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Factories of the Future: Technology, Skills, and Digital Innovation at Large Manufacturing Firms

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Introduction

The manufacturing industry continues to occupy a central place in the American economy. Compared to other sectors, manufacturing plays an outsized role in overall productivity growth rates and innovation across the economy, and remains a promising source of opportunities for workers looking for higher wages. Understanding the contemporary dynamics of the industry can thus yield valuable insight into the future of work and the near-term prospects for growth-generating innovation and technological change. As other work carried out by the MIT Task Force on the Work of the Future has discussed, American manufacturing firms find themselves in a period of uncertainty as well as major opportunity.[1] A host of challenges, including technological advances, international competition, and potential reshoring waves resulting from the COVID-19 crisis and its aftermath, will all be brought to bear on manufacturers' strategies in the years ahead.

While Berger et al.[2] examined a cross-section of manufacturing firms that included a number of different types of manufacturing and firms of varying size, it primarily emphasized small and medium-sized enterprises (SMEs) occupying "high-mix, low-volume" niches within the industry. With regard to technology adoption and changes to the skill profiles of these firms, they observed for the most part firms undergoing incremental technological changes, few of which triggered sudden changes in firm strategy or major layoffs of workers. This SME-focused view from the field suggests that the manufacturing industry is indeed changing, though not at the breakneck pace that would make technology-induced unemployment a major concern.[3] If anything, technological change may be proceeding too *slowly* within manufacturing SMEs compared to firms of a larger scale, and policymakers may want to consider strategies for facilitating technology acquisition and faster adoption at these firms.

The situation may be quite different, however, at large manufacturing firms. Firms in this category employ over 500 workers, and often maintain branches in several locations spread out across the country and abroad. Unlike SMEs, which often lack the resources needed to stay at the technological vanguard, large firms are more likely to maintain the financial position, higher-skill employee base, and internal technical know-how that support adoption of the most advanced technologies to ensure global competitiveness. Large firms tend to be more capital-intensive and productive and are frequently the leading adopters of the most advanced technologies, which often eventually make their way into smaller firms as the business case becomes fully demonstrated. Large manufacturers account for the overwhelming majority of private R&D funding across the industry and are often the first to implement new management practices, which eventually make their way across the industry and into SMEs. If we seek a view of the technological frontier of the manufacturing industry, and all of its associated impacts on the nature of work, we need to look to large firms to provide this view.

This outsized role played by large firms is not a new phenomenon. While government has often sponsored initial innovations, large firms have long been the driving force of commercialization and diffusion of technological change in the industrial economy. The early pioneers of American corporate research, including General Electric and Bell Telephone, established large-scale industrial R&D labs only when they had achieved the necessary scale and position in the market to devote substantial resources to new research programs. Although the initial development of mass production principles was done by government agencies (e.g., the Springfield Armory in Massachusetts), mass production was diffused by large firms such as Ford, which developed innovative combinations of industrial machinery and assembly-line methods.[4] When the adoption of industrial robotics first began in the late 1970s and 1980s, it was large firms, particularly those in the automotive industry, that led the way. As MIT researchers conducted the Production in the Innovation Economy (PIE) project beginning in 2010, they reported that similar paradigm shifts in production techniques at the most advanced firms were possibly on the horizon.[5] Noting a number of potentially transformative new technologies, including additive manufacturing, advanced robotics, and a variety of connective technologies, PIE researchers concluded that a number of new manufacturing "worlds" appeared possible through different combinations of the most advanced technologies.

A decade after the PIE study, what shifts have occurred or are currently underway? What technological changes can we observe at large manufacturing firms, and what implications do these changes carry for skills and education, job quality, and manufacturing ecosystems? As part of its investigations of the manufacturing industry, this research team has taken a detailed look at large manufacturing firms to get a better sense for what the "factory of the future" may look like and what this will mean for the future of work more broadly. A spotlight on these firms may demonstrate the way in which the manufacturing industry as a whole is likely to move in the coming years; technologically sophisticated large firms may offer a window into the industry's future more broadly. Likewise, these firms can also inform a view of how the industry is changing based on what these firms are *not* doing. Since these firms are likely to be among the industry leaders in technology adoption and new production techniques, a *lack* of radical change may suggest that the industry is not on the verge of the kind of technological transformation that some have predicted.

It is important to note at the outset that large manufacturers in the United States are facing a series of critical challenges. Though large firms based in the United States offer a view toward the cutting edge in the domestic manufacturing sector, productivity growth over the past decade has been flat. Especially in recent decades, many have argued that pursuit of short-term shareholder value has constrained innovation.[6] Through shifting incentives brought on by increased financialization and its resulting structural changes, many large firms have offboarded much of their R&D and innovative capacity in the process of vertical disintegration.

China, in particular, represents a new and quite significant competitive challenge, and the Chinese government's Made in China 2025 industrial policy initiative promises to accelerate the dramatic productivity gains already achieved by large Chinese manufacturers in recent years.[7] This presents a serious long-term challenge that American firms as well as policymakers will need to confront. A close examination of the internal workings of large manufacturing firms can provide a window into the sources of productivity in U.S. manufacturing. Firms face a series of headwinds in the drive to increase productivity through technological and skill-based interventions. A careful ground-level view of their operations may yield useful generalizations upon which policy changes can be based.

In keeping with the Task Force's other work on the manufacturing industry, we sought to shed light on these questions through qualitative research techniques that gave us a detailed view of production at large firms. Quantitative research and even surveys tend to miss some of the critical and nuanced factors that are at play in the interaction among organizations, technology, and workers. Over the course of the past two years, Task Force researchers have interviewed 12 large manufacturing companies located in Massachusetts, Michigan, Ohio, and Pennsylvania. Our interviews before March 2020 usually included plant tours. Several of these companies were in the automotive subsector of manufacturing, one was in personal products, and one produced industrial products for a variety of uses. These firms all easily qualified under any definition of "large enterprise," as they all employed well over 1,000 workers, and nearly all of them had a number of branches across the country, if not abroad as well. The interviewees at these firms were usually upper-level management with in-depth knowledge of recent technological acquisitions and changes. These included operations directors, chief technology officers, research directors, and others in similar positions within their firms. Researchers conducted semi-structured interviews focused primarily on changes that had occurred at these firms in the previous five years: which new technologies had been acquired and why; what changes these new technologies had brought to the firm; how workers' tasks had been impacted or redirected; and what new skills were required to successfully implement these technologies. A limitation of our study is that in most cases we did not have interaction with shopfloor workers.

The information collected through this process was rich in detail and offered an in-depth view of processes underway at these firms. However, due to the limited number of firms examined in this study, we cannot draw general conclusions. Instead, we focus our analysis on examinations of detailed case studies, which can demonstrate certain concepts and point the way to broader trends without necessarily offering a definitive account of the phenomena being examined. Case studies are also useful here because they are *exploratory*; we take a concrete look at how large manufacturing firms are changing, while maintaining an openness to different and unexpected observations gathered at these firms. The point here is that, while this is not meant to be an exhaustive study of advanced manufacturing at large firms, it does capture some of the important ways in which the industry is changing and a window on possible futures for the industry.

