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Manufacturing in America: A View from the Field

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MIT work OF THE FUTURE

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Introduction

U.S. manufacturing and its people face great new risks and potential new opportunities. In the fog of uncertainty about recovery from COVID-19, all economic actors have to make investment, hiring, and lay-off decisions based on guesses about whether the economy's rebound will be a sharp V-shaped ascent or a slow exit. Six months into the pandemic, manufacturing overall was faring better than retail and service industries.[1] The National Association of Manufacturers' Third Quarter Outlook Survey (September 10, 2020) found that 72.5% of all manufacturing companies predicted that the number of their full-time employees would remain the same or increase over the next year.[2] When MIT researchers recontacted manufacturing firms in Ohio, Massachusetts, and Arizona that they had visited in past years, they discovered that the companies had continued to operate through the pandemic.[3] Automotive and aeronautics suppliers were hard hit, as demand for their products shrank. But without big changes in what they produced, most manufacturers were doing fairly well, and with the help of the federal Paycheck Protection Program (PPP) had been able to keep the majority or all of their workers.

Before the COVID-19 pandemic, U.S. manufacturing had begun to recover from the severe shocks and losses of the previous decades. Between 2000 and 2016, U.S. manufacturing had shed 5 million workers, and the number of manufacturing establishments had dropped by 22%. Initial explanations of this collapse from economists such as Nobel laureate Gary S. Becker saw this as an acceleration of the more gradual long-term decline of manufacturing. In such views, this was a natural phenomenon, much like the century-earlier decline of the agricultural workforce, as technological advances led to productivity growth and to turning out more goods with fewer workers.

Accounts that focused on productivity growth as explanations for the rapid collapse of manufacturing over a decade and a half have now been largely discredited by the research of Susan Houseman and others who have shown that productivity rose only in the computer and electronics sector, which in that industry can largely be accounted for by a fall in the price of imported inputs and unaccounted-for product improvements.[4] The reality is, rather, that productivity growth in manufacturing in the United States is slow relative to that in other advanced industrial countries, with more workers employed in manufacturing than in the United States. Economists generally acknowledge that manufacturing collapsed under the onslaught of imports of cheaper goods from low-wage countries, particularly from China after its admission to the World Trade Organization in 2001.[5] Still other major factors, such as the pressure of financial markets, contributed to the undermining of manufacturing over those years of decline.[6]

Today, manufacturing companies and their workers face new challenges: technological changes that might allow big companies to take over functions which suppliers now provide; a retirement wave of older manufacturing workers; scattered resources for educating new workers in the skills required for advanced manufacturing systems; and strong competition from abroad. COVID-19 has raised the urgency for U.S. manufacturers to commit to new pathways. One possible trajectory might emerge from wider and more rapid adoption of new automation technologies and new skills. Another pathway might emerge from the U.S. retreat from globalization, which could bring back within national borders some of the outsourced and offshored production of the past 30 years. What may be opportunities in these scenarios for some firms and workers may be risks for others. If automation in large firms allows them to grow but to shrink their workforce, many workers will not do well in the coming years. If tasks that have been outsourced to China are forced by new protectionism to return to the United States, new jobs might be created at domestic suppliers. But prices would rise, and consumers will pay the cost. If large firms grow at the expense of small and medium-sized manufacturers, productivity and U.S. economic growth might accelerate, but the impact on smaller companies, their workers, and their communities may be heavy. On this terrain of new possibilities, the outcomes, winners, and losers are not yet determined. Here, we can identify spaces in which public policies on procurement, trade, R&D, taxes, and workforce education could shape and reshape opportunities for workers and firms.

Decisions on automation, new production, and outsourcing will be made by individual company owners, but much is at stake for the national economy. After years of slow productivity growth and an even slower increase in blue-collar wages, there is a strong case to make for national policies to raise the tides on which manufacturing companies could advance more rapidly. After months of COVID-19, there's new public demand across partisan divides for relocating in the United States the production of goods and services essential to health and well-being: factories for textiles that could make protective clothing, plastics factories that could make room dividers or face screens, and pharmaceutical plants that could make common drugs like acetaminophen as well as vaccines.[7] To design public policies that would make it more likely that U.S. industry raises productivity growth and expands its capabilities for making essential goods within national borders, we need to start from an understanding of manufacturing that is closer to the current realities on the ground than standard models provide.

The research team on manufacturing of the MIT Task Force of the Work of the Future has spent the past two years on factory floors in Massachusetts, Ohio, and Arizona trying to develop such an understanding.[8] In this report, we first consider standard approaches to adoption of new technologies on factory floors; next, we present our research team's "bottom-up" approach and its findings from factory visits on why, when, and how firms acquire new technology; then we outline our team's findings on how firm strategies affect hiring, skill upgrading, and the impact of new technologies on workers; and finally we conclude with some suggestions on levers for change in manufacturing.

THE BIG FEAR: WILL NEW TECHNOLOGIES DESTROY (MOST) MANUFACTURING JOBS?

There has been much speculation about how new technologies might reshape production. Robots, 3D printing, artificial intelligence (AI), machine learning, digital manufacturing, the Internet of Things, and Industry 4.0 all appear to offer a transformative set of options for remaking manufacturing. Research in this domain usually starts from the properties of a new technology and then moves to model and to predict how these technical capabilities might play out when implemented and scaled up. Such scenarios are often illustrated in presentations for wider audiences with a story or two of companies that have already introduced and commercialized such innovations, such as GE's 2017 3D printing of a fuel nozzle tip for a jet engine that replaced a process in which 20 different parts had to be welded and brazed together or a Waymo self-driving car. The implication is that the example is but the first in a wave of similar cases.

Starting four years ago, there were a number of influential research reports (Frey and Osborne, 2013, 2017; McKinsey, 2017; Brynjolfsson and McAfee, 2014; World Economic Forum, 2018) that proceeded in this way, by extrapolation from the technical capabilities of new technologies to the scale-up and implementation of new types of production to predictions of massive job losses.[9] The press reported a broad consensus of experts predicting that robots were on the verge of widespread adoption in manufacturing; that self-driving cars and trucks were about to take over the roads; and that artificial intelligence and machine learning were about to replace human decision-making in a wide variety of tasks. These accounts generated a real panic about whether there would be any work left for humans in the future.

The reports often acknowledged that in the past there had been fears about unemployment whenever new technologies appeared. When, for example, electricity was introduced into factories at the beginning of the 20th century, or when banks installed ATMs at the end of the 20th century, there were dire forecasts of the disappearance of jobs. Always in the past, more jobs had been created, and the fears dissipated. But this time was fundamentally different, the experts claimed. Automation would destroy a vast number of jobs, and too few new ones would be created. There followed a flurry of proposals for regulating new technologies, for taxing robots, and for providing a universal basic income to substitute for wages. It was in this climate of technology predictions and enormous social and political anxiety about jobs that the MIT Task Force on the Work of the Future started its work in 2018. Its objective was to develop fact-based analyses of the impact of new technology.

Two years later, by early 2020, predictions of extraordinary waves of change were already being scaled down. It now appears that fully autonomous vehicles will arrive many years from now, if ever. For the foreseeable future, new automotive technologies are likely to be ones that assist drivers and do not replace them. Expectations about AI replacing human judgment in the workplace are also now being modulated, as a recent survey in *The Economist* on AI has documented.[10] But, while the most rapid and radical scenarios of machines displacing human labor now appear unlikely, COVID-19 has given rise to new predictions about how coping with the virus will induce managers to adopt labor-saving technologies and lead to massive job loss.[11]

Again, these predictions start from the properties of new technology and extrapolations to possible scenarios of adoption on the factory floor. The basic idea is that managers who have struggled through months of trying to maintain production with social distancing, masks, and workers vulnerable to viruses may now find replacing workers with robots a more compelling case. The "lights-out factory," which needs no illumination because it needs no workers on the factory floor, may today seem even more desirable to employers. Now that so many office workers have experienced remote work and Zoom meetings, the psychological barriers to accepting new technology in the workplace are lower.

