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Advancing Manufacturing to New Frontiers
Increasing Opportunities for Society

Manufacturing is on the verge of entering a new frontier that has the potential to revolutionize every facet of society as we know it. Innovative processes, trends, and technologies are transforming the core of manufacturing, and lowering the walls between manufacturing and other sectors of the economy, especially the services sector. Due to the expected impact of this transformation, policymakers, business leaders, and society as a whole will have to adjust their image of manufacturing to this new reality.

In this article, we build on our recent investigations into this transformation and provide insights into the future of manufacturing and its impact on policy, business, and society.[1] Our starting premise is that policymakers and business leaders must come to terms with two developments. The first is that the factory floor—traditionally considered the essence of the manufacturing sector—is an increasingly smaller and more integrated piece of a larger manufacturing enterprise that comprises other traditionally distinct sectors, such as research and development (R&D) in industry and academia, design, consulting services, sales, and marketing. The second development is that, because of this integration, manufacturing can no longer be treated as an expendable, stand-alone puzzle piece that can be cut out and exported as needed. Nor can the manufacturing challenge be addressed

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without considering other business or economic factors, as many current initiatives are attempting to do.

The transformation of manufacturing has been underway for decades. Early signs included the migration of firms toward a combination of manufacturing and support services that integrated manufacturing into the tangible and intangible economies. Decades ago, firms like IBM and Xerox bundled their manufactured products with support services to differentiate their products, build strong relationships with consumers, and increase profit margins. Most recently, Apple blurred the manufacturing/services distinction with the integration of their iPad, iPod, and iPhone products with online services. As manufacturers have moved into services, the service industry has moved toward manufacturing: Microsoft, a software company, also offers computer peripherals such as trackballs and keyboards; Amazon, originally an online bookseller, also builds and sells the Kindle electronic reader; and the British firm Riversimple plans to manufacture hydrogen fuel cell cars and lease them on a per-use basis.

This trend has moved beyond linking support services with manufactured products and is now fully integrating services with products, such that the two become inseparable. Even medicine, the most craft-like of professions, is becoming a blend of human medical skill and manufactured technology. Hardware- and software-based medical tools are used in routine diagnostics and patient care, and increasingly in complex surgery. Innovations in wireless sensing technology—a stronghold of the manufacturing sector—have great potential in the field of personalized medicine. Future advances in tissue engineering could make it possible to grow organs using three-dimensional printing technologies, which would significantly change the boundaries between traditional manufacturing and biotechnology. By creating opportunities for entrepreneurs and companies of all sizes in all sectors of the economy, such advances in manufacturing have the potential to broadly distribute, rather than to concentrate, economic opportunity.

Traditional factories were designed to efficiently produce thousands of identical widgets—what MIT's Sanjay Sarma has called "the tyranny of bulk." Today's advanced manufacturing facilities produce low-cost goods with the efficiency of mass production and the flexibility of custom manufacturing, which allows companies to respond quickly to changes in quantity, quality, and customer demands, thus giving consumers the speed, flexibility, and customization they increasingly expect. Moreover, these advances increasingly generate spillover into sustainability and lower use of resources, which serves the common good while adding to the company's bottom line.

In this policy perspective, we examine the advanced manufacturing enterprise of the future through a lens of four cross-cutting technology areas. We identify converging trends, where the ubiquitous use of information technologies, modeling and simulation, and supply-chain innovations are leading to nearly full automation of the factory floor, and where smart factories are being created that have the ability to respond rapidly to changes in customer demand. We then describe the current global players in these technology areas, and conclude with a discussion of the science and technology advances and policies needed to accelerate and capitalize on advanced manufacturing.

FOUR CROSS-CUTTING TECHNOLOGY AREAS

To assess how advanced manufacturing might change in the future, we examine four strategic areas of technology that have the potential to change future manufacturing dramatically. Two of the technology areas, semiconductors and advanced materials, represent highly developed, mature technologies. The other two, additive manufacturing and synthetic biology, represent emerging technologies that could have a significant impact in the future.

These four areas of technology represent fundamental or platform technologies on which other technologies are built, and the major manufacturing countries have made a significant investment in R&D related to these technologies.

Semiconductors

As the cornerstone of the global information technology economy, semiconductors are critical to economic growth, industrial development, and national security. Semiconductors will increasingly incorporate sensors and other heterogeneous components to deliver increased functionality, even as the linear scaling of circuits slows down. Researchers are exploring new materials and approaches to building circuits, which will eventually lead to completely novel computing devices.