A. OVERVIEW AND KEY THEMES

The large manufacturing firms observed in our study are in the process of substantial change, though the pace and ultimate direction of that change remain uncertain. Firms are experimenting with different models of cutting-edge production—incorporating new technologies into products, trying out new production processes, and looking to onboard new skills for their workers—but no single model appears to be emerging as a "consensus" model. Some firms, for example, are setting up pilot plants to test out highly capital-intensive forms of the "high-mix, low-volume" production niche usually reserved for SMEs. Others are placing big bets on newer technologies with uncertain development trajectories, such as additive manufacturing. Still others are taking a more low-risk route, bringing in technologies that have long been well demonstrated and that can deliver a clear return on investment (ROI).

What these cases present are diverse responses to a rapidly changing future for the manufacturing industry. There appears to be no one clear dominating path. Unlike the mass production revolution nearly a century ago, or the "lean manufacturing" paradigm shift that originated in Japan and spread to the United States beginning in the 1980s, no single new production system or technological paradigm has emerged. There are a number of new features that firms are pursuing, including the increased use of machine-to-machine communication, data, and cyber-physical systems—technologies some have grouped under the general concept of "Industry 4.0" — but these have not yet added up to a single new paradigm. A central aim here is increased *connectivity*, both within and between firms. These technologies promise streamlined machine-to-machine communication and analysis that firms can use to increase their own productivity and more seamlessly engage with their suppliers. The rollout of Industry 4.0 is still in an early stage, with lots of experimentation and proofs of concept. However, these do not yet amount to a coherent repeatable set of organizational practices or artifacts demonstrating substantial improvements in productivity. At this stage, Industry 4.0 technologies appear primarily as add-ons to already-existing practices rather than a comprehensive overhaul of production systems.

One commonality that did emerge from our observations, however, was that workers, whether on the shop floor or in the office, still have prominent roles to play in these firms and will likely continue to do so in the foreseeable future. We examined the impact of new technologies on a range of different manufacturing roles, including production workers, technicians, engineers, and managers. Though each of these roles is undergoing changes as a result of new technologies, they all remain vital to firms' production systems. As we discuss further below, the lights out factory—in which production is entirely automated and few to zero workers are actually engaged in the manufacturing process—remains a distant possibility even for these industry leaders, with rare exceptions. Many of the managers we spoke with have actually been surprised by how much they continue to rely on their production workers in their day-to-day operations and in spotting "pain points" in the manufacturing process in order to improve efficiency. However, there remains a great deal of variation in *how much* workers in different occupations (e.g., production workers, technicians, engineers, managers) are doing in the production process across different large firms, and what exactly this work looks like. In some cases, people experienced increased autonomy and skill demand, and in other cases there was either no change in autonomy or skill demand or a reduction in both. And, despite the fact that production in most of the firms we interviewed still involves a great deal of human labor, firms also vary in the extent to which they are trying to automate certain tasks and jobs. While many firms appear content with maintaining around the same number of workers on the production floor, others are more actively pursuing automation of some work that is currently carried out by their employees.

For the most part, though, we observe firms bringing in new forms of automation to solve issues of quality control rather than shifting the firm toward some completely automated lights out system. While labor replacement may have been a primary stated goal behind previous waves of automation, the managers we spoke with said that the goal of this newer wave of automation is not so much to replace workers but rather to increase precision, safety, and product quality.[8] As Berger et al. research brief on the manufacturing industry suggests, these large firms are using automation for tasks that are "dirty, dull, and dangerous" and not "value added," thus eliminating some of the least desirable parts of manufacturing workers' jobs. Consistent with the findings of the Task Force's final report[9], we found that these changes are not likely to produce a wave of mass layoffs, but may lead to slower hiring in the future.[10]

Technology implementation does not always go smoothly. For example, the interactions between new technologies and firms' existing systems often present serious challenges. As has been documented elsewhere, management practices play an enormous role in determining whether new technology is fully adopted and leads to higher firm performance.[11] New technology affects and is affected by power relations and workloads within firms, often in uncertain ways. The management of data, the "new oil" of the digital economy, can take many directions.[12] In some firms, for example, we observe data scientists using data from sensors to generate algorithms whose dictates technicians and supervisors are expected to follow. In others, already-overworked engineers are asked to work on technology implementation on top of their existing duties.

Some of the firms have also struggled with how to incorporate more “traditional” or domain-specific knowledge of experienced workers into the more automated and technology-intensive systems that they are trying to implement. First, this can require the codification of tacit knowledge, which presents a difficult challenge. Second, workers in various occupations sometimes do not get adequate training or a break from existing duties to learn new ways of working; they are sometimes not paid more even when they acquire new skills. For these reasons, workers may not be enthusiastic about implementing new technology. Firms have developed a number of mechanisms for onboarding these technologies and upgrading workers’ skills in the process. These internal organizational structures are critical to the process by which firms bring in new technologies and ensure that they can make productive use of them. As with technology acquisition itself, we observe a significant variation in training and upskilling strategies, many of which appear to be highly granular and tailored to the needs of specific workers. Managers did not always adjust the risks and rewards of the adoption of new technologies for different groups of workers. When they met resistance, they just assumed that older workers did not want to change.

New forms of individually tailored training can hit limits when there are deeper barriers to technological change at the level of the organization. In several cases, firms described company-wide “cultures” of technological inertness. Acquisition and deployment can be stunted by a deeply ingrained hesitancy toward new technologies on the part of firms’ employees. While often this hesitancy is held to be an inherent property of old organizations, or blamed on particular individuals, the sources of firm-wide resistance to new technology can often be found in firms’ incentive systems. Some of these systems make sense; for example, when a malfunction in a firm’s product can kill people, it is important to move slowly and not break things. Other disincentives for change can be inadvertent, such as large explicit or implicit penalties when experiments fail, or lack of allowance for a period of lower performance while new systems get up and running. In some circumstances, even though technological change would provide clear benefits at the firm level, the incentives built into particular departments or work groups can discourage adoption. New technologies also change power relations; Industry 4.0 provides new visibility to IT departments, for example.

Finally, a dominant trend across these firms is the increased collection, analysis, and visualization of data in the manufacturing process. Most of the firms interviewed have made substantial efforts toward digitization of their manufacturing processes, collecting information from these processes that they then hope to use to improve efficiency. Digitization represents a major opportunity for firms to increase productivity, but it also presents new challenges. The process of aggregating and analyzing data is a major technical hurdle, and requires that firms invest in new data science capacities and hire people with the right skills. Implementation of a data-intensive approach to manufacturing can also run up against some of the headwinds noted above. The push for digitization, often led in a top-down approach and sometimes thrust onto supplier firms by their OEMs, has led to some pushback from these firms and from their workers, who perceive (often correctly) that the new technology as implemented has more risk than reward for them. Some firms, by contrast, have found that digitization makes more valuable the tacit knowledge of frontline workers, who can help interpret anomalies in data and can suggest what data would be helpful to collect.

Most of these technologies have the potential to make all of a firm's stakeholders better off. As the final Work of the Future report points out, the technology implementation we study occurs within a nation of increasing inequality and eroded worker voice.[13] These factors hamper the equitable distribution of the fruits of technology and sometimes firms' ability to successfully implement new technologies.