The difficulties of obtaining inputs from distant, often foreign, suppliers during the early months of the pandemic suggest that companies may find it profitable to produce more inputs in-house rather than from suppliers in order to reduce delays in production resulting from long lead times and overloaded transportation systems. Managers are considering bringing into the company functions that they now purchase from domestic and foreign suppliers. The three decades' long transition of flagship American firms, such as IBM, Hewlett-Packard, R.J. Reynolds, and Dupont, from the vertically integrated structures of the post–World War II decades into today's focused "core-competence" organizations linked through value chains to suppliers around the world may be about to reverse direction.

With a new premium on quality control, shorter supply chains, resilience in crisis, and national production, companies are now considering internalizing some functions that they currently outsource. Vertical integration suddenly looks like a more interesting proposition. The investments that such a shift would require are ones that large firms would be better able to finance and integrate into production; so predictions about COVID-19 accelerating technology adoption suggest larger companies on the horizon. If we start our thinking about the future from the properties of new technologies and try to predict the shape of manufacturing firms of the future, they appear to suggest fewer small and medium-sized firms and fewer workers than in the past. On this view, today's large companies may end up generating a larger share of American production and a larger share of returns in manufacturing.

AN APPROACH TO MANUFACTURING THAT STARTS FROM THE FACTORY FLOOR

Here, we report on findings from a very different research approach. It's one that starts from the bottom up—from the people and the machines already in the plant and from the factory manager's conception of possible options. In order to carry out these "bottom-up" studies, over the past 30 years MIT researchers have walked through factories with managers in the United States, Germany, France, Japan, Hong Kong, and China. They have listened to these managers explain how they organize production, when and how they decide to buy new equipment, how they hire and train workers, and what they see as promising strategies for their business in the future.[12] In the MIT Task Force on the Work of the Future project, a sub-group of faculty and graduate students again focused on analyzing changes in production from the factory floor up. We interviewed owners and senior managers in 44 manufacturing companies in Ohio, Massachusetts, and Arizona, and leaders in 21 industrial ecosystem institutions, such as trade associations, community colleges, unions, and Manufacturing Extension Program offices.[13] In Germany, we visited 11 companies identified as having world-class advanced manufacturing systems. The U.S. companies ranged from a metal stamping firm whose owner described it as on "the cutting edge of low tech" to a photonics company on the far frontier of new technology. Of the 44 U.S. companies we visited between 2018 and the outbreak of COVID-19 in 2020, 10 are U.S. divisions of large multinational corporations, and 34 are small and mid-sized enterprises (SMEs) that employ fewer than 500 workers. Manufacturers in the latter size category represent 98.4% of all manufacturing establishments in the United States, and they employ 43% of all manufacturing workers.[14] Over half of all the companies in which we interviewed are ones that had previously been studied in an earlier MIT project, the 2013 Production in the Innovation Economy research; thus, we had information on many of the same companies at three points of time: 2012, 2018–2020, and early summer of 2020 during COVID-19. (On the selection of firms, see Appendix A.)

The puzzle of slow productivity growth in the U.S. economy has led us to be especially interested in technology and skills in the manufacturing SMEs.[15] The gap between the productive performance of these SMEs and that of large manufacturing firms has widened at the same time that economists have shown a widening gap between the most productive frontier firms and other firms in the same sector.[16] These gaps raise questions about why diffusion of best practices from the most productive firms may have slowed, and what public policies might do to accelerate it. Over the past 50 years, preliminary analysis of SME defense contractors by Benjamin Armstrong has highlighted a widening productivity gap between large manufacturing firms and small and mid-sized manufacturing firms. In the early 1970s, the productivity (measured in shipments per employee) of large manufacturing establishments—plants with over 500 workers—was only about 22% higher than in plants with fewer than 500 workers. By 2012, revenues per employee at plants with more than 500 workers were 96% higher than those at smaller plants.[17] Trying to explain slow productivity growth in SMEs and what appears to be their worsening relative performance seems a critical step in understanding the future prospects of U.S. manufacturing. When, why, and how manufacturing firms acquire new technology; how they find or train workers with new skills—these issues are central to figuring out why productivity lags in smaller companies.

The key questions we asked in all of our 2018–2020 factory visits were simple ones that we posed in the formal interviews and pursued as we walked with the managers across the plant floor. "What technologies did you buy over the past five years? What new skills did you need to work the new equipment? Where did you find people with those skills? What happened to the person who used to work on the old machine?" We had read the literature predicting a massive wave of robots replacing workers over a 5- to 10-year horizon, so we were surprised to find very few robots anywhere. Surely, if the process of robots replacing workers were to take place over the short period that Frey and Osborne or the publications of the World Economic Forum predicted in 2017, by 2018–2020 we should already have been seeing robots moving into the factories. But they were rarely present.

LOOKING FOR ROBOTS

The definition of an industrial robot we used was that of the International Federation of Robotics: an "automatically controlled, reprogrammable multipurpose manipulator programmable in three or more axes." If a 5-axis CNC (computer numerical control) machine were to be counted as a robot, we would have counted more robots in the plants, since several companies had recently acquired advanced CNC machines. But there are good reasons to distinguish CNC machines from robots, our colleagues from an MIT robotics laboratory suggested. Even though a CNC machine can do the same milling as a robot does, a robot can *also* be repurposed for functions like pick-and-place by changing out the end effector.[18] Roboticists think of robots as taking inputs from sensors and making decisions based on those inputs, as well as being flexible enough to perform a variety of tasks which the CNC machine does not do. So we decided to distinguish between purchases of robots and purchases of advanced CNC machines. We also ruled out including automated guided vehicles (AGVs), which are small mobile robots that are used to move parts from station to station across factory floors.[19]

In the Ohio small and medium-sized manufacturing firms we studied, one mid-sized auto supplier that we had first visited in 2010 was subsequently purchased by Japanese suppliers, incorporated into Japanese auto supply networks, and then experienced a major growth spurt. That company in 2018 had 105 robots in plants it now managed—and its Ohio workforce had grown from 120 to 260. But in all the other Ohio SMEs we visited, there had been only one robot purchase over the previous five years: a 6-axis welding robot to work on large tubular sections for a naval defense contract. In the Arizona SMEs, there had been three robot acquisitions; in Massachusetts, one. Indeed, even in the large firms (with over 500 workers) we visited, robots were scarce.[20] In one large division of a multinational company in Pennsylvania, we learned that there had been robots in the plant in the past; but when demand for the parts they were making with the robots fell off sharply, the job along with the robots was transferred to another division of the company. At the time of our visit, the plant had no robots. They were experimenting with a robot that they hoped to use for vision and quality control. The onslaught of rapidly advancing robots that we had expected to find in the heartland of American manufacturing was nowhere in sight.

Our research puzzle shifted as we sought to understand why there are so few robots on factory floors. We began to piece together an understanding of how technology acquisition takes place in small and medium-sized manufacturers. Manufacturing companies of this size are mainly suppliers that sell many different parts to customers in different industrial sectors. They are high-mix/low-volume producers that need to purchase and maintain equipment which enables them to make parts to sell to a varying set of customers. In a typical case of the firms we visited, the manufacturer's parts were heading to defense, semiconductor, medical, and sporting goods companies. More than half of the Ohio companies we visited (15 of 27) have had at least one defense contract since 2008.[21] A number of the SME managers commented casually in our discussions that their defense contracts were the ones that motivated and allowed them to finance the purchase of new technology. This suggests that U.S. Department of Defense procurement policies may play an outsize role in the entry of advanced manufacturing technology into manufacturing SMEs.

