Who Profits from Industry 4.0?
Theory and Evidence from the Automotive Industry[*]

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[*] We acknowledge helpful comments from Jim Bessen, Kristin Dziczek, Avi Goldfarb, David Keith, David I. Levine, Chuck Sabel, Jennifer Tae, and seminar attendees at Case Western Reserve University Department of Economics, Oregon State University College of Business, and the 2018 American Social Science Association, the 2018 Industry Studies Association, the 2018 Strategy Science and the 2018 Academy of Management annual meetings. We thank Gayatri Choudhury and Katrin Gurvich for excellent research assistance. We are grateful for financial support from the Boston University Technology Policy Research Initiative, the Kauffman Foundation, and the Joyce Foundation.

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Abstract: We develop a framework linking organizational and industry architectures to value creation and value capture, and apply it to the case of Industry 4.0, the coordinated use of digitally-enabled technologies like robots, sensors, and AI. We argue that if factory owners develop automation methods that capitalize on their greater access to the context in which production data is generated, they will be better able to prevent value from migrating to "digital entrants" that offer automation consulting and data analytics. Manufacturers can do this by adopting an organizational architecture that empowers shop-floor workers to combine their local knowledge with digital tools. Conversely, to the extent that digital entrants develop a more abstract version of these tools that they spread across industries, they will capture more value.

Keywords: value creation, value capture, automation, industry architecture, industry 4.0

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Introduction

Recent advances in artificial intelligence, robotics, and sensors will likely lead to many innovations, including autonomous vehicles and smart manufacturing (CEA, 2016). In manufacturing, the combination of these technologies is referred to as "Industry 4.0": sensors on robotics and other equipment engage in continuous collection of data in real time, wi-fi transmits this data to a central location and sophisticated software tools analyze this data and predict performance (Agrawal, Gans and Goldfarb, 2018). These new technologies are being developed and adopted both by traditional manufacturers and by firms we call "digital entrants" that offer automation consulting and data analytics.

A key question for business strategy is how value will be created and distributed among these groups. In this paper, we develop a framework that links organizational and industry architectures to value creation and value capture (see Figure 1). We apply our framework to the case of Industry 4.0, focusing on its development and implementation in the automotive industry. We find that the effect of Industry 4.0 on value creation and capture depends critically on a firm's management paradigm, and particularly how this paradigm influences views about the nature of knowledge in the firm (Cattani, 2006; Roy and Sarkar, 2016).

Notably in our setting, some managers believe that knowledge can be easily generated from data even if the data is separated from the context in which it was generated. Such a separation enables remote data analysis, facilitating a separation of brain work and hand work in accordance with the management principles of Frederick Taylor. Other firms follow a "Pragmatist" management paradigm which emphasizes that knowledge is context-dependent; thus, knowledge cannot easily be generated from data that is separated from the context in which it was created.

Many academics and practitioners implicitly assume that context is relatively unimportant, that data can be aggregated fairly easily. For example, Frey and Osborne (2013) argue that recent advances "enable computer capital to rapidly substitute for labour across a wide range of non-routine tasks," such that the jobs of almost half of U.S. workers are at risk. In contrast, consider the following anecdote from a manager at a large automaker. The manager reported that his team was having a problem with a machine vision system sometimes falsely claiming that a product was defective. Eventually they realized that the problem was related to the fact that the facility had massive skylights. On cloudy days when the sun was at a certain angle, the cameras could not see well, and reported more defects. While this pattern was obvious to those at the plant, someone located elsewhere would have had a hard time figuring out this pattern from the machine vision data alone. More generally, when context is important, workers and managers need to be near the place that data is generated. When context is not important, those looking at data near the place it was generated and those seeing only the data (perhaps at a remote location) would arrive at the same conclusion.