We illustrate these higher-level findings through case studies presented below. The first section provides examples of large firms experimenting with new technologies and new production processes, and discusses how these changes reshape the structure of the manufacturing firm and make new demands on workers. The next section focuses on organizational and cultural change that affects how firms deal with new technologies. The third section considers examples of how firms are equipping their workforces to better handle the latest technologies. In the final section, we discuss the growing trend of data-intensive manufacturing, and describe the various headwinds that some firms have faced in trying to roll out ambitious digitization programs.

B. TECHNOLOGICAL CHANGE AND THE NEW MANUFACTURING

Large manufacturing firms are planning future factories, and in some cases are already setting up early models and pilot programs. This is inherently an exercise in prediction, since firms need to anticipate how markets will shift and which new technologies will become more sophisticated and more useful in the years to come. Firms must also examine their comparative advantages and decide how to remain competitive in an uncertain future. For all firms, new technologies will be a critical feature of the next iterations of their factories.

There appears, however, to be a variety of technology-intensive models, and firms anticipate adopting different models depending on their market niche. Increased technological sophistication at some firms allows for more flexibility, responsiveness, and customization in the production process rather than simply higher output. Other firms anticipate moving in quite the opposite direction, looking to automate the few remaining tasks performed by workers. Thus, there appear to be several manufacturing technological frontiers, some quite labor-intensive and flexible, and others closer to an even more technologically intensive form of mass production. Which route firms choose to take depends on a series of considerations, including the quality level of products; the organizational culture, including the relationship between management and labor; and the complexity of the production process. In contrast to the German firms studied by Shah et al., in the United States, large firm managers generally have a great deal of power to make these decisions so long as they are considered to be in the interests of shareholders; they are generally not constrained by unions or works councils.[14]

Case Study: A large industrial parts manufacturer looks toward a labor-light future

At a large manufacturer specializing in a number of industrial products and services, a select number of factories may soon be transformed into something close to the "fully automated" system of manufacturing that popular narratives on the future of work tend to envision. For large product lines used only in large-scale industrial machinery, the firm relies on a labor-intensive process and very few features of this process are automated. For smaller products, however, the firm looks constantly at new forms of automation and new ways of getting labor out of the process. Augmenting the drive to automate was a recent shift in the firm's strategy as it moved away from the highest-quality products and toward "just-good-enough performance," in the words of a high-level strategist. The firm no longer needed to place as much emphasis on "maximum performance," and this made the manufacturing process easier to automate.

To this end, the firm established a new factory in Europe that serves as a pilot plant for implementing a system of producing smaller components, which is more automated than the firm has ever developed. Even though the plant is located in a low-wage region for European standards, management felt that the expertise at this plant was right for experimenting with high-automation systems. The system involves extensive use of robotics, including collaborative robots (cobots), which can handle the smaller-sized subcomponents in this process, and relies on interconnected, Internet of Things (IoT)-heavy machinery—"flowlines of machines communicating with each other." While this is still not the lights out factory fully realized, it is certainly "labor-light," compared with the firm's already highly automated plants. The firm is now working on its next iteration beyond this pilot plant: The head of manufacturing R&D told us his goal in the next five years is "to make a labor-less factory."

Significantly, there is little customization of this firm's products at the scale produced in these automated factories, and, as noted previously, the firm does not need to emphasize tight quality controls in the process. This highly regularized and mid-tier performance niche appears to be a key variable in determining the firm's automation strategy. These small-component factories are already highly automated, however; so the next wave of automation that the firm undergoes is unlikely to displace a large portion of the firm's workforce, which will still play a necessary role in manufacturing large-scale components. Significantly, the firm is considering setting up new factories in the United States on the model of the European pilot plant. If labor-light production of these components can be shown to be feasible, the relatively high costs of labor in the United States will no longer be a barrier, and reshoring of production——but not necessarily jobs—is likely to occur.

Case Study: A large tire manufacturer experiments with high-mix low-volume production

The case noted above offers a vision for a future factory in which workers play lesser roles in the production process. In contrast, the majority of the firms we interviewed presented an alternative, one that is technology-intensive, digitized, and relies critically on a high-skill workforce during the production process for at least some products. In all of these cases, the firms are moving toward a more customized model of production. One case that best illustrates many of these trends is a large tire manufacturer's foray into "high-mix, low-volume" production. The firm decided to launch this project nearly five years ago, when firm leadership realized that there was a growing shift toward customization and specialization in the tire industry, particularly in the luxury car market, one that is likely to continue with the expansion of the electric vehicle (EV) market. This put the firm in a difficult position, as it did not have its production system at any factory oriented toward customization; it remained a true mass production–oriented manufacturer. Generally, batch sizes produced by this firm were in the tens of thousands, but OEMs had started to demand up to 20 different types of products for a single vehicle, which required a great deal of specialized tire production. The firm's competition abroad had caught wind of this trend, and had started to move into niche production that could compete in this growing market.

In response, the firm constructed a pilot facility in the Midwest where it stationed a highly skilled small team of engineers and production workers and used the most advanced technologies to experiment with mass customization. The goal was to achieve a new system of production that would be oriented toward batch sizes of about 75 tires, which had never before been attempted by the firm. Though the team planning the facility did not explicitly use the terms "IoT" and "Industry 4.0," most of the new technologies deployed in the plant were among those typically associated with those terms, including sensors and other data-intensive devices. The team was small, with only about 15 employees; each was highly skilled and needed competence in a wide range of tasks. Every new employee received a new title and job description: They were now "innovation techs" rather than engineers and production workers. The innovation techs included three to four people who were just out of engineering school, as well as 10 to 12 people who had been at the firm for many years with less formal training. The project required people who could understand the new machines and combine this understanding with knowledge gained over a decade or more. As a member of this team told us, "You can get machines that talk better than ever, but what we really needed were people who could understand what they were saying."

The firm brought in new and highly instrumented equipment, creating a "completely blank slate," which gave the innovation techs ultimate leeway in developing new techniques. Management felt that the project should not be situated within an existing facility, since there was a chance that the facility's "established ways of doing things" would affect the new system. After nearly a year of experimenting with different techniques, the pilot plant was "first tire ready." The firm's plan, pre-COVID-19, was to open a new plant in Europe that would use the techniques developed by the Ohio plant. Europe has a larger market for customized tires, and so stationing a plant closer to that market made more sense for the firm. To that end, the firm had sent teams from Europe to Ohio to inspect the plant and take note of what the innovation techs had developed and to translate it to the new European facility.

It is unclear the extent to which these high-skill, low-volume plants will characterize the company's production. Along with the effort to develop new production methods for customized production, the company also was embarking on an effort to close mass production plants in the United States and move them to Mexico, with a similar nature of work but much lower pay.

Case Study: A leading industrial equipment firm takes a bottom-up approach

Another large firm we interviewed appeared to have already undergone some of the changes envisioned by the firms noted above. This large industrial engineering firm provides equipment and automated solutions to manufacturers in a number of subsectors, including automotive. When other large firms are looking to automate, this particular firm works to identify and solve customer problems by providing the requisite hardware, software, and training. The firm developed many of these solutions in-house, as its plants actively innovate to address problems in production. By serving as the lead user of its own products, the firm can better meet the needs of its customers. Our conversations with the firm focused on its frontier efforts to move beyond automation alone by establishing fully connected factories, where the smart use of equipment and production data can allow for more nimble manufacturing—a vision often labeled "Industry 4.0."