Robots are still not very flexible and not easily programmable for alternative uses. Several of the factory owners we interviewed volunteered that they wished they could buy a robot; but to justify such a purchase, they would need a larger single order than any they usually won. The owner of a firm that sells parts to Tesla told us that if only he had known four years earlier how much he would sell over the years to Tesla, he would have bought a robot. But Tesla did not make long-term commitments—in fact, U.S. OEMs are only rarely willing to do so. In a firm that makes metal roofing parts, the owner said he "really wanted" a robot and had once almost gotten a job big enough to make purchasing a robot a good business decision.

Equally telling for the point that today a robot is purchased only when a single operation that it can perform will be needed on a large, repeated order: those few companies we interviewed that had robots used them for only one and the same operation. An Arizona company told us that it had taken them almost seven years to figure out which one operation their robot could perform effectively. "What was the trouble? Why did it take so long?" we asked. "Hubris," they said. "We thought we could get it to do more than it could."

Why not reprogram the robot? Why limit it to a single operation and job? Part of the answer has to do with the physical properties and limitations of a robot available for sale on the market today: its grippers, its sensing capabilities, and its safety in the presence of humans.[22] But often, the obstacle is total cost. We heard during the interviews that the purchase price of a robot is only about a quarter of the total cost of installing a robot, a figure confirmed for us by Tom Ryden, executive director of MassRobotics. The rest of the cost is that of programming the robot and of all the work needed to integrate the robot into a workcell. A workcell might need an assembly line with a conveyor belt bringing parts to and from the robot between different steps; it might include a robot that picks parts out of a bin and adds them to an assembly, which would then need to be conveyed along to another step in the process in the plant; or it might have conveyor belts to bring parts to a robot for coatings or sealants. The workcell might even have a setup like that in a German plant where we watched a conveyor belt on an assembly line bring a 45-pound leaf blower to a robot which lifted the tool up, turned it over and around for final inspection by a worker, and then lowered the blower into a cardboard box that moved out on a conveyor belt into the shipping department. In all of these setups, there needed to be a control system and camera with a fence or screen to protect nearby workers.

An industry of professional integrators offers services to companies to assist in integrating the robot onto the factory floor. When we asked companies that had bought robots or that were considering a purchase about working with integrators, the comments were mostly negative. Sharing company information with an integrator raises fears of losing intellectual property. One CEO who had experience with trying to work with an integrator claimed that integrators sell their services by telling your competitor how they solved your problems. Whether true or not, it seems to be a widely shared sentiment.[23] The bottom line is that getting the robot to do a task different than the one for which it was originally programmed—and for which the operations leading up to and those leading away from the robot have already been installed—is very costly and requires skills that often do not reside within the SME. A disillusioned CEO told us of Yaskawa Motoman robots he had purchased in the 1980s that now took up space in a dusty back corner of his warehouse, and we heard of more recent generations of robots now standing idle on factory floors.

The challenges of integrating new technology are not only ones for small firms. A senior manager of one of the large multinational firms whose plants we visited in Germany and in the United States told us of the difficulties of bringing Industry 4.0 systems into plants: "It's usually not the software part of the process that's hard, but what the companies have not yet done in getting to 'lean.' We start by asking customers, 'Describe your process, and make a standard, and then digitize'…. it's a journey. It's hard asking customers for a value stream map, while they're saying, 'Let's start with artificial intelligence.' Industry 4.0 only works when you have standards. It doesn't work to connect your chaos; then you just get connected chaos."

WHY DO FIRMS ACQUIRE NEW TECHNOLOGIES?

Few of the SMEs are buying robots today, but virtually all of the companies we visited from 2018 to 2020 had purchased other new equipment and new software over the past five years. We visited plants with new and advanced computer numerical controlled (CNC) machines, 3D printers, laser plasma and water jet cutters, fiber lasers, sensors, servo-press metal stamping machines, and press brakes. Firms were also buying new software: SolidWorks, SAP data analytics, GibbsCAM CNC 3D software, and blockchain platforms. Many SMEs as well as large firms have acquired technology to capture data on production processes. Recording and collecting data has become a kind of badge of being an advanced manufacturing company.

One of the larger Ohio SMEs in our sample makes massive storage and construction equipment. This is very labor-intensive and high-skill craft work. The company recently invested $250,000 in a data analytics system (SAP-ERP) that monitors what each employee is working on at any given time and how long it takes to complete each task. The system works with barcode scans: Each employee has their own barcode; they scan their code when they start a new task and when they complete it. It used to take over a week for management to see how long certain production lines took to identify problems; now it takes a couple of hours. Managers can respond in the afternoon to what employees did that morning. The firm is nearly all unionized, and labor costs are high. The manager said that without these measures to improve productivity by 1% or 2%, they would be outcompeted by open-shop manufacturers. But they still haven't figured out how to use much of the vast quantity of data the system generates. Across many of the interviews in firms of all sizes, we heard the same lament: They do not know what to do with all the data they are registering and storing.

Across the sample, we found differences in the patterns of technology acquisition between SMEs and technology acquisition in large firms. A number of companies explicitly invested in new technology in order to reduce the number of workers they needed on the shop floor. The managers interested in new technology for its job-eliminating potential were mainly ones in large firms.[24] They described their ultimate objective as a "lights-out factory," or a "labor-lite" plant, one in which machines could do the full range of tasks that workers currently perform. Getting rid of workers would ease the problem of finding workers with appropriate skills, lower the wage bill, reduce the need for training, and minimize the hassles of dealing with the resistance to change that managers face whenever new technology is introduced. Several also added: Where there's a human, there's an error. The fewer the workers involved, the higher the quality and the productivity gains that could be made, they believed.

But an equal number of large company managers explicitly rejected this mantra. They told us that ideas about how to improve production often came from workers on the factory floor. It's the interaction between production workers and design engineers, they said, that drives changes in the plant that improve quality and sometimes lead to new products. A large U.S.-headquartered multinational described their technology development units, where young technically savvy employees work side by side with older workers. It was the old workers who really pushed the technology forward. The manager explained: "You can get machines that talk better than ever, but what we really needed were people who could understand what they were saying." He added: "To do Industry 4.0 to a German standard would cost a lot and we'd never get the returns. We need scalability and transferability." A plant manager of a large manufacturer in the Boston area told us what they aim for is not "lights out" but "lights dimmed," since most of the people on the shop floor are now sitting in front of computer screens analyzing output statistics, not standing on assembly lines. The number of workers in this Boston-area plant is half what it was 20 years ago. But managers believe they will always need people on the factory floor to be talking with their design engineers in order to get new product ideas and process improvement.

The German managers all insisted that with the automation that had already taken place over the past 40 years, they had eliminated all the jobs on the factory floor that could be cut. The only tasks in which the Germans saw future automation leading to job cuts were office jobs. Even before COVID-19, American managers of both large and medium-sized firms echoed the same predictions: that the next significant job losses would be in white-collar work. The enormous shift of office employees to remote work after March 2020 has undoubtedly accelerated this process.[25] The main objectives for Industry 4.0 technology that the German managers emphasized were greater connectivity among operations within the company, greater integration of their operations with those of customers, and greater control over quality.

Improving quality emerged in the interviews as a major reason for buying new technology. One of the large U.S. firms that sells robotic systems told us: "The majority of companies we sell automation to don't reduce their headcount. We sell on the premise of increasing productivity, but when we go back, no one's reduced their headcount. They buy welding robots and redeploy, but they don't fire anyone. What's changed? Quality is the number one reason people automate. Look at the quality of cars today." A major U.S. aerospace firm manager told us that automation was a way to get higher quality in an industry in which errors are extremely dangerous and costly, rather than a way to shed labor costs—which are a relatively small fraction of their cost structure.