For our empirical application, we focus on the U.S. automotive sector. We do this for several reasons, including (i) its importance to the U.S. economy as a whole, (ii) its intensive use of robots relative to other industries, which lead us to believe it will be an early adopter of Industry 4.0, and (iii) the widespread presence within the U.S. auto industry of both the Taylorist and Pragmatist paradigms. Historically, U.S.-owned firms have been more associated with Taylorism, while Japanese and German-owned firms were more likely to be Pragmatist. As we discuss below, these paradigms contain elements with strong complementarities, making it hard for firms to shift among them. Thus, our discussion about how Industry 4.0 will differentially affect these two types of firms holds the management paradigm fixed.

Our paper makes several contributions. First, we develop a framework that links organizational and industry architectures to value creation and value capture. We do this by highlighting that value migration *within firms* likely affects the nature of value migration *across firms*. Our framework builds on existing literature on value creation and capture (e.g., Brandenburger and Stuart, 1996) and value migration (e.g., Jacobides, MacDuffie and Tae, 2016). We believe our insights and framework will be useful to other scholars seeking to understand how new technologies or other shocks may affect the distribution of value within an industry. Second, we then use this framework to offer several predictions about how Industry 4.0 will affect firms in the U.S. automotive manufacturing sector. Thus, our findings have practical implications for managers in an important sector of the economy. Third, our analysis of the auto sector highlights the important role played by two different industrial paradigms, which we believe will critically influence which firms will create and capture value. Thus, our research also provides insights to scholars and practitioners about the role of management strategies.

The paper proceeds as follows. We first introduce the concepts of industry and organizational architecture, describe how technological change and firm strategy shape and are shaped by them, and link these architectures to value creation and capture. We then describe how certain choices in organizational architecture are frequently observed together with a specific industry architecture, leading to the clusters of practice we call Taylorist and Pragmatist. Next we describe the new types of firms, which we call “digital entrants,” that have emerged due to Industry 4.0: robotics makers, integrators, and data analytics firms. We then present our empirical setting, the US automotive industry, and the qualitative evidence showing that, while still in an early stage of implementation, Industry 4.0 already has led to the emergence of digital entrants and incipient developments in value migration. We provide propositions about how

Industry 4.0 will affect value migration in the automotive industry, especially when considering the interaction between the technology shock and the existence of Taylorist and Pragmatist paradigms in manufacturing. Finally, we conclude with implications of our framework beyond our particular application to Industry 4.0 and the automotive sector.

Industry Architecture, Organization Architecture, and Drivers of Value Migration

Our framework links architecture to value (see Figure 1). Below, we describe our key terms, and how they relate to previous literature. A key contribution is to link the strategy literature on industrial architecture with literatures from economics and sociology on organizational architecture. Below, we first describe the relationship between value and industrial architecture, giving examples from the literature. Next, we look at organizational architecture, and then the interaction between industrial and organizational architecture. We do not assume any one factor is the primary driver; in particular, we do not assume that technology determines architecture.

(Insert Figure 1)

We define "value creation" as the worth of the outputs generated by different kinds of firms and workers; "value capture" is the return that an economic actor receives. Following Brandenburger and Stuart (1996), we do not assume that value creation and value capture are necessarily correlated. In fact, sometimes a firm can increase the size of its share of the economic pie by reducing the total amount of value created (Helper and Levine, 1992). Finally, we define "value migration" as the process that occurs when there is a change in who captures value along the value chain, which can occur due to a change in the "industry architecture" (Jacobides, Knudsen and Augier, 2006) or organizational architecture (Braverman, 1974).

Industry architecture

Industry architecture describes which firms do what and which firms take what in a value chain at a point in time (Jacobides, MacDuffie and Tae, 2016). We conceptualize an industry architecture as having three elements:

> *Players:* the types of firms that make up a value chain, e.g., lead firms and their suppliers.
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> *Interfaces:* the relationships between the players. There may be a quite clear division of labor between firms in the industry, or the boundaries may be fuzzy and characterized by great deal of knowledge and task overlap (Takeishi, 2002). The nature of interfaces between firms (the governance of their relationship) is correlated with the nature of interfaces between components (the 'mirroring' hypothesis (Colfer and Baldwin, 2016)).[1]
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> *Technologies:* the production process the players use. Aspects of this process are correlated with the emergence and power of new players (and sometimes, but not always, exogenous emergence of a new technology is a cause of value migration).