The model plant we visited leverages cutting-edge data collection and processing systems to maintain high product quality and promote flexibility in high-mix, small-batch production. Teams of workers can gather on the plant floor to consult the safety and efficiency data displayed on a large, interactive screen. On a multiproduct line, a vision system tracks workers' hands to facilitate error prevention by allowing workers to spot issues in real time. Modular production tools allow for lines to be rapidly switched over. Automation does not assert a dominant presence; indeed, the plant reduced its use of robots after a sharp demand decrease in 2016 led management to close some highly automated lines. Instead, the plant's success grows, in part, from the firm's connectivity-enhancing sensor systems and software.

The plant leadership also emphasizes the importance of worker training and engagement. While new technology may demand a broader set of skills, it can also help workers in their plant add value on day one, with just a few hours of training. They also recognize the value of domain knowledge, gleaned from years of experience: The plant is developing a new training program that pairs recent graduates with workers nearing retirement. In general, both the plant and firm want workers to actively participate in the production and innovation processes: "I don't want them to have to accept [new changes, like new technology]," said one interviewee. "I want them to be part of the journey with it."

Indeed, the plant engages in a bottom-up approach to spotting inefficiencies in their existing systems and further improving productivity. Workers on the factory floor are encouraged to spot pain points wherever they might occur so that these can be resolved and the production system made smoother. The firm sees intensive worker engagement with management as the only way to encourage this kind of on-the-job problem solving. There must be worker "buy-in" and input from workers at all levels, and the workers themselves must feel that they are playing an active role in technological change at the factory. To that end, management works closely with workers when new technologies are rolled out and organizes meetings to ensure that they are well acclimated to these changes. Production workers were most involved at the problem definition phase; a centralized technology group generally formulated solutions. The plant has also added incentive-based programs to encourage workers to contribute. Workers can now receive bonuses for coming up with useful ideas that contribute to more efficient and flexible production. This approach has been rolled out by the company across its facilities in the United States.

This new Industry 4.0 system has already had many successes, spanning in complexity from a simple updating of older instructions for a certain technology to ideas for entirely new technologies that the firm can develop and implement itself. In one particularly striking case, a new idea from a factory floor worker transformed, with management support, into a fully developed software product used across the firm. The firm is now taking into account these experiences in looking to develop its own advanced factory. Significantly, the firm does not anticipate a return to the form of highly automated production that it relied on before the demand downturn forced it to pivot. Rather, it anticipates a deepening of the approach to flexible production that it has developed in response. On the demand side, the firm anticipates increasing customization and orders for small batch sizes. The firm thus envisions a more connected and digitized version of the factory it currently operates, with continued opportunities for worker input.

C. ORGANIZATIONAL AND CULTURAL CHANGE

For large firms, maintaining the technological edge requires a host of organizational and institutional capabilities to implement new technologies. Technological change within these firms is often a highly deliberate process; technologies are scoped out, assessed, and then brought into the firm usually in a pilot process. This is another way in which large manufacturing firms at the technological frontier differ from their SME counterparts, which tend to approach new technology acquisition through more ad hoc systems, a result of more limited resources and capacity to plan. Below, we present cases that illustrate how large firms have organized their approach to new technologies and the changes they will deliver. Again, we observe a range of approaches, particularly with respect to the *pace* at which firms are willing to proceed with certain new technologies. While some firms are making "big bets" that cutting-edge technologies will result in expanded new markets and sources of profit, others are moving forward more slowly and in a piecemeal fashion, acquiring only technologies demonstrated to deliver immediate returns on investment.

Acquiring new technologies can also pose serious implementation challenges. Certain technologies require that workers receive new training, and there is occasionally a mismatch among workers' current skill sets, team organization, and the demands of newer technology. In some cases, workers resist new technology: They may feel threatened or feel that they lack the incentives to invest time and resources to adapt to these changes. These challenges require organizational structures and a firm culture to facilitate change. A company culture and the general attitude among its workers toward new technologies can play a major role in either facilitating or delaying technology acquisition and internal change. Beyond the issue of culture and attitudes, new technologies may shift internal power dynamics between groups. For example, they may give new discretion and control to information technology (IT) workers, who focus primarily on software and connectivity, at the expense of operational technology (OT) workers, who deal mainly with hardware and controls, and might feel as if they have lost out in the process.

Here again, we observe a significant degree of variation in the willingness and capacity of firms to adapt to new technologies. While some firms appear to be held back by deeply ingrained practices and cultures of slow adaptation to technological change, others are forging ahead and making bold advances into new areas outside their traditional core competencies. The firms in this latter category challenge a common notion about large manufacturers as being technological laggards—compared with the more fast-paced and "disruptive" giants of the tech sector. Our observations suggest that despite being legacy companies with decades—if not over a century—of established practices, these firms are indeed capable of serious disruption and new initiatives that put them on the cutting edge of manufacturing technology. Moreover, excursions into new technological territory do not have to involve the whole company or put core business models at risk. Firms can experiment with new technology through more modular adoption to change particular "cells" within a production system rather than the entire production floor. In other cases, firms have found it best to start with a clean slate in developing new production techniques, creating entirely new factories that can be designed with new production demands in mind.

How to retain the best features of the "old" ways of doing things along with legacy systems while moving into new technological areas is a puzzle that these firms are still working out. Indeed, many of the skills and domain-specific capacities that these firms have relied on for years are useful when taking on new technical challenges. Firms have developed various means of combining the domain-specific, legacy knowledge of experienced workers with the newer technology-savvy skills of younger workers. In many cases, firms looked to combine the synergy of this "older" form of knowledge with the "newer" technologically advanced knowledge to create the most effective use of their workforce's skill set. Technological change at these firms appears to be both disruptive and continuous, since the use of new technologies requires marshaling many of the techniques and capabilities built up at the firm over a longer period. Three cases below illustrate these trends in different contexts and with varying results.

Case Study: An automotive OEM struggles to digitize

As noted above, some large manufacturers have struggled to break with rigid work cultures and long-established ways of doing things when trying to introduce new technologies. One large automotive manufacturer we interviewed serves as a prime example of this phenomenon. Recently, this firm had initiated a company-wide effort that would represent a major leap forward in bringing digital tools into manufacturing processes at new and existing factories. This digitization effort would link key features of production processes together and streamline efforts to spot inefficiencies and redundancies in a wide variety of tasks. It would also introduce the use of "digital twins," an emerging technique that models a physical artifact in digital space so that the predictive analysis can be carried out without having to examine the device itself. The digitization campaign would also encourage blending descriptive analytical models with 3D modeling rather than information presented in narrative form, which is difficult for the firm and its suppliers to incorporate, for example, in models that allow the prediction of likely failure modes. Overall, the digitization effort aims to increase efficiencies along the course of the firm's manufacturing cycle—from upstream design phases to the shop floor itself—and to reduce waste at each point along that cycle.