The German managers emphasized ways in which Industry 4.0 automation would contribute to flexibility. They defined flexibility as the ability to make a greater number of different products and to fill smaller orders. A manager we met in a big plant summed it up: "Lot size one is the goal." The vision of a more flexible production system contains the possibility of a more vertically integrated enterprise less dependent on suppliers. What suppliers provide to their customers today are products and services that with current technology the large company cannot efficiently make in-house. With technologies like 3D printing that could produce "lot size one," the need for suppliers would be reduced, and lead times would be shortened. One of the large German companies described transitioning a product line from gaspowered tools to cordless battery-powered tools. Until recently, the firm had purchased all their batteries and electronics from suppliers. Now that their main product is changing, the managers define the new challenge as one of bringing more of the electronics in-house. They have already begun the process by making battery packs that they previously purchased from suppliers. A division of a large U.S. consumer goods manufacturer told us it had learned how to make it more profitable to bring in-house the direct online sales of its products that previously had been outsourced. An American aerospace company described using new equipment to make some components that suppliers once provided, because there was now only a sole supplier and its prices had risen. The company figured out how to make the component for less. From our small sample of 21 U.S. and German large companies, it is impossible to draw firm conclusions about the extent of the reversal of previous trends toward outsourcing whatever could be outsourced. But comparisons with responses from MIT research interviews with managers of large firms over the past 20 years suggest that some new tectonic shift in business models may be underway.

WHEN DO SMES ACQUIRE NEW TECHNOLOGY?

In contrast to the large companies, many of the SMEs we interviewed bought new technology only when there was a new job in sight that required the machine. One company bought a new 25-foot-long bed mill when they realized the laser mill they had could not produce the volume they needed for a customer with a big project coming up. They bought a third robotic welding cell for a job that covered most of the cost of the down payment on the robot. For working on this new equipment, they then had to hire press-brake operators and others with different skills than those of the current workforce.

A third-generation metalworking family firm we had visited in 2012 and 2018 now does 60% of its business with prime contractors for the U.S. Navy. The Navy urged them to use robotic welding, so the company bought a robotic 6-axis welding robot to work on large tubular sections for naval programs. The company had already been certified for automated welding, but it took four more years before the Navy certified the reliability of their robotic welds. This slowed down getting the funding and raised questioning again from older, more conservative family owners about the wisdom of acquiring equipment in advance of orders in hand. The only employees able to use the robot at the time of our visit were five welding engineers, Ohio State graduates.

Technology acquisition in SME manufacturing often means modifying existing equipment with new software and hardware rather than purchasing new machines. One contract manufacturer specializing in metal-stamped parts mainly for roofing and construction has been doing well and expanded the workforce from 65 when we first met them in 2012 to 80 in 2020. The revenue per employee grew from $300,000 to $550,000 over that period. Over the same years, the company started to add design services for some of its customers. As it became a "solutions provider"—the owner calls this "the Holy Grail of manufacturing"—they hired six engineers with master's degrees. When the owner thinks about new technology, though, his approach is to modify machines he already owns. Instead of buying servo-presses, they have added accessories to their old mechanical presses like the feed, which is now computerized, and sensors, which can determine if there are defects in the finished products. He explained: "There's no real benefit to us buying a new press—you buy an old one and rebuild it and put on high-tech accessories, then you've built all your high-tech stuff in-house." Still, the owner would like to have a robot, as it would waste less raw material. He told us that he is waiting until they have a job large enough to justify buying one.

Even when managers do buy new technology, they rarely get rid of the old. When new equipment is introduced, it enters the factory floor alongside the old machines. This layering of technology of different generations was a striking feature in virtually all of the SME plants we visited. One fourth-generation family-owned metalworking business owner proudly showed us Davenport milling machines that had been purchased by his father in the 1940s alongside new CNC machines purchased over the past decade. About half this firm's volume is in automotive parts; the rest is spread over diverse customers ranging from construction to guns. As the company expanded its capabilities over the past decade, the workforce grew, from 15 workers in 2009 to 55 workers today in a brand-new plant. The owner explained that the old Davenports on the shop floor turn out higher precision parts and higher volume output than he can get on the new CNCs, but on the old machines the setup time for each job is very long—about 20 hours a job. Working on these machines takes very experienced machinists who have developed their skills over many years. Far from getting rid of the old milling machines, the owner looks for every opportunity to buy additional used ones when other companies go out of business.

The new CNC machines can be set up more quickly, often in a few hours, by younger machinists with skills that can be acquired in an eight-week certificate training program in a local trade school. The CNC machines allow for smaller job lots and for being used by less experienced and lower-wage workers. The owner explained that having machines with these diverse capabilities makes it possible for him to bid on a wide variety of different contracts. In fact, the most recent and expensive of the new CNC machines were purchased during the pandemic and allowed the company to bid on a job making parts that would go into ventilators. Bringing in new technology alongside older equipment, waiting for new jobs before making new purchases, modifying old machines with add-ons, like new controls or sensors—these conservative practices have allowed the companies to survive and even prosper in rough times. Of the 21 companies in the group that we had first studied in 2012 and then revisited in 2018–2020 before the pandemic, all but two reported having hired more workers and doing more business than at the time of our first visit eight years earlier. (As for the two other companies: One was struggling because it had lost its main automotive customers who were offshoring; the other was heading to bankruptcy because of a disastrous acquisition.)

INNOVATING TO EXTEND FIRM CAPABILITIES

Those firms which did initiate new products and bought new technology to advance those projects were of special interest to our research team, because they suggested paths of adaptation that might lead SMEs to higher productivity and to internalization of functions that could root more new manufacturing in the United

States. Among these companies were ones that can be characterized as innovating to extend the range of products they were already making. One firm we had visited first in 2012 and again in 2018 makes thermal heaters for use in chemical processing in industries like semiconductors. They decided to expand their products' capabilities by embedding power supplies in the heaters and by developing "smart heaters" with digital controls linked to the internet. To develop the technologies they need for these new products, they had a lengthy and expensive search process to identify and buy an out-of-state company specializing in power supplies. They wanted the intellectual property, but even more, they wanted the highly skilled engineers and workers of the company they were acquiring. They needed those skills for work on developing the new smart heaters. In this case and others, a pattern emerged in which new projects drove the acquisition of new technology and then a search for workers with skills on the new technology.

At one Arizona firm (225 employees), they had been making the same product for 50 years—analogue load cells that measure force. The managers tried to figure out what else they could sell to customers. On the higher volume cells, they do use robots and automated visual inspection. But there are only limited possibilities for automation, because there are so many different sizes and shapes (some 16,000 SKUs). We observed people at workstations hand assembling tiny parts under well-lit magnification. There's much experiential tacit knowledge involved in making a load cell. The manager noted that there are 500 Chinese load cell manufacturers. But because of this tacit knowledge element, the Arizona managers are not too worried about protecting their intellectual property. They have now developed digital load cells and a variety of other services for customers. To make the new digital cells, they have had to hire electronic engineers; the old ones were all mechanical engineers. And they've added production engineers to work on customizing products for customers.

At a pipe company we first visited in 2012, the family business makes repair parts. Business was booming when we returned in 2018. The new manager was the niece of the manager we had interviewed on our earlier visit. The company founder—the current manager's grandfather—was a repeat inventor, who had also conceived a kind of "guillotine" to use in extreme cases to slice through and seal off leaks in pipes. Developing this took years. This is a typical story for U.S. SME innovators who have to rely entirely on resources they have in-house, without finding the kind of supports in technical assistance and finance that German or Chinese firms can locate in their ecosystems. The pipe company has finally been able to commercialize the new product and sell it along with services. Technicians go out along with the product to help carry out the delicate and risky operation. They offer a money-back guarantee if the operation does not succeed. Customers have also been asking for other services. In the past, they wanted a metal part; now they also want a design for the part, 3D models, and pictures. Customers want to specify paints and materials for extreme water temperatures in which the parts will be used. In 2012, there were two engineers in the plant; to develop the new products, they have hired seven more engineers. They have also hired salespeople with engineering degrees, whereas in the past they used salespeople who were independent agents working on commission.