Advanced Materials

Broadly defined, advanced materials are those with new or innovative internal structures that yield superior properties and facilitate transformative or disruptive changes in manufactured products. The insertion of advanced materials into products traditionally takes a significant amount of time but the process can be accelerated through the implementation of integrated computational materials engineering (ICME), an area of increasing interest in the materials community. The ICME approach takes a systems view that unifies design and manufacturing to accelerate and optimize the insertion of materials into products. Once implemented, ICME can reduce development schedules and concomitant costs while tailoring materials to specific product needs. Since ICME techniques loosen design constraints and facilitate the optimization of material choices, they offer enormous economic potential.

Additive Manufacturing

Commonly known as 3D printing, additive manufacturing is a layer-based processing technology with the potential to shift manufacturing toward more distributed production models. Unlike traditional processes, additive manufacturing machines can produce any geometrical design without costly retooling. Creating products via additive processes rather than conventional subtractive processes can increase flexibility and customization, reduce material waste, decrease the need for large product inventories, and provide novel digital supply-chain possibilities for product design and delivery.

Synthetic Biology

Synthetic biology is a nascent discipline that seeks to manufacture biological products and systems inexpensively and rapidly. With the capability to manufacture biological substances from radically engineered biological systems, synthetic biology could reframe the manufacturing sectors of pharmaceuticals, biofuels, environmental sensors, agriculture, biological computing, and materials. Through their impact on health care, food production, computing, and the environment, synthetic biology processes have the potential to transform societies and thus also could have national security implications.

A GLIMPSE INTO THE FUTURE: A SIMULTANEOUS AND BROADENING CONVERGENCE OF TRENDS

Our research into advanced manufacturing points to an increasingly automated world that will rely less on labor-intensive mechanical processes and more on sophisticated processes that are information-technology intensive. This trend will likely accelerate as advances in manufacturing are implemented.

Advances in semiconductors will be driven by low-power wireless devices with constantly improving sensing and data-handling capabilities, which will create a vision of a cyber-physical world with ubiquitous computing capability. Nanoelectronics will become pervasive in energy (energy-efficient buildings and smart-grid control), transportation (autonomous or self-driving vehicles), and medicine (implantable devices, prosthetics, and biocompatible imaging systems). Meanwhile, interconnected systems of sensors will create intelligent local environments (smart homes and autonomous transportation), which could lead to an "Internet of things" or cyber-physical systems. As the cost of chip production continues to rise exponentially, the search for lower cost options may open the door for user-programmable chips or customizable chips with desired functionality—for example, bringing system-level customization and flexibility like that in an MP3 player to the chip level to create an "iPod at the chip level."

Additive manufacturing could partially address the growing customer demand for flexibility and customization. Although additive manufacturing may likely never compete with mass production in all areas, it is beginning to have an impact in several markets, including prototyping and design, rapidly creating tools for traditional manufacturing processes, directly producing parts with innovative geometries, and performing maintenance and repair on one area of a part without having to create an entirely new part. Thus, additive manufacturing processes can impact many facets of advanced manufacturing, from the early design stages to production and even after-market maintenance and repair.

Developments in materials and systems design approaches such as ICME will likely accelerate the insertion of advanced materials into products. For example, technically or economically infeasible battery chemistries could be avoided by employing computational tools and combinatorial chemistry, thus shortening development times for related energy-storage products. Ultimately, ICME has the potential to dramatically shorten the materials development cycle from the present 10 to 20 years to as little as 2 or 3 years. Nonetheless, a range of technical and non-technical barriers, including issues related to information storage and sharing, must be overcome before the benefits of ICME can be fully realized.

Synthetic biology could change the manufacture of biological products. Coupled with advances in genomics, proteomics, systems biology, and genetic engineering, synthetic biology has the potential to design and produce complex new manufacturing systems. The catalyst for new products will be increased understanding of cellular functions and disease models.

The semiconductor industry will continue to push the limits of miniaturization, looking to biologically inspired designs, nanoscale, and self-assembly to create new multifunctional materials for information processing, as well as future health and energy applications. For example, one of the German Fraunhofer Institute is developing new biocompatible materials and a manufacturing process that combines 3-D inkjet printing and a laser-based polymerization technique for cross-linking with precision.

In addition to these trends for individual technologies, other technology-agnostic, cross-cutting trends are emerging in the manufacturing sector. Over the next 20 years, these trends will continue to change manufacturing in many ways.

The concept of advanced manufacturing will continue to push new frontiers.

Advanced manufacturing innovations, both on and off the factory floor, will displace many of today's traditional processes. To advance, manufacturing will continue to rely on scientific and engineering R&D, information technology, sophisticated design, automation and modeling tools, a highly trained workforce, and innovative business models. These advances will allow companies to adapt rapidly to customer needs and to compete in new markets. Labor-intensive processes in some of today's manufacturing sectors will continue to be replaced with data-intensive, automated processes that rely on sensors and robots.

