually all facets of the modern manufacturing enterprise and contributed to a transformation in how today's products are designed, made, and used. Cloud computing provides a myriad of benefits to manufacturers large and small, including: speeding innovation cycle times, accelerating time to market, facilitating collaboration, supporting supply chain integration, enabling new business models, increasing operational efficiency, reducing costs, and increasing employee and customer satisfaction. Countries' public policies can exert a significant impact on the development, diffusion, and adoption of cloud-enabled manufacturing in their industrial sectors, which matters greatly because countries that fail to put the right cloud-computing policies in place are likely to fall behind in this new industrial revolution.

ENDNOTES

1. Katharina Candel Haug, Tobias Kretschmer, and Thomas Strobel, "Cloud Adaptiveness Within Industry Sectors—Measurement and Observations," *Telecommunications Policy* 40, Issue 4 (April 2016): 291-306, http://www.sciencedirect.com/science/article/pii/S0308596115001238.
2. Ibid.
3. Daniel Castro, "Cloud Computing Requires National Policy Leadership," (Information Technology and Innovation Foundation, August 2010), 1-2, http://www.itif.org/files/2010-cloud-computing.pdf?_ga=2.83948633.1111104882.1496092846-851887776.1494256561.
4. There's also a hybrid "cloud-enhanced" model that's becoming increasingly common, whereby a thin client is installed on a device, but it accesses computing and storage services in the cloud. This model is typical of applications that require sophisticated user experiences or heavy graphics; experiences that would be degraded in a web browser.
5. For more information on cloud computing deployment models, see National Institute of Standards and Technology (NIST), "The NIST Definition of Cloud Computing" *NIST Special Publication 800-145*, (NIST, September 2011), http://nvlpubs.nist.gov/nistpubs/Legacy/SP/nistspecialpublication800-145.pdf.
6. Stephen J. Ezell, "A Policymaker's Guide to Smart Manufacturing" (Information Technology and Innovation Foundation, November 2016), https://itif.org/publications/2016/11/30/policymakers-guide-smart-manufacturing.
7. Sherry M. Stephenson, "The Linkage Between Services and Manufacturing in the U.S. Economy," (Washington International Trade Association, May 23, 2017), http://americastradepolicy.com/the-linkage-between-services-and-manufacturing-in-the-u-s-economy/#.WT1AQlUrKUk.
8. Ezell, "A Policymaker's Guide to Smart Manufacturing."
9. Pat Garrehy, "Manufacturers Are Looking to the Cloud," *Food Manufacturing*, April 21, 2015, https://www.foodmanufacturing.com/article/2015/04/manufacturers-are-looking-cloud.
10. Diego Tamburini, industry strategist, Autodesk Manufacturing, phone interview by Stephen J. Ezell, April 28, 2016.
11. Haug, Kretschmer, and Strobel, "Cloud Adaptiveness Within Industry Sectors," 297.
12. Ibid., 301.
13. Bureau of Labor Statistics, "Information Capital by Measure for Major Sectors and NIPA–level Industries," June 14, 2017, https://www.bls.gov/mfp/special_requests/prod3.itcapbymeasure.xlsx.
14. Ibid.
15. Bureau of Economic Analysis, "Input-Output Accounts Data, Use Tables/Before Redefinitions/Producer Value, 1997-2015," June 14, 2017, https://www.bea.gov/industry/xls/io-annual/IOUse_Before_Redefinitions_PRO_1997-2015_Summary.xlsx.
16. Right Scale, "State of the Cloud Report 2015," (Right Scale, 2015), http://assets.rightscale.com/uploads/pdfs/RightScale-2015-State-of-the-Cloud-Report.pdf.
17. Jeff Edwards, "IDC Survey: Majority of Manufacturers Use Cloud," *Cloud Solutions News*, April 21, 2015, https://solutionsreview.com/cloud-platforms/idc-survey-majority-of-manufacturers-use-cloud/.
18. Ibid.
19. "The Rise of Cloud Computing in Manufacturing," *Boss Magazine*, January 2017, https://thebossmagazine.com/cloud-computing-manufacturing/.
20. "Gartner Says by 2020 "Cloud Shift" Will Affect More Than $1 Trillion in IT Spending," *Gartner*, July 20, 2016, http://www.gartner.com/newsroom/id/3384720.
21. EIU surveyed 360 senior executives in 2015. The Economist Intelligence Unit, "Ascending Cloud: The Adoption of Cloud Computing in Five Industries," (The Economist Intelligence Unit, March 2016),

https://www.eiuperspectives.economist.com/technology-innovation/ascending-cloud-adoption-cloud-computing-five-industries-0.