As the business has expanded, the manager has purchased CNC milling and welding machines. They mill directly out of steel blocks in a day or two; welding and casting with the old manual machines could take up to eight weeks. One CNC machine cuts out six different steps on six different machines. The accuracy of the CNC machines is unbeatable on the manual machines. They no longer need to ship parts offsite to X-ray for quality testing. To work on the new CNC machines, they retrained some of the old operators. The manager met with all of the old workers two years ago and told them that customers wanted stuff faster. That's the wave of the future. She said: "Those of you on manual machines, either learn how to use the new machines, or retire, or leave." All but four agreed; one retired; one of the others would eventually come around. We asked: "Did you fire the others?" She said: "No. There was still work to be done on the manual machines."

When a researcher phoned to learn how the company was faring during COVID-19, the news was that they were planning a move to a much larger facility. This opportunity came up in the midst of the pandemic. When they move into the new plant, the manager plans to hire another 10 to 12 operators from vocational high schools with which the company now has joint programs. Some of the new hires will have had internships at the company. The operators will have basically the same skills as the current workforce.

We found that another spur to acquiring advanced technologies is extending the capabilities of a firm when it integrates functions that had previously been outsourced. An Arizona company, for example, described buying a robot to do brush nickel plating (of parts going to a semiconductor customer). Because of the health hazards of nickel plating, they had previously had this work done by a subcontractor. The robot, however, can be set off at a distance from the workers in the plant. Lead time with the outside supplier had been 14 to 28 days. Now that plating takes place in-house, lead time is down nine hours. They have started to deal directly with steel makers instead of with buyer middlemen. They now process and sell the products of their own recycling; previously they had paid others to haul the trash away. "Vertical integration has made things more complex and has allowed the firm to survive," the owner told us. Between 2012 and 2020, the firm's workforce grew from 500 to 600.

We checked on this firm during the pandemic and learned that they were doing well and had hired more workers. We asked about problems with supplies. They had a team working for three months to find alternative domestic sources for sheet metal, wire harnesses, fittings, magnets, cutting tools for the waterjet, and specialty copper that they had been buying from suppliers in Mexico, China, and Europe. The lead time on the German products went from 6 to 26 weeks. The biggest issue was transportation and logistics. We asked if in the future they would use domestic suppliers. They told us that instead they will try to make as many as possible of these inputs in-house. Their recent technology purchases have been ones to implement the in-sourcing, including new bandsaws, welding, box building, frames, and stamping. They are buying equipment to do nickel plating that requires complete submersion, and that means acquiring automated cranes. The firm also is investing in new software, since they plan a hybrid model with more people working and communicating from home.

HIRING WITH LOW EXPECTATIONS AND LOW COMPENSATION

In the interviews we conducted in 2018–2020 before COVID-19 hit, when we asked about hiring workers with the right skills, the response that came up again and again was the difficulty of finding *any* workers to hire. In fact, in those years, labor markets were tight and unemployment rates were low in Ohio, Massachusetts, and Arizona. Most of the companies turned to temporary work agencies for new recruits. After the temporary worker's first 90 days on the job, the company would decide whether or not to employ the worker on a regular basis. If they decided to hire the worker, they would pay the temporary work agency an extra fee.

This system produced the second major problem that the companies experienced: tremendous turnover and churn. One company reported annual turnover of 50%, while another described hiring 100 people from the temporary work agency and finding at the end of the year that they were able to keep only 10 of them on a regular basis. Interestingly, in both of these two cases, the companies found solutions that dramatically improved the situation. The first company raised wages and provided the new employees with more training—the annual turnover promptly fell to 10%. This company's workforce grew from 50 to 80 between 2012 and 2018. The second company had 12-hour day and night shifts, and had been paying a dollar an hour over the minimum wage. The owner acknowledged that in the years after the financial crisis, he had been "milking the recession." As Amazon moved into town and started offering $15 an hour and training, this employer (like some others in the Cleveland area we interviewed) realized he needed a new approach. He raised wages and said that while Amazon's promise of training had so far created less pressure on them than the wage hike, he could imagine people demanding that in the future, too. He began offering bonuses to current employees who recommended new hires and whose referrals resulted in new workers who stayed on the job. The bonuses were scaled according to how long the new worker remained. He reported: "Our turnover's slowed down a bit, but attendance is still an issue. If you miss a day of work, you get three points and missing 15 days can get you terminated. But if you work overtime, you can earn a negative point. One of the factory workers came up with this idea and it's working."

The dilemma of "no workers to hire" and the success of the solutions these two companies found to hiring and retention suggests there may not have been an absolute lack of people willing to work in manufacturing even in the boom years right before COVID-19, but rather a dearth of people willing to work long shifts for close to minimum wage and no training.[26]

Other interviews confirmed this picture by stressing the very minimal qualifications that employers were seeking. In a majority of the interviews, the employer said that no particular degree or training was essential for their entry-level hires; even a high school diploma was not necessary. What counted was "work ethic," and most employers defined work ethic for us as "showing up on time" and "showing up at all on a regular basis." In a somewhat more demanding mode, the employers talked about looking for people "who were good with their hands; who liked to work on their cars." A member of the research team who had participated in the factory visits of the 1980s that led to the MIT *Made in America* (1989) study remembered this qualification as the same one employers had emphasized 40 years ago.

HIRING FOR SKILLS

It was usually when employers focused on particular pieces of equipment—old or new—which were *already* on the factory floor that their thoughts about the kinds of skills they wanted to be able to hire became more specific and linked to particular kinds of training. When a worker with specific skills was needed, employers sometimes said the most desirable hire would be someone who had already had the same job—at another company. Absent that opportunity, employers favored workers who had had a short course on machines close to those the worker would use on the job, such as an eight-week credentialed course on CNC machines.

Most of the employers described community college associate's degrees as irrelevant to their needs. In terms that echoed common sentiments, the owner of a metalworking firm with 40 employees described a local vocational education technical school's program: "They have beautiful CNC and welding equipment, but they don't really train anyone." He described going to a local community college and offering to pay a student's tuition if the student would go to school in the day and work a second shift at night. He said: "We tried to get them into older machining equipment, but no one was interested. They're too busy with flashy stuff like 3D printing. But we're in mass production. I can't even make tooling less expensive with additive manufacturing. I don't need kids trained on 3D printing." None of his hires had previous machining experience. He looks for "basic math skills, basic aptitude and attitude, and people who show up on time and play well with others."

During the interviews we conducted during COVID-19, the manager of the metal-stamping firm who had described his firm as "the cutting edge of low tech," told us: "We were terrified back when we first applied for the PPP, and were planning for massive layoffs because we expected demand to stop. So we put in place a massive workforce education program to upskill people instead of furloughing or laying anyone off. We were going to use PPP funding to pay them—but we've been so busy with production we haven't had a chance to implement it.."

The manager noted that Precision Metalforming Association (PMA) has a metalform.edu online program with hundreds of classes on factory-related topics, such as tolerances, math, etc. "This has worked really well for us in the past," he said. "We've developed an internal curriculum in conjunction with a PMA consultant so it's specific to our company. We already spend three times more dollars and four times more hours on workforce education than our peer firms—it's not a coincidence we're doing well. We want to train both our older workers and new guys, especially because we aren't able to find press operators. In the old days, you could just put it in the newspaper, but now you can't get any pool of labor. So we 'hire aptitude and teach ability'—men and women; we hire nontraditionally, especially ex-convicts re-entering the workforce."

A manager of a metalworking firm with 200 workers said: "Community colleges push for associate's degrees. What works for us is on-the-job training." About a dozen of his workers were using Thors, an online program that starts with a pre-test of engineering abilities and continues with online tutorials. This manager pointed out that new machine interfaces on CNC machines have become easier to use, and so operators need less training. Work with 3D modeling and computer programs—in contrast to the paper blueprints of the past—is intuitive. Several older workers sitting around the table with the manager at our interview laughed and told us young workers have 3D "wired in their brains"—they've done computer gaming since they were kids so they don't need special classes.