Value migration and industrial architecture. An example of value migration from changing industry architecture is the change in which firms were able to capture value in the personal computer industry. In the early days of the industry, IBM dominated the value generation and appropriation process due to its unrivalled R&D effort, its ownership of key elements of the computer platform (such as the operating system), and its ability to determine industry standards (what could be connected to an IBM-compatible system) (Jacobides and Tae, 2015). However, an effort to improve time to market led IBM to bet on modularity, and it subsequently relinquished control over the operating system and the microprocessor. While IBM was busy

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[1] The correspondence between product interfaces and organizational interfaces is not perfect (Colfer and Baldwin, 2016). Moreover, product interfaces do not necessarily drive organizational interfaces; sometimes the causality runs the other way, as in the short-lived automotive flirtation with modularity described below.

fighting off competitors in its own segment (such as Apple and Compaq), it paid less attention to the competition coming from other segments – more specifically, the competition for standards being won by Intel and Microsoft, with the former also achieving quality guarantor status at the consumer level through branding (Curry and Kenney, 2003; Jacobides *et al*, 2006). Increased modularity and open architecture led to the waning dominance of computer makers in the industry architecture compared to suppliers such as Intel and Microsoft. Computer makers (OEMs) saw their share of the computer industry's market capitalization fall from more than 80 percent to less than 20 percent from 1978 to 2005 (Jacobides and MacDuffie 2013).

Shapers of industry architectures: Strategic action. As the personal computer industry example illustrates, firms are not merely passive observers in the shaping of industry architecture (Jacobides 2005; Ferraro and Gurses, 2009). For one, firms and industry associations spend considerable resources trying to manipulate industry regulations through lobbying and other practices. Firms also maneuver themselves so that they become the "bottleneck" in the flow of added value along the production chain. For example, firms can take action to gain control over the complementary assets of the industry (Teece 1986), and to avoid being dependent on other actors by enhancing the fungibility of the components required in their production process (Jacobides *et al*, 2006). Such strategies aim to adapt the industry architecture to the firm's current capabilities. An alternative is to actively manage the firm's capabilities so that the firm can occupy a better position in the value chain. This can be a difficult step, since routines that form the basis of capabilities are often painstakingly developed over a long time; sometimes firms can acquire capabilities on the market.

Jacobides, MacDuffie and Tae (2016) use the auto industry to illustrate these strategic interactions. In the 1980s and 1990s, US and European OEMs were threatened by the rise of

Toyota and its innovative production system, which had higher productivity and quality and faster development time. In response, these automakers tried to shift to a new production paradigm based on modularity and outsourcing. Modularity meant establishing common interfaces across several car models, for example for the way that an instrument panel would be attached to a car's interior. Outsourcing meant buying more parts from financially-independent suppliers. These initiatives are separable; for example, automakers could have bought more small parts from outside and added them to subassemblies (modules) designed and assembled inside. With the encouragement of consultants, academics and financial analysts (who were happy to see OEMs shedding assets, thus improving their return on assets) they decided to increasingly outsource these subassemblies/modules to suppliers. Crucially, in order to reduce the cost and complexity of product design and to improve lead times, OEMs were willing to hand off not only the manufacturing of subassemblies, but also a good part of their design.

In order to handle the increased responsibilities, suppliers merged with one another and with spun-off OEM parts divisions to create "megasuppliers," combining plastics molding firms with seat makers or electronics firms to bid on instrument panel modules. The mega-suppliers hoped to create industry-standard modules, which would allow them to command higher margins. OEMs initially were not attuned to this risk; they intended to emulate the example of the computer sector, which they saw as having a fast pace of innovation and high performance on technological and financial criteria. The OEMs initially missed the fact that this combination of modularity and outsourcing "is precisely what caused computer OEMs to lose both power and their share of value capture to specialized suppliers of key modules." (Jacobides *et al*, 2016).