Managers believed that the major barrier to implementing such a program was the firm's deeply ingrained culture that can make it difficult to introduce new ways of doing things. While there are certain teams within the firm that are more agile and adapt to new technologies and methods, these are predominantly the groups that "started from scratch"—for example, the autonomous vehicle (AV) research group. For more long-standing employees in well-established units within the firm, our interviewees said resistance to new technologies is common. This attitude exists even at senior-level management: As one interviewee put it, "The short answer is everyone is a barrier." Compared to newer automotive companies, it is more difficult to break existing work habits and expectations: "It is harder to change something that has been in existence for such a long time." Compounding this ingrained resistance to major overhauls like the digitization initiative is the fact that the firm's different work teams remain highly siloed, with little communication across groups. So, while certain teams are generally in favor of technological upgrading, this enthusiasm does not spill over into other parts of the firm's workforce.

Part of the challenge in introducing new systems and technologies into the existing legacy system are the implicit and explicit incentives that exist within the firm and across its suppliers. As an example, when it came to making later-stage changes to the design of a product with a supplier, the firm's design-change management process created a great deal of waste and "non-value-added" tasks due to inconsistencies in file formats while sharing information. When designs came in from suppliers, managers would have to reformat and recheck them in order to avoid inconsistencies, a process that generated a significant amount of extra work and further back-and-forth with the suppliers. The firm delayed streamlining this system with new software, because the managers who do this work are not incentivized to reduce these inefficiencies.

Managers can even become "territorial" about these kinds of changes and actively resist them, as they would potentially reduce a major part of their daily tasks and threaten their job security.[15]

However, the firm had some successful experiences rolling out new technology in other plants. In introducing cobots equipped with machine vision systems to replace human inspectors, management and the union carefully addressed some of the incentives and fears mentioned above. They placed a cobot in the break room before it was introduced on the shop floor so that workers could interact with it informally and gain trust in its safety features. New jobs in the plant were found for the inspectors before the rollout. This pre-planning took time but ultimately gave the company buy-in from long-tenured workers who understood the causes of many defects and worked together with engineers to properly calibrate the vision system, which initially reported many false positive indications of problems.

Case Study: An automotive manufacturer prepares for the electric vehicle revolution

Like the tire manufacturer noted above, a large automotive firm also began exploring the potential for increased flexibility in the manufacturing process. In doing so, the firm began to envision what this form of production would look like. Anticipating a major expansion of the electric vehicle (EV) market, and in particular EVs that run entirely on battery power, this firm has begun to plan out its own new EV factory, taking into consideration what technologies and skills will be necessary to transition to full EV production. Importantly, the firm projects that the expansion of EVs will increase the demand for "differentiated customer experiences," meaning more customized cars for different needs. Predicting that personal ownership will decrease dramatically in the coming two decades and that ride-sharing and other alternative forms of vehicle use will increase, the firm anticipates that cars and EVs in particular will become increasingly customized products to meet specific demands of different "customer personae." If demand for custom EVs increases, the firm believes it cannot afford the lengthy time period that customized auto manufacturing can take (often up to six months), and needs to develop a system for high-speed customization.

The firm is thus implementing plans for a new EV factory that makes use of a set of technologies that facilitates connectivity on the plant floor and rapid pivoting on the production line. The factory involves little fixed automation. Instead, the production process will be quite labor intensive, with employees working in flexible "cells" that rely on various augmenting technologies, including "external reality" (XR) vision systems to facilitate rapid inspection, collaborative robots (cobots), and exoskeletons. The production system will also require intensive use of real-time data, so that workers can immediately spot defects, which may become more frequent than in classic mass production techniques. With the implementation of these new technologies, the firm envisions a number of new high-skill job types emerging—or already-existing jobs becoming more important—including autonomy engineers, digital twin technicians, predictive supply network analysts, and robot testing coordinators.

To meet the technical demands of efficient customized production, the firm anticipates major investments in both technology *and* people. Workers will play essential roles in these future factories, and they will likely be higher skilled than the firm's current workforce. Cultivating such a workforce will raise substantial challenges, however. The firm has already observed a reduction in job applications from individuals with IT-intensive backgrounds; if this trend continues, it may be difficult for the firm to recruit the necessary number of technology-savvy engineers and production workers. The firm has thus begun to consider how to equip already-existing employees with the skills to use the technologies noted above, and has launched two external research partnerships with universities in order to develop new training programs toward that end.

Case Study: A welding firm makes a big bet on additive manufacturing

Other firms are more aggressive and willing to tolerate changes in technological strategy. At a large welding machinery firm, technology acquisition has always been a critical part of the firm's business strategy, and has long been on the cutting edge of the latest technology waves. This firm embraced the robotics wave of the 1980s and was already using digital interfaces and connectivity tools in robotics by the early 1990s. It continued to make advances in computerized power supplies with digital sensors into the 2000s, which had a dramatic impact on welding productivity rates. In many ways, the firm was "ahead of the curve" and had to wait for the market and customers to catch up to fully implement its new tools.

For its next big step forward, the firm has made a big bet on additive manufacturing, and has invested substantial resources into a new additive branch. Additive manufacturing is a growing subsector, but its full potential remains uncertain, and it is still largely confined to one-off customized production.[16] The firm anticipates a highly expanded market in the coming years—estimated at $250 million by 2025—and believes it is well situated to be a leading player in additive manufacturing, since many of the technological bases and skills needed for welding are transferable to 3D printing. As one representative told us, to be really good at 3D printing "you need to live and breathe welding, and that's what we do." The firm also uses a tightly managed supply chain and can ensure the quality of the materials used in metal 3D printing products. Customers routinely ask the firm for traceability back to steel suppliers, and the firm can provide this information. The firm aims to specialize in large-scale specialized parts that might take months to build using traditional tooling methods. With 3D printing, the firm aims to deliver these parts in a matter of days rather than weeks or months.

While a market for these large-scale specialized parts already exists, it is unclear how much it will expand in the coming years and whether this shift toward additive manufacturing will really pay off. However, this example offers a striking case of a firm able to take a major risk on a new technological domain by adapting its legacy specialization to a new context. The firm credits a culture of consistent technological adaptation for this ability. Additionally, worker buy-in and existing incentive structures have reduced internal resistance to change; while at other firms the introduction of a major new technological domain might be confronted as a threat, workers at this firm see new technology as an opportunity. It is this combination that allows the firm to effectively combine the old and the new in moving into an entirely new market.

D. NEW TECHNOLOGIES, NEW SKILLS

As noted above, major technological changes often make new demands on workers. When piloting a new program, venturing into a new technical area, or attempting to increase productivity with new technology, firms have to devise ways of helping their workers adapt to new technologies and gain the necessary skills. In some cases, production workers lose autonomy over decision-making to robots; their job becomes manipulating parts for which robots (at least for now) lack sufficient dexterity, while meeting hourly production targets recorded on "digital dashboards." In other firms, as they incorporate new technology, employees across the board begin to work in higher-skill roles. In these instances, new technologies implemented on the shop floor often lead to production workers acting more like engineers, with a more sophisticated technical understanding than what had been required of them previously. This in turn can "trickle up" to managers and coordinators, who increasingly take on roles involving data analysis and planning.