WHEN NEW TECHNOLOGY DRIVES THE SEARCH FOR NEW SKILLS

For most SME employers, it was buying new equipment that triggered action on workforce skills. Sometimes, as in the pipe repair parts company and in the firm that purchased the 6-axis robotic welding machine, this meant hiring engineers. The company making immersion heaters bought another firm to acquire skilled workers who could develop new products. But most often, when managers brought new equipment onto the factory floor, they identified current workers and encouraged them to figure out how to use it.

One of the SMEs (mainly defense contracting; 95 workers) gave us an idea of how this can work best. The manager talked about buying GibbsCAM 3D software for its functionality for their new 5-axis CNC machine. The skills required for the software are a general knowledge of machining and ability to use computers, "a kind of marriage between machiners and programmers—a high school degree and maybe classes at community college, but the degree is not important." What matters is "to have a creative mind that can see something before it has been created." They chose "four strong leaders on the plant floor to learn the new software—group leaders, but not at the senior-most level, for the senior leaders aren't that interested in learning the new technology." These were workers young enough to be willing to learn new things, but experienced enough to be able to assess the quality of the product.

One of the workers they selected talked to us about his initial reluctance to accept the assignment and concern about whether he would be able do it. He ended up watching half-hour YouTube videos on his own and mastered the software. He talked about being able to import customers' software without a glitch and to do in seconds what once would have taken weeks. In the past, he said, they turned away business because the job wasn't worth the amount of time it took. Five years ago, it would have taken weeks of trial and error to make the curve on the blade of a jet engine; now the software does the calculations in seconds.

ASSOCIATION TO PROMOTE SKILLS

We found some managers who acted—independently of the immediate needs of their own firms—to band together with others to create programs for training young people in skills for manufacturing. In 2002, Roger Sustar, whose Ohio company, Fredon, is a manufacturing supplier in defense contracting, got together with a dozen other SMEs in the same sector and started programs to interest students in manufacturing careers. At the time, cooperation among companies in the same sector for any purpose was so unusual that some of the companies were concerned they might be violating antitrust laws, and consulted lawyers to be sure that cooperation for promoting training would not get them into legal trouble. Since then, the organization has flourished, collaborating with regional community colleges to create new degree programs in manufacturing. Today, the Alliance for Working Together Foundation (https://thinkmfg.com) has over 500 member companies. In Arizona, Modern Industries helped design a 3½–year apprentice program that is accredited by the state. Apprentices work full time while they are in the program, and they also take two community college classes each semester. All the Phoenix community colleges participate, and the company takes between six and a dozen apprentices at a time. The program involves performance testing and on-the-job experience. The community college develops a curriculum, and the apprentices select their own classes. The only common requirement is to complete a project, defined by the National Institute for Metalworking Skills (NIMS), a national standards and credential-granting association. These were promising cases of collaborations to develop a new skilled manufacturing workforce, but we did not find many such examples.

IMPROVING WORK

The introduction of advanced technology has changed working conditions for the better in some of the plants we visited. There has been a major campaign over the past decade to convince parents and young people that a manufacturing plant today is not the "dirty, dull, dangerous" workplace of the past. But our factory tours showed that the picture is still a mixed one. Where robots have been introduced, we could see that they often transformed tasks that had previously strained human bodies. A robot in a very large German factory lifted heavy tools that previously had been hoisted for final inspection by two workers. The new system was programmed to create a buffer zone of tools moving toward the robot and the single worker still needed on the job for the inspection. With the robot and the buffer zone, the worker could take a break when needed, and not at pre-determined times. It allowed the worker to choose to work more quickly at some times of day, and more slowly at other times. The robots we saw in a plant in Arizona that did metal plating and that spread chemical compounds on metal parts replaced workers who once had to suit up in protective clothing to ward off damaging chemical fumes.

Artaic is a small Boston company that makes customized mosaics for large commercial surfaces. Owner Ted Acworth programmed and set up robots to do the otherwise tedious task of placing individual tiles. But one of the firm's competitive advantages is being able to send samples out in two days. To make the samples, workers need to place tiles in sample squares manually. They use a device Acworth invented that he calls Whack-a-Tile, basically, a monitor set up horizontally with light directions to assist workers in putting the sample together quickly. Each Whack-a-Tile is set up to take best advantage of the individual work styles and hand positions of each employee. Aside from the ergonomic advantages for the workers, it allows the company to identify and teach best practices. When COVID-19 arrived, the factory was too small for all workers to practice social distancing. Acworth adapted the Whack-a-Tile so employees could work on them at home and did not have to move onto unemployment.[27]

At an Arizona small metalworking job shop, the owner had just replaced some old manual machines with new lathes (VF2 HAAS). With these, one person can deal with three to five machines—basically feeding in the metal stock with programming done by a programmer. On the old manual lathes, one worker dealt with one machine. The owner is also purchasing two 5-axis HAAS machines. He's now thinking of buying a robot that could feed the machines. Why these changes and huge capital expenditures in a small operation that works from week to week with 15 to 20 customers? He explained to us that before buying the factory 20 years ago, he had worked on a Boeing assembly line, which he experienced as "boring brain-dead work that no human being should do." He plans to retire soon and leave the business to his sons. With the new machines and a few trained workers, the sons' principal tasks would be to program the machines.

In factories where workers had been doing very heavy lifting or monotonous repetitive tasks, automation seems liberating. We saw in these firms the potential for automation to reduce physically stressful, "brain-dead" work. In these cases, adoption of automation to facilitate work depended on individual managerial decisions. We do not yet know what it would take to make such choices more commonplace.

IMPLICATIONS FOR MANUFACTURING AND WORKFORCE TRAINING POLICIES

What can we learn from this close-up view of manufacturing? First, there appears to be considerable scope for increasing the productivity of SMEs. The research we have conducted suggests that the most powerful lever to achieve this would be accelerating the process of new technology acquisition. Obviously, tax policy, interest rates, and the overall state of the economy are major factors in determining decisions on capital investment. Our observations of the very slow pace of introduction of new machinery were ones made at a time when the economy was booming: from 2018 until the outbreak of the pandemic in 2020. One of the main reasons to accelerate that pace is to bring equipment into the plants that would reduce the average time of jobs—as we saw, for example, with the new 5-axis CNC machine and GibbsCAM 3D software that allowed the defense contractor to accept jobs that would have taken weeks in the past and with the CNC machines in the pipe factory that cut down the time of making the parts on the old manual machines. Manufacturers also emphasized that automation improves quality and reliability. It advances toward the flexibility of “lot size one.”

A second desirable outcome to follow from a more rapid acquisition of new technology and replacement of the old would be an increase in demand for new skills and training opportunities. One might think that managers would see community college, vocational education classes, and workforce education as seeds for growing the broadly skilled workers they will need in the future. The reality we found was that most companies have little appetite for formal education and degrees. They want specific skills for specific tasks that they need done now. A virtuous process of demand for skills feeding into demand for workforce education appears to operate in quite another way. The sequence we saw repeated in firm after firm was first bringing in a new machine, and then looking for ways to acquire new skills. The managers would do this either by encouraging current workers to figure it out using materials on line or sometimes by hiring workers with new skills or even, as we saw in one firm, actually buying another company to get its skilled engineers and workers.

In the tight labor market of 2018 to pre-pandemic 2020, companies did snap up community college students, often before they even completed their classes and graduated. As one of the community college presidents pointed out to us regretfully, in tight labor markets the interest in technical education and enrollments drop sharply. The long-term dynamic that the interviews revealed is one in which acquisition of new technology drives and precedes the search for skills.