Eventually the OEMs realized that this change in industry architecture was costly for them, and backed away from modularity. Although frustrated by the OEMs' reluctance to yield control, suppliers also began to recognize that it would be very difficult to accumulate the capabilities necessary to perform the new duties, and that they were not very willing to take on the regulatory liabilities that came with greater responsibilities. The fact that the automotive industry has a slower product lifecycle, and is characterized by incremental change also contributed to lack of drastic change in the industry architecture. Thus, in contrast to the case of the computer industry, automakers were able to change their strategy back, preserving a more or less constant value appropriation within their industry.

Shapers of industry architectures: Technological convergence. A change in technology can lead to a dramatic change in industry architecture. Rosenberg (1963) used the example of the machine tool industry. In 1820, there was no separate machine-producing industry; each manufacturing firm made its own (simple) tools. In the early 19th century, the U.S. military began a half-century of effort, funded by an “extraordinary sum of money,” to create small arms with interchangeable parts (Hounshell, 1984). These funds helped government armories and private firearms makers to develop specialized, precision machinery for use in their factories. In the 1850s these manufacturers realized that their tools would be useful in making sewing machines, a product whose demand was growing exponentially. Machine-tool makers adapted their tools to this industry, and created new ones to solve problems in sewing machine manufacture. These new tools turned out to be useful in making bicycles, which in turn helped foster the auto industry. Thus, “machine tool production emerged as a separate industry consisting of a large number of firms most of which confined their operations to a narrow range of products.” (Rosenberg, 1963 p. 421). The use of machinery to cut metal into precise shapes involves just a few operations, mostly turning, drilling, and grinding. Machines that perform these operations confront similar problems, such as power transmission, control devices, feed mechanisms, friction reduction, and problems related to the properties of metals (such as their response to heat and stress). Solving these problems in one industry generates solutions applicable to other industries.

Thus, the history of industrialization often involves both increasing specialization of firms within an industry (firms using machine tools typically no longer make them), and also of convergence across industries (firms making machine tools serve many industries). Pavitt (2003) illustrates this history with other, more recent, examples. Breakthroughs in fields such as material shaping and forming, understanding properties of materials, and continuous chemical processes, allowed for the emergence of new instances of the specialization/convergence phenomenon: activities such as materials testing and the production of measurement and control instruments moved away from firms that were also end-users, and were taken up by newly formed specialists.

Organizational architecture

An organizational architecture determines which groups within firms create value, and which take value. We conceptualize organizational architecture as being made up of similar elements as industry architecture:

Players: groups within a firm, such as managers, or production workers.

Interfaces: the relationships between the players. There may be a quite clear division of labor between occupations in the firm, or the boundaries may be fuzzy and characterized by great deal of knowledge and task overlap (Helper and Kuan, 2018). A key aspect of organizational architecture is aligning incentives of individuals to work together; Brickley, Smith, and Zimmerman (1996) define an “organizational architecture” as comprising a firm’s 1) assignment of decision rights within the company, 2) methods of rewarding individuals, and 3) structure of systems to evaluate performance (p.4).

Technologies: the production process the players use. Aspects of this process are correlated with the emergence and power of new players; as with industry architecture, exogenous emergence of a new technology is often a cause of value migration.

Shapers of organizational architectures: external technology. An extensive literature argues that technological change is the key driver of the evolution of organizational architectures. For example, Brynjolfsson and Hitt (2000) describe how advances in computer integrated manufacturing technology led a large medical products manufacturer to move toward a more decentralized organizational architecture, eliminating piece rates, giving workers authority for scheduling machines, and increasing lateral communication and teamwork.