22. Dan Emerson, "Cloud Computing's Effect on Manufacturing," *Area Development*, (2016), http://www.areadevelopment.com/advanced-manufacturing/December-2015/Cloud-Computing-Effect-on-Manufacturing-234455.shtml.
23. Ibid.
24. Intel, "Leveraging the Cloud for Big Data Analytics," *Healthcare IT News*, December 19, 2016, http://www.healthcareitnews.com/sponsored-content/leveraging-cloud-big-data-analytics.
25. Ibid.
26. Ibid.
27. OrboGraph, "Leveraging the Cloud for Big Data Analytics," December 15, 2016, http://orbograph.com/leveraging-the-cloud-for-big-data-analytics/.
28. Baker Tilly, "Cloud Computing and Other Strategy-Enabling Technologies," (Baker Tilly, June 19, 2014), http://www.bakertilly.com/insights/cloud-computing-and-strategy-enabling-technology/.
29. E-Path Learning, "3+ Reasons to Train Using a Cloud-Based LMS," http://www.epathlearning.com/assets/Manufacturing_Top_3_Reasons_To_Train_Using_LMS.pdf.
30. Tooling U-SME, "Tooling U-SME: The Pinnacle of Manufacturing Training," http://www.toolingu.com/about.
31. Coursera, "Understand Manufacturing's Fourth Revolution," https://www.coursera.org/specializations/digital-manufacturing-design-technology.
32. Louis Columbus, "Where Cloud Computing Is Improving Supply Chain Performance: Lessons Learned From SCM World," *Forbes*, February 12, 2014, https://www.forbes.com/sites/louiscolumbus/2014/02/12/where-cloud-computing-is-improving-supply-chain-performance-lessons-learned-from-scm-world/#175bac2967d3.
33. Accenture, "Supply Chain Management in the Cloud: How Can Cloud-Based Computing Make Supply Chains More Competitive?" (Accenture, 2014), 4, https://www.accenture.com/t20150523T022449__w__/us-en/_acnmedia/Accenture/Conversion-Assets/DotCom/Documents/Global/PDF/Dualpub_1/Accenture-Supply-Chain-Management-in-the-Cloud.pdf.
34. Amber Markim, "8 Ways Cloud Technology Is Changing the Game For Supply Chain Management," *Cerasis*, July 23, 2015, http://cerasis.com/2015/07/23/cloud-technology-in-supply-chain-management/.
35. Accenture, "Supply Chain Management in the Cloud," 7.
36. Paul Taylor, "Pfizer Moves Supply Chain to Cloud," *Financial Times*, September 11, 2012, https://www.ft.com/content/1608e5d6-fc59-11e1-ac0f-00144feabdc0?mhq5j=e3.
37. Accenture, "A New Era in Life Sciences: Cloud Computing Changes the Game," (Accenture, 2013), https://www.accenture.com/fr-fr/~/media/Accenture/Conversion-Assets/DotCom/Documents/Local/fr-fr/PDF_4/Accenture-Insight-Life-Sciences-Cloud-Computing.pdf.
38. Taylor, "Pfizer Moves Supply Chain to Cloud."
39. Ibid.
40. Ibid.
41. The Economist Intelligence Unit, "Ascending Cloud," 11.
42. Trevor English, "How Cloud Computing is Changing Engineering," *Autodesk Inventor Blog*, March 7, 2017, http://blogs.autodesk.com/inventor/2017/03/07/cloud-computing-changing-engineering/.
43. Ezell, "A Policymaker's Guide to Smart Manufacturing," 10.
44. "Airbus: Reimaging the Future of Air Travel," *Autodesk*, https://www.autodesk.com/customer-stories/airbus.