How to promote a more rapid acquisition of advanced manufacturing technologies and the development of new skills? For many manufacturers, the prospect of a new contract seems to be the key incentive. We learned in the course of the interviews that about half of the SMEs we visited had defense contracts from time to time. Defense procurement appears to play a major role in their technology plans. In some cases, a specific contract requirement (like the Navy’s demand for robotic welding) can be the spur for acquisition. In other cases, companies told us that by careful planning, they were able to buy equipment on defense contracts that they would subsequently use in their commercial market projects. We wonder whether there might be ways for the Department of Defense to design procurement from their prime contractors to provide additional incentives for technology upgrading in lower-tier suppliers. Whether or not such policy innovations are possible, it would be desirable to try to eliminate the current disincentives to acquiring new technology on defense contracts. As we heard in the interviews, the long process of certification of parts made with new equipment and the lengthy delays in payment that result have the effect of reinforcing old conservative instincts that hold back change. And in bad times, like the COVID-19 pandemic, the very unequal power relations between the large prime contractors and the SME suppliers make the latter vulnerable to pressures to cut their margins. On that point, too, procurement policies that addressed the needs of lower-tier suppliers could make a difference.

FEDERAL AND STATE PROGRAMS FOR MANUFACTURING

Another set of possible levers for promoting technological change might be federal and state programs that today support innovation in manufacturing.[28] Manufacturing USA, a federal initiative launched in 2014, today brings companies, universities, trade associations, and state government manufacturing initiatives together in 14 national "manufacturing innovation institutes," each focused on a specific set of advanced manufacturing technologies. Starting with America Makes, an institute to support the development and commercialization of additive manufacturing, the manufacturing institutes include programs on technical textiles, photonics, robotics, biofabrication, clean energy, composites, lightweight materials, digital manufacturing, flexible electronics, biopharmaceutical manufacturing, semiconductor materials, chemical processing, and recycling and reuse. Despite this broad range, which covers many of the technology fields in which SMEs work, we found only one of the companies we studied had had any significant interaction with the institutes. The active industrial participants in Manufacturing USA programs and the recipients of its benefits are large companies.[29] The original objectives of promoting development, scaling up, and commercializing advanced technologies obviously designated large companies with applied R&D capabilities and large-scale production as the most likely targets for involvement and support.

Today, however, we need to take a wider view of how the technological capabilities of suppliers affect the productivity of their customers and the overall performance of the industrial system. In order to implement policies that would take into account this broader perspective on the industrial system, new collaborations and divisions of labor may be needed between Manufacturing USA and the existing old federal programs targeted on SMEs. The largest of these federal programs is the 30-year-old Manufacturing Extension Partnership (MEP) in the Department of Commerce's National Institute of Standards and Technology (NIST). The principal objective of MEP has been assisting SMEs through outreach programs and consultancies to implement "lean" practices in the organization of their businesses. Recently, a few of the state MEPs have announced new programs to support the introduction of advanced manufacturing technologies.

Some states, like Massachusetts, have targeted support to SMEs in advanced technology areas. We interviewed a Massachusetts company with 15 employees working in flexible electronics, nanotechnology, and roll-to-roll lithography that won $2.3 million in a statewide competition (Massachusetts Manufacturing Innovation Initiative: M212) to build collaboration among small high-tech firms in the region. These are firms that often are one another's suppliers and customers. The winner told us of using the funds to buy a new electron microscope for one of his suppliers in the newly formed network in order to allow the supplier to improve the quality of his products. With old equipment, the supplier had not even been able to see the defects in the products they were sending out. Those defects then limited the quality and the kinds of products that their customers could make. The examples we saw of interdependencies in the industrial system suggest that a much larger-scale investment by national and state governments could make a big difference in accelerating the diffusion of advanced manufacturing technologies and practices and in closing the gap between the most productive enterprises and the others.

Such new programs would contribute in yet another way to manufacturing. They could help rebuild an industrial ecosystem which would provide semi-public goods like workforce training, diffusion of new technologies, support for innovation, shared facilities, and shared expertise.[30] SMEs could combine these with their own in-firm resources. In the post–World War II years in which American manufacturing was strongest, large vertically integrated companies provided many of the commonly available resources on which SMEs drew. Large companies supported the communities in which their plants were located. They trained their own workers, some of whom eventually moved into smaller firms. Large companies helped to diffuse new technologies to their suppliers. Local banks knew local companies and could provide loans for new projects and support during difficult times. Under pressure from financial markets and competition from the 1980s on, vertically integrated corporations became "core competence" companies. They outsourced and offshored production. The stream of common resources that had once flowed from these companies into local industrial ecosystems dried up. While the reality of the industrial ecosystems in the boom years of American manufacturing was perhaps never as bright as suggested in this brief sketch, the reality of the industrial ecosystem over the past 25 years is bleak. Each firm is on its own, with only the resources it has within its own control to draw on. The growth and expansion of community colleges, of various programs for developing manufacturing skills, of state-led support, such as that in Massachusetts, for innovation in small manufacturers have improved the picture somewhat, but "home alone" remains the common situation of U.S. manufacturing SMEs. A shift in federal and state manufacturing programs to extend their reach beyond large companies could help rebuild the industrial ecosystem.

THE IMPACT OF TECHNOLOGICAL ADVANCEMENT ON JOBS

What effects would an accelerated adoption of advanced technologies be likely to have on workers? Would raising productivity through the introduction of new technology lead to higher wages? Or to more job losses? Or both? A major concern has been whether automation and, specifically, the introduction of robots, would kill jobs. Empirical evidence from survey research in France, Canada, Germany, and the Netherlands in factories that have introduced robots shows a very mixed picture with jobs increasing in some early adopting businesses while declining in non-adopting competitors, jobs in some parts of the plant growing and in other functions shrinking, and jobs in firms engaged in international trade growing.[31] Our sample was too small to draw any general conclusions, but the SMEs we interviewed all had grown their workforce over the five years before COVID-19, even after introducing new equipment.[32] The pattern of layering new machines alongside old machines means that there was still work to do even for workers with older skills. Given the age of those workers, it seems likely that they will retire before the machines they work on are retired from the factory floors. In some cases, the old machines perform functions that cannot (yet) be duplicated on newer equipment, and the skills required to work on them have required years of experience. As these skilled workers disappear, the machines will likely also disappear.

However, the more promising pattern that dominated in the cases we saw was one in which the introduction of new technology led to upskilling of workers, either through the hiring of new workers with the requisite skills or, more often, through having workers learn new skills. In some cases, the machine venders come in to teach people how to use the new equipment. Often, workers turn to the internet for short tutorials on YouTube or Thors or other similar online classes. The success of a diversity of workforce training institutions, apprenticeships, and online programs that have been developed over the past decade and carefully studied across the country (South Carolina, Florida, Ohio, Tennessee, and Massachusetts) may lead to a greater willingness of manufacturing managers to participate and invest in these programs.[33] At present, however, the deep skepticism of many manufacturing managers about formal workforce education means that the route to skill upgrading, as the examples we have provided suggest, tends to run from the acquisition of new technology to the demand for new skills. As the worker who mastered GibbsCAM 3D software in order to work on a new CNC machine told us: "Technology takes a step, then workers take a step forward, too. People grow with the software."

THE FUTURE OF MANUFACTURING JOBS

Finally, we tried to explore what impact new trade policies were having on the companies. Could protectionism bring new jobs back to U.S. manufacturing? A few of the companies complained that the rise in steel prices made it more difficult for them to compete with foreign producers. Most of them, however, said they would be able to pass on the added costs to their customers. Not one of them had thus far been able to recapture tasks that had been outsourced to China.

One of the managers observed: "American manufacturing has been transformed. It's become highly engineered, highly specialized, and highly customized. I see this across all manufacturing. This is a different country. It's no longer the mass production of the past. So the mass production industries in China will not be returning to the U.S." Our observations in the factories suggest that it will take more than erecting trade walls around the borders of the economy to transform the activities within. The extraordinary resilience of the companies and their workers during the tough times of the 2008–2010 economic recession and then through the COVID-19 pandemic suggest that there are resources and energy that could be mobilized for the changes needed to make manufacturing again an engine for good jobs and growth.