Manufacturing will become increasingly globally linked, as automation and digital supply-chain management become the norm across enterprise systems.

Globally distributed manufacturing systems—including design, R&D, and corporate headquarter services—will also allow companies to look outward for innovative ideas to help them differentiate their products and respond rapidly to customer needs as they compete in new markets. Manufacturing processes will also likely be more resource efficient as companies strive to integrate sustainable manufacturing techniques into their business practices to minimize waste, while at the same time reducing costs and vulnerability to supply-chain uncertainties.

Advances in IT will increasingly allow manufacturers to make data-driven decisions based on customer needs.

The future of information technology will be driven by networks of sensors connected by wireless devices that transmit vast amounts of information to and from cloud servers, creating what is known as a cyber-physical world that has ubiquitous computing capability. Manufacturers will take advantage of this available data to become more flexible and agile in their response to customers. As new tools are available to analyze massive datasets to detect patterns, accelerate discovery, and reduce risk, manufacturers will be able to improve the degree of product customization. Additive manufacturing technology offers the promise of customization at the level of the individual consumer, as product designs can be downloaded from the Internet, customized with easy-to-use software, and manufactured or printed on the spot.

Advanced manufacturing will become increasingly reliant on modeling and simulation tools.

At present, modeling and simulation are commonly employed to avoid costly prototyping and testing while improving material and product performance. However, modeling and simulation also have the ability to improve manufacturing processes, factory-level practices, and supply-chain activities. As the number of sensors and data increases, the prediction and accuracy of modeling and simulation at all levels will increase. Increased computational power will also enable the modeling and simulation of more complex systems.

Advanced manufacturing jobs will not be on the factory floor.

Advanced manufacturing jobs will increasingly be tied to modeling and simulation and data analysis rather than to manual labor. Workers will observe and take action, as necessary, to correct and improve production processes on the factory floor. The role of workers and entrepreneurs will focus on design, modeling and simulation, and using real-time data to make rapid decisions about changing production processes. Many of these jobs will be done outside the factory floor.

A strong service sector is increasingly dependent to the manufacturing sector.

Many companies already offer services that extend their reach to the customer. IBM is an oft-cited example that focuses more on the customer than on computers and software, yet the company's services derive from its manufactured products. Strong service provides an important source of inputs to the manufacturing process, ranging from R&D, design and supply-chain management to customer relations, including customer feedback and input into the design and production process. These non-factory "service" jobs are therefore essential.

GLOBAL PLAYERS

The United States is a leader in most areas of advanced manufacturing; however, other countries have increased their investment in R&D as the foundation of advanced manufacturing and have actively sought to establish innovative manufacturing facilities within their borders. Many countries are beginning to show signs that they may soon overtake the United States, at least in some areas. These trends are exemplified by the four technology areas described above.

With respect to semiconductors, fabrication facilities for contract manufacturing (foundries) are growing in Southeast Asia, with a corresponding decline in the United States. Foundries and independent manufacturers in Southeast Asia are more willing than U.S. companies to accept the risk of developing innovative technologies and are now competitive from an R&D perspective. The attrition of the U.S. semiconductor manufacturing base may continue to affect research in infrastructural areas, such as materials and instrumentation, manufacturing technology, and tooling.

Internationally, Japan, Taiwan, and Korea have an established position in the industry, with China ramping up its foundry capabilities. China is also rapidly moving up the value chain by investing in chip architecture and design, aided by government policies that attract foreign manufacturers to set up foundries in the country. An important strength of the European Union (EU) is its cross-border public-private partnerships in France, Germany, and across the EU. The EU also has coordinated Framework Programme efforts by funding specific areas of interest, such as the 10-year Future and Emerging Technologies Flagship Initiatives that mirror those in the United States.

While the United States has a dominant position in the semiconductor industry, the result of the global spread of the semiconductor manufacturing supply chain is that companies that started as contract manufacturers are now competitive in cost as well as innovation. Furthermore, there is reduced control over the system; as a result, electronic products manufactured overseas, both defense and consumer goods, may be susceptible to tampering and counterfeiting.

In the area of integrated computational materials engineering, the United States is currently among the leaders in developing computational tools, but other countries, especially within the EU, are making significant investments. Germany, the United Kingdom, and Sweden are exploring ICME concepts, especially those related to automotive and defense applications, whereas France has ongoing work to meet its needs in nuclear and defense applications. China's computational capabilities have been increasing, along with the number of ICME-related publications; however, China's potential remains unclear. Market forces may begin to prompt other countries, such as Singapore and South Korea, to begin to explore ICME approaches for consumer electronics. Australia is also doing work in ICME, especially on lightweighting, an activity that aims to reduce the weight of products without sacrificing cost or performance.