45. “Bionic Partition Project,” *Autodesk Research*, https://autodeskresearch.com/projects/bionic-partition-project.
46. Kylee Swenson, “What Is Generative Design?” *Autodesk*, June 8, 2016, https://redshift.autodesk.com/what-is-generative-design-2/.
47. Louis Columbus, “Why Auto Manufacturers Are Turning To The Cloud For Greater Innovation,” *Forbes*, December 1, 2015, https://www.forbes.com/sites/louiscolumbus/2015/12/01/why-auto-manufacturers-are-turning-to-the-cloud-for-greater-innovation/#5e13b61e1fe7.
48. “Aston Martin: Accelerating the Automotive Design Process,” *Autodesk*, https://www.autodesk.com/campaigns/autoevolution/design-and-class-a.
49. Ibid.
50. Accenture, “A New Era for the Automotive Industry: How Cloud Computing Will Enable Automotive Companies to Change the Game,” (Accenture, 2014), 7, https://www.accenture.com/t20150914T170053__w__/us-en/_acnmedia/Accenture/Conversion-Assets/DotCom/Documents/Global/PDF/Industries_18/Accenture-Cloud-Automative-PoV.pdf.
51. Ibid.
52. Accenture, “A New Era for the Automotive Industry,” 18.
53. “What Is 3D Printing?” 3D Printing.com, accessed October 12, 2016, http://3dprinting.com/what-is-3d-printing/.
54. The vehicle’s chassis is 3D printed. The Blade’s engine, body, and seats are traditionally manufactured.
55. Divergent3D, “Story,” http://www.divergent3d.com/.
56. Michael Molitch-Hou, “Divergent 3D and PSA Group Overhaul Auto Manufacturing with 3D Printing,” *Engineering.com*, September 22, 2016, http://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/13181/Divergent-3D-and-PSA-Group-Overhaul-Auto-Manufacturing-with-3D-Printing.aspx.
57. Julie Ritzer Ross, “How the IoT and the Cloud Are Changing the Face of Manufacturing,” *Chief Executive*, January 6, 2016, http://chiefexecutive.net/how-the-iot-and-the-cloud-are-changing-the-face-of-manufacturing/.
58. Peter C. Evans and Marco Annunziata, “Industrial Internet: Pushing the Boundaries of Minds and Machines” (GE, November 26, 2012), 10, www.ge.com/docs/chapters/Industrial_Internet.pdf.
59. Ibid.
60. Marco Annunziata, chief economist and executive director, Global Market Insights, General Electric, phone interview by Stephen Ezell, June 13, 2017.
61. Ibid.
62. Michael Fitzgerald, “An Internet for Manufacturing,” *MIT Technology Review*, January 28, 2013, https://www.technologyreview.com/s/509331/an-internet-for-manufacturing/.
63. John Koten, “A Revolution in the Making,” *The Wall Street Journal*, June 10, 2013, http://www.wsj.com/articles/SB10001424127887324063304578522812684722382.
64. Ross, “How the IoT and the Cloud Are Changing the Face of Manufacturing.”
65. James R. Hagerty, “How Many Turns in a Screw? Big Data Knows,” *The Wall Street Journal*, May 15, 2013, http://www.wsj.com/news/articles/SB10001424127887324059704578472671425572966.
66. James Manyika et al., “The Internet of Things: Mapping the Value Beyond the Hype” (McKinsey Global Institute, June 2015), 68, http://www.mckinsey.com/~/media/McKinsey/Business%20Functions/McKinsey%20Digital/Our%20Insights/The%20Internet%20of%20Things%20The%20value%20of%20digitizing%20the%20physical%20world/Unlocking_the_potential_of_the_Internet_of_Things_Executive_summary.ashx.

67. Roland Moore-Colyer, "Cloud Tools Help Harley-Davidson Leave Legacy IT in its Dust," *V3*, April 22, 2015, https://www.v3.co.uk/v3-uk/news/2405098/cloud-tools-help-harley-davidson-leave-legacy-it-in-its-dust.

68. Smart Manufacturing Leadership Coalition, "What Is Smart Manufacturing?" YouTube video, 8:19, posted June 16, 2014, https://www.youtube.com/watch?v=Hcq4e9D4uL8.

69. Fiona Barry, "Pfizer Hails Portable Manufacturing as Latest in Lean," *In-Pharma Technologist.com*, November 19, 2014, http://www.in-pharmatechnologist.com/Processing/Pfizer-hails-portable-manufacturing-as-latest-in-lean.

70. Michael E. Porter and James E. Heppelmann, "How Smart, Connected Products Are Transforming Companies," *Harvard Business Review*, October 2015, 8, https://hbr.org/2015/10/how-smart-connected-products-are-transforming-companies.

71. Sharon Gaudin, "Ford Uses Microsoft Cloud to Seamlessly Update Cars," *Computerworld*, March 17, 2015, http://www.computerworld.com/article/2898103/cloud-computing/ford-uses-microsoft-cloud-to-seamlessly-update-cars.html.

72. Ibid.

73. Stephenson, "The Linkage Between Services and Manufacturing in the U.S. Economy."

74. John Maggiore, "Remote Management of Real-Time Airplane Data," *Boeing*, accessed January 8, 2015, http://www.boeing.com/commercial/aeromagazine/articles/qtr_3_07/AERO_Q307_article4.pdf.