Upskilling of this kind requires deliberate strategies to train employees and provide them with new skills. The predominant method that we observe in these large firms is for the firms to develop their own training programs in-house rather than rely on external institutions. This ensures that employees are equipped with the skills most relevant to the new tasks that they need to perform. In our observation, firms prefer a much more tailored approach to training, even going as far as to gear training programs to individual workers' experience and needs. Rather than firm-wide blanket programs that aim to impart the same set of skills across the board, these firms are experimenting with more personalized training as an alternative path. The examples below demonstrate some of these trends.

Case Study: High-skill production work at an automotive parts supplier

A decades-old, multinational Japan-based Tier-1 automotive parts manufacturer has been successful in integrating old and new technologies. The firm has long been situated at the technological frontier, and has made a number of major investments in new technologies over the past two years, particularly in IoT, vision systems, and advanced process controls. The equipment on the factory floor is highly interconnected, and rich data is generated to track the operations of various machines. Much of this real-time data is used for predictive maintenance, and the multinational has achieved significant cost savings through the careful monitoring that sensor-based predictive maintenance allows. The firm's North American factories have developed a highly integrated method of monitoring: Each machine has a tablet-based display showing exactly what that machine is doing and whether any problems are likely to arise: "If you're walking around on the plant floor," one firm representative told us, "you can glance at the displays and know immediately what's happening." This information from a series of machines is collated into department-level displays, which in turn can all be combined into a single supervisory display monitored by higher-level factory managers who can easily "see the entire plant" and "glance over throughout the day and investigate any persistent issues." "In the old days," said this representative, "you'd have to do exploratory repair, change some pumps and see what works, or randomly guess at what's happening."

Interestingly, the managers we spoke with had different interpretations of the impacts of this new technology on the nature of work. Operational managers believed that the integration of these new technologies had made a number of new demands on the firm's workers, who have had to accommodate themselves to the factory floor's new higher-tech basis. As one interviewee told us, production work "used to be pretty straightforward," with a mix of basic mechanical work and some troubleshooting with shop floor machinery. The new IoT-heavy approach has intensified the features of the job that involve more technical knowledge and troubleshooting, since the monitoring technology alerts workers to problems before they arise, and shop floor workers are often expected to signal potential issues. Production workers have thus become "quasi-engineers" with a deeper understanding of the machinery and monitoring technology. The Canadian plant has found highly skilled shop floor technicians to be in such demand that they need to pay them more than leadership positions. In contrast, the firm's IT managers thought that the new algorithms allowed production workers to focus more on manual dexterity. They acknowledged the pressures to increase output, and argued that the algorithms they developed for predictive maintenance improved performance by eliminating reliance on technicians' "tribal knowledge" of when to replace components.

The firm believes that hiring degreed engineers is too costly, and has found that the unique set of skills required to run its interconnected system are not well targeted by any cost-effective external training programs, including those offered by local community colleges. Instead, the firm relies on in-house training to get its workers up to speed. The same shift has occurred with higher-level workers such as project coordinators. In the same way that the traditional role of production workers has been made more demanding and complex, project coordinators have become "quasi-data scientists," as much of their work now deals with the interpretation of collated information from a cross-section of shop floor processes. Rather than hire more actual data scientists, the firm has simply "asked people to do more," which again has forced these coordinators to learn new skills. Whether workers were paid more to do more was not clear. In some cases, one factory manager acknowledged that their data does seem to be replacing skill, and in the long run they may not need as many people on the shop floor.

The disconnect between IT and OT can make it difficult to turn data-rich knowledge into continuous improvements. One of the firm's U.S. factories had begun to collect data for predictive maintenance on a certain set of machines, as part of the factory's goal to "make invisible things visible" across their machines.

Without consulting the repair technicians, the firm turned their factory data into an algorithm that could simulate with 95 percent accuracy when the fans that cool a brazing line would need maintenance. When that model first indicated that those machines were in need of repair, the employees working directly with the fans (many of whom had 30 years of experience) doubted the data scientists who had never worked on the shop floor, and resisted the directive to perform maintenance. Yet, the predictive maintenance algorithm proved correct; eventually the factory workers came around, and the firm realized they "don't need to be firefighting as much."

In the firm's identical Canadian factory, similar predictive maintenance algorithms allowed the plant to go from three or four fan-related catastrophic failures per year down to four years without any unplanned fan downtime. This example illustrates the transition that is ahead for many workers. "The most complex thing isn't the equipment or technology; the most complex thing is what people value," said one senior manager. "Our maintenance people love swooping in with their capes and fixing equipment. They'd say the job is to fix something, but I'd say a better job is to stop something from breaking!" However, implementing this seemingly common-sense idea is not straightforward. Supervisors may feel technicians are not working hard if they don't see them fixing urgent problems; technicians may worry about their job security if there are fewer urgent problems to fix. Firms need to adjust incentive systems to ensure workers value these efforts.

Case Study: Planning technology acquisition and skills upgrading at a large automotive firm

One large automotive manufacturer provided a good example of the slower and more deliberate approach to technology acquisition noted above. At this firm, technologies are carefully assessed for their immediate impact, and they are only brought in after a full implementation plan has been developed. As the firm looks toward a more EV- and AV-intensive future, technology acquisition is key to maintaining flexibility in production lines and in preparing the firm for potential major changes in response to shifting markets. Once new technologies are identified, the firm extrapolates from these technologies the skills that it needs workers to develop. In a cyclical fashion, the firm thus begins with technology decisions, then decides which organizational changes are needed to accommodate these technologies as well as which new skills and training programs are needed for its workforce. Finally, it then uses the results of these efforts to inform decisions about further technology acquisitions.

An example of this iterative process began with a workshop which started with a careful review of over 70 different new technologies that the firm was considering. Workshop participants "went through the nuts and bolts" of each technology, asking if the firm was ready to implement the technology in the short term, whether the firm could afford to do so, and what new skills operators and production workers would need in order to work effectively with the technology. They also asked whether the new technology would require any organizational change on the plant floor and whether these changes were advisable. From there, the management team prioritized the different technologies for adoption based on market predictions and feasibility.

Once decisions were made about technology adoption priorities, the firm focused on equipping employees with the necessary skills. The firm believes that employees can generally be brought up to speed fairly quickly, since the differences between new and existing technologies are often not significant enough to require training from square one. In those cases in which the employees do need to start from the basics, the firm uses training modules from external sources that are tailored specifically to certain technologies. The firm has also found that once workers acquire a new set of skills to work with new technologies, it becomes easier for these workers to adjust to new technologies further on; skill upgrading begets further skill upgrading. The complete set of training programs is ultimately highly personalized; the firm develops "a plan for every person," which fits training strategies for specific employees on specific machines. The training is spaced out over a period of time, and the employee continues to work while undergoing further training.

E. DATA AND DIGITIZATION CHALLENGES

As noted above, a common theme observed at a number of large firms was a new focus on data collection and processing capabilities in an attempt to locate pain points and improve efficiency. Nearly every firm we encountered had begun or made serious strides toward a more digitized or "smart" manufacturing strategy, in which information from machines and products is collected in a continuous process and used to further streamline that process. In some extreme cases, firms had already brought in data scientists. Digitization poses many challenges for these firms, however, even those that have been on the cutting edge of digital technology in their production processes for years. Gaining advantage from digitization in manufacturing is not just a technical matter of solving a discrete set of problems, but rather of making broader changes to firms' internal work patterns, cultures, and incentives.