With about $1.2 billion in worldwide sales of systems, materials, and services in 2010, additive manufacturing is a small but rapidly growing industry. The United States is in a strong position to continue as an industry leader in many areas of additive manufacturing, including the manufacture and purchase of low- to mid-priced machines. In terms of total installed base (i.e., all commercially available additive manufacturing machine types currently in use), the North American region leads with 43 percent of machines, followed by 30 percent in Europe, 23 percent in the Asia/Pacific region, and the remainder in other areas.

Europe is a leader in the segment of the additive manufacturing market that manufactures direct metal, and the EU has strong research centers, such as the Fraunhofer Institutes in Germany, Katholieke Universiteit Leuven in Belgium, and Loughborough University in the United Kingdom. Israel also has emerged as a global player, due to a single company, Objet Geometries, which has sold nearly as many machines (albeit at lower prices) as all the European companies combined.

Japan was an early adopter of additive manufacturing technology, but Japanese companies recently have had less success in selling machines to manufacturers beyond its borders. The situation is similar in China. There is some growth in Taiwan and Australia but, as in China, the growth is mainly in use rather than in innovation and development. A few Asian companies have recently emerged that appear to have a global presence.

Several governments, including that of the United States, are investing in synthetic biology because of its potential impact on national security. It is estimated that the U.S. government provides roughly $140 million each year for synthetic biology research; the EU invests roughly one-third to one-quarter that amount.

China has recently developed an interest in synthetic biology and has research goals similar to those of the United States. But, like Western countries, China is having trouble defining and assessing the potential impact of the relatively immature synthetic biology field. Biotechnology funding in China is through government programs, such as the 863 Program (National High-Tech R&D Program), the 973 Program (National Basic Research Program), and the National Science Foundation of China, and many biotechnology projects that could be classified as synthetic are funded under these programs. A dedicated research-funding strategy has been proposed in China for synthetic biology, but it has been delayed due to a lack of a consensus about a definition for the discipline.

CONCLUSIONS

We have argued that advanced manufacturing is a concept that goes beyond the factory floor, and that it is a focal point for much of the convergence in the global economy with respect to the pervasiveness of information technology, the role of R&D, the use of modeling and simulation tools, and the importance of sustainability. If the United States is to sustain its leadership in manufacturing, it needs to make advances in technology and policy. On the technology side, for example, the drive to produce low-power, lower-cost microprocessors will spur the exploration of lower-cost fabrication methods, as well as new materials and mechanisms for charge transfer devices. Complementary advances will be needed in chip design, chip architecture, and design-automation technology. Alongside materials advancements, the development and deployment of materials via ICME approaches will require the creation of models, databases, and tools for rapid experimentation.

Advances in additive manufacturing will include higher quality and more available materials, control and understanding of process, machine qualification, and design tools and software. In synthetic biology research, the next steps are to increase fundamental knowledge of genetics, bioengineering, standardization, and the predictability of working with complex genetic circuits.

Just as important, multiple policy boundaries must be addressed. For example, U.S. policy issues that set the stage for advanced manufacturing will provide a foundation for an entrepreneurial economy. In each of the four technology areas examined, research is expensive and requires substantial investment and incentives, from basic research to development and deployment, as scale-up is often as high risk as early stage research. Regulations will have to be rewritten to account for new ways to produce products through additive manufacturing and synthetic biology. Ethical and safety concerns are among the important regulatory issues that must be addressed. Other factors such as intellectual property rights and protection, immigration policies, quality of education, and national security interests are also important.

Modernizing education will be critical to long-term success in R&D and in the commercialization of products in each of the areas examined. Advances in modeling and simulation, as well as analysis of large datasets, will help build a flexible workforce that can work across disciplines and respond to changing conditions beyond the factory floor. Opportunities exist for those who can integrate science, engineering, creativity, and culture into their work.

Most importantly, policymakers will need to understand that the manufacturing sector has changed and will continue to evolve in a direction far different from in the past. Policymaking across the board must be tailored for this new reality so the manufacturing sector will not be constrained by the ideals of traditional manufacturing.

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1. Our work draws from a report prepared for the National Intelligence Manager for Science and Technology in the Office of the Director of National Intelligence. Stephanie S. Shipp et al., "Emerging Global Trends In Advanced Manufacturing," IDA Paper P-4603, March 2012. Available at https://www.ida.org/upload/stpi/pdfs/p-4603_final2a.pdf.

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