75. Paul Mathai, "Big Data: Catalyzing Performance in Manufacturing," *Wipro*, accessed January 8, 2015, http://www.wipro.com/documents/Big%20Data.pdf.

76. Ibid.

77. John Maggiore, "Remote Management of Real-Time Airplane Data," *Boeing.*

78. Keith Smith, "ENT213: How Boeing Is Using AWS to Transform Commercial Aviation," (power point presentation, November 14, 2013), https://www.slideshare.net/AmazonWebServices/ent213.

79. Brandon Butler, "How Boeing is Using the Cloud," *NetworkWorld*, April 3, 2014, http://www.networkworld.com/article/2175805/cloud-computing/how-boeing-is-using-the-cloud.html.

80. Ibid.

81. Ibid.

82. Accuride, "About: Industry Leadership and Experience," http://www.accuridecorp.com/about/.

83. Emerson, "Cloud Computing's Effect on Manufacturing."

84. Ibid.

85. Jonathan Gross, "Accuride Corporation Deploys Plex Online Cloud ERP Solution to Improve Operational Efficiency," Pemeco Consulting, August 7, 2012, https://www.pemeco.com/accuride-corporation-deploys-plex-online-cloud-erp-solution-to-improve-operational-efficiency/.

86. Emerson, "Cloud Computing's Effect on Manufacturing."

87. Ibid.

88. Gross, "Accuride Corporation Deploys Plex Online Cloud ERP Solution."

89. MakeTime, "What Is MakeTime?" https://www.maketime.io/faq/what-is-maketime/.

90. Tim Shinbara, vice president manufacturing technology, Association of Manufacturing Technology, phone interview by Stephen Ezell, May 30, 2017.

91. Ibid.

92. Proto Labs, "Manufacturing Services," https://www.protolabs.com/services/suite-of-services/.

93. Proto Labs, "Who We Are," https://www.protolabs.com/about-us/who-we-are/.

94. Kevin McDunn, chief technology officer, UI Labs, phone interview by Stephen Ezell, June 9, 2017.

95. Ibid.

96. Seeking Alpha, "Proto Labs: A Phenomenal Growth Story," https://seekingalpha.com/article/3965850-proto-labs-phenomenal-growth-story.

97. "*Forbes* Best Small Companies 2014," *Forbes*, https://www.forbes.com/companies/proto-labs/.

98. Seeking Alpha, "Proto Labs: A Phenomenal Growth Story."

99. James Barkley, Digital Manufacturing and Design Innovation Institute, phone interview by Stephen Ezell, ITIF, March 4, 2016.

100. Kevin McDunn, chief technology officer, UI Labs, phone interview by Stephen Ezell, June 9, 2017.

101. Caralynn Collens, chief executive officer, UI Labs, in-person interview by Stephen Ezell, February 14, 2017.

102. Joann Muller, "How Ford Is Using Big Data To Change The Way We Use Our Cars," *Forbes*, October 22, 2015, https://www.forbes.com/sites/joannmuller/2015/10/22/how-ford-is-using-big-data-to-change-the-way-we-use-our-cars/print/.

103. Ibid.

104. "Ford Pilots New Siemens Software Using Google Earth Technology to Virtually Navigate Assembly Plants and Enhance Global Manufacturing Collaboration," *Ford*, December 9, 2013, https://media.ford.com/content/fordmedia/fna/us/en/news/2013/12/09/ford-pilots-new-siemens-software-using-google-earth-technology-t.html.

105. Accenture, "A New Era for the Automotive Industry."

106. Nick Ismail, "How Cloud Computing Can Transform the Pharmaceutical Industry," *Information Age*, October 14, 2016, http://www.information-age.com/cloud-security-pie-sky-123462595/.

107. Ibid.

108. Accenture, "A New Era in Life Sciences."

109. Numerate, "Numerate Forms Drug Discovery Collaboration with Merck to Utilize Numerate's In Silico Drug Design Technology," March 14, 2012, http://www.numerate.com/numerate-forms-drug-discovery-collaboration-merck-utilize-numerates-silico-drug-design-technology/.

110. Ibid.

111. Michael Mandel and Bret Swanson, "The Coming Productivity Boom," (Technology CEO Council, 2017), 20, http://www.techceocouncil.org/clientuploads/reports/TCC%20Productivity%20Boom%20FINAL.pdf.

112. Doug Henschen, "Merck Optimizes Manufacturing With Big Data Analytics," *Information Week*, April 2, 2014, http://www.informationweek.com/strategic-cio/executive-insights-and-innovation/merck-optimizes-manufacturing-with-big-data-analytics/d/d-id/1127901.