Shapers of organizational architectures: firms' strategy. Many aspects of organizational architecture are complementary, in that firms perform better if they adopt several practices together. For example, if firms adopt flexible work practices together with flexible equipment, their performance will improve by more than if they adopted each practice separately (Milgrom and Roberts, 1995). A literature on "high-road" practices argues that increasing worker skill while adopting strategies such as frequent new-product introductions allows firms to be profitable while paying a higher wage (Osterman, 2018). There is evidence that firms actually adopt policies in complementary ways. For example, Aral et al (2012) find that the adoption of human capital management software is greatest in firms that have also adopted performance pay and human resource analytics practices. In contrast, Helper and Martins (forthcoming) find that high road practices are complementary in performance among U.S. auto suppliers, but not in adoption. Because significant change often involves adjusting several aspects of organizational architecture at once (e.g., worker selection, wage policy, marketing strategy, equipment purchase), an existing architecture may exert a powerful pull on the direction of technology development. In addition, the interests of owners and managers diverge from those of workers.

An example of how organizational architecture affected technology development and adoption is the case of CNC (Computer Numerical Control) Machine Tools. Machine tools cut away metal to make a precise, durable component. Traditionally, machine tools were operated by highly skilled machinists, who decided what sequence of cuts a machine should make, chose which tools the machine should use (lathe, mill, drill, etc.), made fixtures to hold the part steady while it was being cut, and determined the speed at which the machine operated.

From the 1950s to the 1970s the US Air Force subsidized development of automated machine tools (Noble, 1978; Kelley, 1994; Kelley and Helper, 1999; Hirsch-Kreinsen, 1993; Bushnell, 1994). Initially, instructions were coded into tape-guided machines ("numerical control"). In the 1970s and 1980s, firms introduced computer numerically controlled (CNC) machine tools that were programmed using a computer. In both cases, the goal was to enable complex products to be produced without companies needing to depend on skilled labor. The Air Force and defense contractors ended up with a highly abstract programming method which initially was quite complex, expensive, and fault-prone. They rejected a simpler technology, "record playback," which would have simply recorded the actions of skilled machinists to make a repeatable process. The result was a technology that, after much tribulation, could make more complex parts than even the most skilled machinist could make – but which continued to require the input of skilled technicians; the goal of a continuously operating "lights out factory" (with no workers) remains elusive. The most effective operation of the technology involves both specialized programmers and skilled technicians on the shop floor who can modify programs to take into account ever-changing variables such as tool wear.

Machinists in some plants gained computer programming skills as computers took over the direct determination of “feeds and speeds.” More often, however, machinists became less skilled, mostly watching for errors by the automated equipment while firms gave programming and problem-solving duties to engineers. The main outcome was that the jobs were separated,[2] with significant pay differentials. Even taking into account the pay differentials, integration of programming and operating was associated with higher productivity (Groshen et al, 2018).[3] Noble argues that a desire to reduce worker bargaining power led management to choose the less-productive (but arguably more privately profitable) path.

Management Paradigms

In this section, we bring together industry architecture and organizational architecture, arguing that they are linked by management paradigms, including views about the nature of knowledge. A priori, firm and industry organization features could be combined in numerous ways, within and across these two categories. Empirically though, we observe that in manufacturing two combinations occur frequently, suggesting that the choices we observe are characterized by strong complementarities. We call these pervasive combinations “paradigms.”

The first paradigm is the philosophy of Taylorism which underlay much of US manufacturing practice in the 20th century. In this view, developed by practitioners such as Frederick Taylor and Henry Ford, and academics like Alfred Chandler, firms could achieve low

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[2] According to the US Department of Labor’s Occupational Information Network (O*NET), two occupations are now involved with CNC machine tools. The median wages of the 146,000 “Computer-Controlled Machine Tool Operators, Metal and Plastic” in 2016 were $18.21 per hour; these workers operate machines – the job description does not mention programming. Conversely, the job description for “Computer Numerically Controlled Machine Tool Programmers, Metal and Plastic” does not mention actually operating a machine; these workers (25,000 in 2016) earned a median wage of $24.32 annually. Finally, there is a “machinist” occupation, employing 396,000 workers, who earned an average of $20 per hour.