While digitization is clearly a priority for these firms, full-scale digital transformations are still in an early phase. Most of the firms were exploring use cases to test out the benefits of a data-intensive approach, but these were fairly isolated within the broader range of the firms' operations. Collaboration between data-specializing employees and production workers—described to us as "getting IT to work with OT"—can also present a major challenge. Data scientists brought in externally often lack the domain-specific and tacit knowledge built up by long-standing operations workers and mechanical engineers and may therefore find it difficult to translate data collection and analysis into actual shop floor improvements. Likewise, production workers can sometimes be kept in the dark about the efforts at their firms to harness data and can be skeptical of its benefits. There appear to be several strategies for dealing with this disconnect, and some of the firms we encountered are already exploring these options. One possibility is to get operations workers and data analysts to work more collaboratively to help ensure that people working with data better understand the dynamics of shop floor decisions and that operations workers can better trust and see the benefits in a more data-intensive approach. Another approach is to upskill production workers and train them in the data models, or to hold joint training sessions on digitization with both OT and IT employees.

Case Study: An automation and Information systems manufacturer leads the way on digitization

At one large firm specializing in industrial equipment and automation devices, the process of digitization and introducing connectivity has already been underway for some time. On the production floor, metrics are gathered at each point in the process, and these are monitored continuously by shop floor workers. Much of this data-gathering is devoted to predictive maintenance, which has become increasingly precise in recent years. This can occasionally result in major changes: Recently, the firm's data-gathering indicated that the air on the production floor was becoming too dry during the winter, and so the firm installed overhead humidifiers that have made a substantial impact on product quality and processing time. The shop floor has an entire "control room" dedicated to monitoring assembly lines and anticipating problems. Previously, the monitoring process would check what needed to be replaced only once a week, but this can now be done in real time. The firm's increasingly data-intensive baseline has gradually made new demands on the workforce, requiring more fluency with digital technologies. "We used to say computer skills were optional," one representative told us, "but now everyone needs to work on computers." At this point, "everyone at the plant uses data, from manufacturing engineers on the shop floor to managers."

The firm has continued to expand its use of data and analytics as it looks for new opportunities to spot pain points. A major challenge to digitization, as discussed above in the example of the automotive firm that had begun a major firm-wide digitization overhaul, is firm-specific culture and resistance to this type of technical change on the part of employees. As one representative told us, "Culture eats strategy for breakfast." Without getting employees onboard with digitization, it is difficult for the firm to implement a comprehensive data-based approach and see its benefits. This appears to be, in part, not only a matter of retraining already-existing workforces, but also of bringing in new employees already equipped with skills in working with data.

The firm has also been on the front line of digitization in helping its industry customers scale up their own use of data. Recognizing that many of these manufacturers struggle with the "disconnect between OT and IT," the firm has developed a course designed to help operators connect with data specialists to figure out how to better utilize generated data. The firm is now developing a course that helps IT employees gain a better sense of the dynamics on the shop floor. Initially, the firm struggled with problems that arise when trying to get OT and IT to work together more productively. The firm has found that it sometimes has "too much data" to know how to analyze it in a way that makes sense. In the process of turning all this information into actionable steps for improvement, the firm has found that production workers and technicians need to play a key role in data interpretation and hypothesis generation. Only when hands-on experiential knowledge of the production process can be brought to bear on the vast amount of data the firm collects can this information be translated into new efficiencies. For example, in one case, a firm found a puzzling increase in defects during the winter in one plant but not in another; operators explained that dry air was the root cause. The plant solved the problem by installing misters and tracking humidity.

Conclusion

As these case studies illustrate, the prospects for new forms of technologically sophisticated, digitally enhanced manufacturing have shifted from theory into practice for many of the industry's largest firms. However, large-scale "frontier" manufacturing remains open to several potential directions. Among the firms highlighted in this brief, there exists a substantial degree of variation in both technological choices and approaches to skill building.

The cases lead us to several overarching observations:

1) Significant automation-induced job loss is not imminent or visible on the horizon.
Even among the most advanced firms in the manufacturing sector, technological changes do not appear to portend a coming wave of job displacement for manufacturing workers, nor do they indicate that a true lights out model for manufacturing is a near-term possibility. Firms are increasing automation and digitization, but in ways that build on already-existing capacities using the workers upon which they currently rely. In many cases, manufacturing workers are being asked to *do more*—in particular, to acquire new competencies with advanced technology—and in some (but not all) cases, they remain indispensable to firms in spotting pain points in the production process and in bringing their domain-specific knowledge to bear on newly incorporated technologies.

2) "Digital transformation" requires organizational transformation—but we saw much disagreement and confusion about how to achieve this. While proponents agree that data collection and connectivity are key to Industry 4.0, no single way of combining these features inside firms has yet emerged. Firms differ greatly in determining which new tasks are assigned to which occupations, and what incentives and decision rights people in those roles face. However, our cases reveal at least two areas where almost all the firms we studied have significant potential to streamline production and link up elements in the process that are currently disconnected. These include, first, better integrating the internal groupings within firms that are too often siloed from one another, such as the OT and IT units. Improving the relations between OT and IT—by, for example, familiarizing IT with the dynamics on the shop floor, or equipping OT with an improved understanding of new technology—would aid in the rollout of new technologies and help synthesize domain knowledge with higher-tech competencies. Second, new technology could be used to streamline *inter-firm* processes. The relations between OEMs and their suppliers, for example, could be made more efficient using shared digital infrastructure and platforms. A more seamless process of supplier-OEM interaction could lead to faster production cycles and iterative improvements. The ultimate effect would be a more robust supply chain, with suppliers and OEMs able to speak the same language and collaborate more effectively. However, appropriability issues have stymied progress in this area, as discussed below.

3) **Large firms could be better connected within their regional manufacturing ecosystems.** While some firms interviewed had relationships with some of the higher education institutions in their region, many of the industry's largest firms remain "home alone"—unlike their counterparts in manufacturing-heavy countries like Germany and Japan, American large industrial firms rarely draw on ecosystem institutions and shared resources. Despite major initiatives at the federal and state levels in the past decade, the national manufacturing ecosystem remains underdeveloped[17] with respect to training and supplier development. We found it curious how rarely external ecosystems came up during our interviews: With a few exceptions, such as one-off industry-university partnerships, these firms rely solely on their own internal resources in charting out their strategies. Reviving the "industrial commons," a robust shared set of assets and resources from which industrial firms can draw, could assist these firms in faster technology adoption and skill building. Though stronger connections between firms and the industrial ecosystem would be socially beneficial, individual firms currently lack the incentive to make ecosystem-based investments themselves, thus necessitating broader public interventions. New manufacturing-oriented institutions and scaled-up versions of those already established, such as the Manufacturing USA network and the Manufacturing Extension Partnership (MEP), could become more heavily integrated into the leading edge of the industry. With both deep uncertainties and major opportunities looming for the manufacturing sector in the years to come, new strategies for building up the industrial commons led in partnership by the federal government and state governments are worth exploring.