Appendix A: How the Firms Were Selected for Interviews

The original sample of SME firms were drawn for the Production in the Innovation Economy (PIE) project. They were purchased from a data contractor who had identified them in a contract with the Small Business Administration to study "high-impact companies." These were defined as companies with "sales that [have] at least doubled over a four-year period and which have an employment growth qualifier of two or more over the same period." (Spencer L. Tracy, Jr., "Accelerating Job Creation in America: The Promise of High-Impact Companies," Corporate Research Board, LLC for SBA Contract Number SBAHQ-10-M-0144, www.sba.gov/sites/default/files/HighImpactReport.pdf). He sold PIE a list of all the firms with NAICS codes corresponding to manufacturing firms that had doubled their revenues and increased employment between 2004 and 2008. From them, we extracted a list of all 3,596 manufacturers that had more than $5 million in annual revenues and more than 20 employees. These firms looked to be at least reasonably healthy on the eve of the 2008 financial crisis. From these, we drew the 53 SMEs that we interviewed in 2010–2013 in Massachusetts, Ohio, Arizona, and Georgia. In 2018, we wrote to the firms that we had interviewed in Ohio, Massachusetts, and Arizona and requested a return visit. Before COVID-19 intervened to halt travel, we were able to reinterview 27 of them. To these we added 18 other companies in the same NAICS codes (mainly metalworking, automotive, and electronics) in close geographic proximity to the original sample. The new additions were drawn from data purchased from YourEconomy, a program based in University of Wisconsin's Institute for Business and Entrepreneurship.

Interviews in the 10 large U.S. firms were obtained through MIT contacts and other referrals, an approach often called the "snowball" method. Only three of them had been previously interviewed in the PIE research.

Three of the German firms we interviewed were return visits to companies that had been studied for the PIE research. The others were robotics manufacturers and firms identified by the World Economic Forum as "lighthouses" exemplifying transition to Industry 4.0. Julie Shah, Christopher Fourie, and Lindsay Sanneman led the research on the robotics and electronics firms.

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5 Autor, David H., David Dorn, and Gordon H. Hanson. (2013). "The China Syndrome: Local Labor Market Effects of Import Competition in the United States." *American Economic Review*, 103 (6): 2121-68.DOI: 10.1257/aer.103.6.2121.

6 See Chapter Three, "What Happened to Manufacturing?" in Suzanne Berger with the MIT Task Force on Production and Innovation, *Making in America: From Innovation to Market* (2013).

7 Lund, Susan, et al. "Risk, resilience, and rebalancing in global value chains." August 6, 2020. *McKinsey Global Institute*, accessed September 2, 2020, https://www.mckinsey.com/business-functions/operations/our-insights/risk-resilience-and-rebalancing-in-global-value-chains.

8 After icy winter weeks of interviewing in Ohio factories, the team dubbed itself the "Ohio group." The "Ohio group" also conducted the interviews in Massachusetts, Arizona, and Germany. Participants included Suzanne Berger, Susan Helper, Michael Piore, Elisabeth Reynolds, Lindsay Sanneman, Daniel Traficonte, Anna Waldman-Brown, Lukas Wolters, and Maggie Yellen. In Germany, Johns Hopkins SAIS Professor Jonas Nahm led the team.

9 See review of this literature in Lukas Wolters, *Robots, Automation, and Employment: Where We Are*. MIT Task Force on the Work of the Future, May 13, 2020 White Paper, accessed September 21, 2020, https://workofthefuture.mit.edu/research-post/robots-automation-and-employment-where-we-are/.

10 "Artificial Intelligence and Its Limits," Technology Quarterly, *The Economist*, June 11, 2020.

11 "The fear of robots replacing workers has returned: But do not expect tech-induced lay-offs just yet," *The Economist*, June 30, 2020, accessed August 26, 2020, https://www.economist.com/finance-and-economics/2020/07/30/the-fear-of-robots-displacing-workers-has-returned.

12 *Made in America* (1989) inspired subsequent MIT research projects on U.S. production. They are reported in *How We Compete* (2005), *Making in America* (2013), and *Production in the Innovation Economy* (2014).

13 The findings of the first year of this project which were based on work in Ohio are reported in Anna Waldman-Brown, "Redeployment or Robocalypse? Workers and Automation in Ohio Manufacturing SMEs," *Cambridge Journal of Regions, Economy and Society*. doi:10.1093/cjres/rsz027. The report on the ecosystem will appear as a separate document.

14 The statistics are from 2017 from the U.S. Census Bureau (Statistics of U.S. Businesses) and were released in March 2020.

15 Syverson, Chad, "The Slowdown in Manufacturing Productivity Growth." Brookings Brief, August 2016, accessed September 21, 2020, https://www.brookings.edu/research/the-slowdown-in-manufacturing-productivity-growth/.

16 Andrews, Dan, Chiara Criscuolo, and Peter N. Gal. "Frontier Firms, Technology Diffusion and Public Policy: Micro Evidence from OECD Countries." OECD Productivity Working Papers, No. 2, OECD Publishing, Paris, 2015.

17 Benjamin Armstrong's calculation based on Census of Manufactures, 1972–2012.

18 See the discussion of the difference between CNC machines and robots in: https://robodk.com/blog/difference-robots-cnc-machines/.

19 We saw AGVs in those German plants with wide enough aisles to allow them to maneuver safely; we saw none in the U.S. plants we visited.

20 We did not, however, visit any auto assembly plants, where since the 1980s robots have been installed on factory floors. Thirty-three percent of robots globally are in the automotive sector.

21 This figure comes from Benjamin Armstrong's analysis of data from USAspending.gov and from the data on SME manufacturers in the Small Business Administration's "Dynamic Small Business Search" database.

22 See: L. Sanneman, C. Fourie, and J. Shah (2020). "The State of Industrial Robotics: Emerging Technologies, Challenges, and Key Research Directions." *Under review*.

23 A more positive view of the potential of integrators emerges from research by Susan Helper, Robert Seamans, and Raphael Martins, "Who Profits from Industry 4.0?," December 9, 2019, unpublished paper.

24 With one exception: a small job shop where the owner planned to replace all the old equipment with new CNCs; get rid of all the current workers; and install his two college-educated sons as programmers of the new automated shop.

25 The magnitude of the shift can be overstated. Bick et al. "Commuting Patterns During COVID-19 Endure; Minorities Less Likely to Work from Home." Federal Reserve Bank of Dallas, September 1, 2020, accessed September 3, 2020, https://www.dallasfed.org/research/economics/2020/0901.

26 See also the analysis and conclusions of Andrew Weaver and Paul Osterman. 2014. "The New Skill Production System: Policy Challenges and Solutions in Manufacturing Labor Markets," in *Production in the Innovation Economy*, edited by Richard Locke and Rachel Wellhausen. Cambridge, MA: MIT Press. Paul Osterman and Andrew Weaver. 2014. "Skills and Skill Gaps in Manufacturing," in *Production in the Innovation Economy*, edited by Richard Locke and Rachel Wellhausen. Cambridge, MA: MIT Press.

27 Researchers visited Artaic and also contacted them after COVID-19. The company's experience was written up in the *Boston Globe*, https://www.bostonglobe.com/2020/04/26/nation/adapting-crisis-mosaic-maker-moves-its-factory-operations-employees-homes/.

28 Dan Traficonte. (2020). "Collaboration in the Making: Innovation and the State in Advanced Manufacturing." *Science and Technology Law Review*, 21(2), 328–375. https://doi.org/10.7916/stlr.v21i2.6830.

29 This account is based on a research memorandum detailing visits to three Manufacturing USA institutes and three rounds of interviews with the one Ohio company that had had significant interaction with America Makes. Dan Traficonte, February 6, 2020.

30 See *Making in America* (2013) for a longer discussion of these issues.

31 See Wolters, 2020.

32 Again, with the exception previously discussed of the two firms doing badly.

33 William B. Bonvillian and Sanjay E. Sarma, *Workforce Education* (forthcoming 2021). Cambridge, MA: MIT Press.