113. Mark Doms and Daniel Castro, "Data is the Key to the Factory of the Future," (United States Department of Commerce, Economics and Statistics Administration, October 2, 2014), http://www.esa.doc.gov/under-secretary-blog/data-key-factory-future.

114. *Contact Pharma*, "Merck Awarded for its Use of Big Data, Cloud Computing to Boost Vaccine Yields," April 12, 2014, http://www.contractpharma.com/contents/view_breaking-news/2014-04-02/merck-awarded-for-its-use-of-big-data-cloud-computing-to-boost-vaccine-yields/.

115. Arnal Dayaratna, "Merck Aims to Harness Capabilities of Amazon Alexa to Tackle Type 2 Diabetes with Alexa Diabetes Challenge," *Cloud Computing Today*, April 13, 2017, https://cloud-computing-today.com/2017/04/13/1076008/.

116. "Merck Uses Amazon Web Services to Develop Voice-Enabled Chronic Disease Management Tools," *Drug Discovery and Development Magazine*, March 16, 2017, https://www.dddmag.com/news/2017/03/merck-uses-amazon-web-services-develop-voice-enabled-chronic-disease-management-tools.

117. U.S. Energy Information Administration, "Natural Gas Gross Withdrawals and Production," accessed February 28, 2017, https://www.eia.gov/dnav/ng/ng_prod_sum_dc_NUS_mmcf_m.htm.

118. Bureau of Economic Analysis, "Input-Output Accounts Data, Use Tables/Before Redefinitions/Producer Value, 1997-2015"; Authors' calculations.

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

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

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

122. NIST MEP, "2015 NIST MEP Annual Report," (NIST MEP, 2015), 8, https://www.nist.gov/sites/default/files/documents/2016/11/14/annual-report-2015-final.pdf.

123. Manufacturing Foresight, "Democratizing Manufacturing: Bridging the Gap Between Invention and Manufacturing," (Manufacturing Foresight, December 2016), 22, http://mforesight.org/download/5113/ .

124. Deloitte, "Manufacturing USA: A Third-Party Evaluation of Program Design and Progress," (Deloitte, January 2017), https://www2.deloitte.com/content/dam/Deloitte/us/Documents/manufacturing/us-mfg-manufacturing-USA-program-and-process.pdf.

125. Castro, "Cloud Computing: An Overview of the Technology and the Issues."

126. Barb Darrow, "Intelligence Community Loves Its New Amazon Cloud," *Fortune*, June 29, 2015, http://fortune.com/2015/06/29/intelligence-community-loves-its-new-amazon-cloud/.

127. The White House, "Executive Order—Creating a National Strategic Computing Initiative," news release, July 29, 2015, https://www.whitehouse.gov/the-press-office/2015/07/29/executive-order-creating-national-strategic-computing-initiative.

128. Stephen J. Ezell and Robert D. Atkinson, "The Vital Importance of High-Performance Computing to U.S. Competitiveness" (Information Technology and Innovation Foundation, April 2016), https://itif.org/publications/2016/04/28/vital-importance-high-performance-computing-us-competitiveness.

129. Doug Brake, "A Policymaker's Guide to Rural Broadband Infrastructure" (Information Technology and Innovation Foundation, April 2017), http://www2.itif.org/2017-rural-broadband-infrastructure.pdf?_ga=2.218339929.1991926981.1497921863-851887776.1494256561.

130. Doug Brake, "Comments to Federal Communications Commission on Spurring Broadband Deployment," (Information Technology and Innovation Foundation, June 15, 2017), http://www2.itif.org/2017-fcc-comments-broadband-deployment.pdf?_ga=2.145913588.1991926981.1497921863-851887776.1494256561.

131. Daniel Castro and Alan McQuinn, "Unlocking Encryption: Information Security and the Rule of Law," (Information Technology and Innovation Foundation, March 2016), http://www2.itif.org/2016-unlocking-encryption.pdf.

132. Ezell, "A Policymaker's Guide to Smart Manufacturing," 33.

133. Nigel Cory, "Cross-Border Data Flows: Where Are the Barriers, and What Do They Cost?" (Information Technology and Innovation Foundation, May 2017), http://www2.itif.org/2017-cross-border-data-flows.pdf.

134. Patrick Wauters et al., "Measuring the Economic Impact of Cloud Computing in Europe," (Deloitte, on behalf of the European Commission, 2016), 11, http://ec.europa.eu/newsroom/document.cfm?doc_id=41184.

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