4) **When workers' opinions and ideas are incorporated into decision-making about technology adoption, firms have good outcomes.** Worker domain and systems knowledge proved valuable time and time again as firms looked to workers to identify pain points and facilitate technology adoption. This resonates with earlier research in the automotive and other industries that showed early introduction of workers to the adoption of new technologies led to higher firm performance.[18] Often, achieving these solutions is complicated by a lack of institutions for worker voice or poorly aligned incentive systems. Instead, management may dismiss concerns as "resistance to change." However, resistance to change is likely to be as much an organizational challenge as one at the individual level.

Even though management practices are a key determinant of productivity levels, and research confirms that strategies where technology is used to complement workers can contribute significantly, these practices are not well dispersed. Management is like technology in that diffusing new practices is hard, and delivers both private and social benefits.[19] Thus, manufacturing ecosystems should be strengthened with institutions to research and spread these practices, for example, helping firms to reduce their siloes and developing worker capabilities so that they can participate in innovation.[20]

5) Regional manufacturing training systems should blend broader, foundational knowledge provided by educational institutions with more specialized, on-the-job training provided by firms. Many of the firms examined here have begun to develop new approaches to training, some of which are tailored to the workforce at the individual level. While these firm-led strategies can be valuable for workers, they do not provide the broad knowledge that is required for new workers to gain a solid foundation on which to build more specialized skills. This more foundational knowledge can be acquired in partnership with educational institutions like community colleges or university programs. How to blend the broad training available at these institutions with the increasingly targeted approach taken by large firms remains a challenge, despite some promising examples.[21] One possibility is to use new forms of training, such as online learning, to make the transition from general skills to on-the-job specialties. These new forms can be productively combined with traditional institutions like apprenticeship, which combines foundational knowledge and on-the-job training. Given the aging workforce and impending retirements ahead, our finding that workers are still valuable at even the largest and most technologically sophisticated firms has important implications for education and training policy. We believe that manufacturing will remain a fruitful career path into the foreseeable future, even while the aggregate number of manufacturing jobs may not grow. It is essential to not only provide incentives that can bring the next generation into manufacturing training and education, but also more broadly promote manufacturing jobs as an option for students and trainees.

6) While the United States leads the world in digital manufacturing software development, it lags in its adoption. The United States has significant strengths in digital manufacturing, specifically its leading position in creating new software. Our interviewees at foreign-owned companies described a shifting of power over product and process design to the U.S. operations as more off-the-shelf software is incorporated into manufacturing. However, the United States also faces significant gaps in adopting digital manufacturing, and productivity growth has not been as robust as might be expected given all the new technology available. One reason for this gap may be the effects of financialization, which focuses on short-term gains and hinders investment in long-term capability building. Traditional skills in manufacturing, many of which are necessary even in a digitized world, have been weakened as a result. Some examples include knowledge of processes such as die making, forming, and machining.[22]

These six points provide a picture of the current landscape and horizon with respect to large manufacturing firms. There is significant transformation ahead for these firms if they are to maximize the benefits of new technologies while improving worker productivity and job quality. The country's ability to rebuild and grow the manufacturing sector and deepen capabilities in the industry will largely depend upon larger firms' success at this transformation.

The manner and pace of firms' adoption of digital technologies has effects that spill over into the rest of the economy. Done right, this adoption could spur significant investment in U.S. manufacturing, as firms compete on technology rather than on low wages, and could create good jobs as workers are involved in quickly diagnosing and solving problems, increasing uptime and generating innovative new products, and are able to share in the gains of their increased productivity. On the other hand, technology could be adopted in a way that, while not leading to a large decrease in job quantity, could significantly decrease job quality. Production workers might see themselves losing autonomy to robots, and facing stagnant wages, significant increases in monitoring, and pressures to work more quickly.

We see opportunities for new policies and practices by both the public and private sectors. Many policy ideas have been put forward about how to strengthen manufacturing in the US, including both policy recommendations that would increase private profits and increase social welfare. Our work speaks specifically to the following areas:

Encourage technology development and implementation that complements workers' skills. New software is being developed that makes programming and data analytics easier; robots can be designed to be responsive to workers. [23] Firms and government can encourage such developments by, for example, directing federal R&D toward human-centric technology development (like the NSF Future of Work at the Human-Technology Frontier research agenda), encouraging participatory design in manufacturing,[24] and including worker representatives in institutions such as Manufacturing USA.

More broadly, encourage greater technology adoption by large and small firms that takes a longer-term view toward productivity growth. Firms can increase productivity growth by choosing technologies that drive innovation rather than "so-so technologies" that have a minimal impact.[25] Businesses should consider adopting longer time horizons in which ROI can be accounted for beyond just one year; public policy should encourage this trend, for example with corporate governance reforms that encourage longer-term investment horizons.

Invest in manufacturing ecosystems to create the positive spillovers that come from a regionally connected system for educating and training workers and building capacity among SMEs within supply chains. Subsidize SME's investment in new technologies and organizational transformation so they are more capable partners. Incentivize communities to build their economic development strategies on their unique local assets, for example, by broadening the Defense Manufacturing Communities program to include non-military ecosystems.

Encourage the next generation to embark on a manufacturing career through incentives like subsidized tuition for training and education in work-based learning such as apprenticeships. Focus in particular on pathways from high school to further education in industry-recognized certificates or two-year degrees. Ensure that these programs teach fundamental principles of both "operations technologies" (OT) and "information technology" (IT).

Enhance education and research in management best practices for digital transformation that engage all stakeholders. Many of the actions listed above would be profitable for firms, but require a complex organizational transformation. Both public and private investments can ease this transformation by, for example, building upon the Manufacturing USA institute model to create public-private consortia focused on developing and diffusing innovative management techniques.

Ultimately, if there is to be a robust future for U.S. manufacturing, it will require new investments in technologies, organizations, and workers. Beyond that, however, there needs to be a broader commitment to shared prosperity. This requires strengthening institutions to improve job quality including increasing worker voice, expanding coverage of programs like unemployment insurance, and/or raising the minimum wage.[26] A strategy that supports workers, firms, and the broader manufacturing ecosystem to invest in the long term for a more competitive manufacturing industrial base will create significant benefits for the nation.

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15 One area of potential transformation lies in data sharing. In addition to using a common data-based infrastructure and shared standards, firms could pool their data with the goal of deriving higher-level findings for data-intensive manufacturing strategies. While some characterize data as the "new oil," in other fields, such as software, data for industrial uses has not yet been proven to be as transformative. Much of this may be due to the currently siloed nature of manufacturing data, as each firm attempts to reinvent the wheel in its own way. A potential issue is that "data as oil" is a flawed analogy: While both data and oil may be ubiquitous and important, data (unlike oil) is "non-rival"—many firms can use it at the same time. Thus, in principle at least, firms could share data and still profit from it. In fact, pooled data could be significantly more valuable than data held by individual firms. Large amounts of diverse training data are often required in the analytics and machine learning applications that power firms' digitization initiatives. If the current atomization of data could be overcome through new data-sharing/pooling strategies, data could be more readily utilized to improve firm and regional competitiveness, lifting all boats. Potential new ecosystem resources and institutions could aid in this process. For instance, consortia of regional firms could co-own anonymized (and harmonized) data as "commons" and help firms (and academics) spot emerging threats as well as creative opportunities to improve efficiencies.

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