[3] https://avworkforce.secureenergy.org/wp-content/uploads/2018/06/Groshen-et-al-Report-June-2018-1.pdf

costs by running specialized machines at high volumes and maintaining a strict division of labor both between planning and execution and between tasks on the shop floor. This view has been challenged from a variety of perspectives that we group together as Pragmatist. These alternative perspectives, coming from practitioners such as Toyota and students of "socio-technical systems," are diverse but generally argue for smaller lot sizes, more experimentation, and a greater decision-making role for shop-floor employees (Kenney and Florida, 1993; Adler, Goldoftas and Levine, 1999; Bergren, 1994). Figures 2 and 3 summarize these differences, and implications for the design and use of automation.

(Insert Figure 2) (Insert Figure 3)

A key feature of these managerial paradigms is their view about the nature of knowledge. For our application, two aspects are important: 1) the extent to which data can be separated from the context in which it was generated (discussed in the introduction) and 2) the extent to which the environment is stable. Environmental stability was a key enabler of Taylorism. Firms could make predictions about technology, markets, and demand that enable long-term plans and investments to pay off. Government policies promoted this stability, such as actions to manage aggregate demand through fiscal and monetary policy (Piore and Sabel, 1984).

Such an environment had implications for firms' organizational architectures as Figure 2 illustrates. Stability meant that interfaces could be simple, with little knowledge overlap. Since operations were stable, it made sense to design a fixed division of labor with workers specializing in narrow tasks. The value of specialization meant that it also made sense to have a planning function separate from operations (Chandler, 1977). Planners could become better at planning if they were not distracted by other tasks, and the lower-skilled work of production could be done by lower-paid people (Taylor, "Shop Management," pp 98-121, cited in Bushnell, 1994 chapter 1.) Planners and engineers developed new products and scanned the horizon for new technologies, which they implemented all at once, in large leaps, like the hare in his famous race with the tortoise (Hayes and Abernathy, 1980).

Shop floor workers were considered interchangeable; their work was considered inherently unskilled. They were supposed to follow orders and not expected to contribute ideas. Due to worker organizing it became difficult to fire workers, but companies did not take advantage of the knowledge of their long-tenure workers, whose understanding of context was not held to be valuable (Helper and Henderson, 2014).

Stability affected the technology that firms developed; investing in high fixed costs to enable low variable costs made sense, because products could be run long enough to amortize the fixed costs. Equipment was designed for heavy use, both because it was assumed production runs would be long, but also because workers were not believed to be capable of being careful (a self-fulfilling prophecy.) The data needed to run a business was held to be transferable across industries (i.e., context was not especially important), with managers receiving MBAs not tied to a particular industry. At auto assembly plants, robots have been common since the 1990s in the welding and body shops (the world's first working robot was installed at a GM facility in 1961).[4]

The Taylorist paradigm was associated with an industrial architecture also characterized by arm's-length, non-permeable interfaces. Designs were thrown from automakers "over the wall" to suppliers, who had little ability or incentive to harmonize the designs with their equipment. Suppliers competed fiercely against each other for work based on competitive bidding; contracts were explicit, to enable "apples–to-apples" comparisons of bids. This

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[4] Robotic Industries Association. "UNIMATE — The First Industrial Robot: A Tribute to Joseph Engelberger." 2017. https://www.robotics.org/joseph-engelberger/unimate.cfm

cutthroat competition selected for a supply base with low overhead and therefore low technical capability; one-quarter of auto suppliers in the 2011 survey had zero engineers (Helper and Kuan, 2018). Due to their customers' price-squeezing tactics, automation at suppliers was less common, and robots remained rare. (Out of approximately 20 site visits to second-tier suppliers conducted for the 2011 survey, only one firm had robots; more firms had relatively fixed automation, like transfer presses.)

In the Taylorist view, top management at automakers can design duties for suppliers and shop-floor workers; deep skill in executing these duties is not really necessary. Robots have many characteristics of an ideal worker; "they don't complain, get tired, or want to join a union," as one supplier manager told us (we heard variants of this from several interviewees). A strict application of this view would suggest that robots simply replace workers. Automation in principle allows engineers' conceptions to be implemented directly, without intervention by unmotivated, rent-seeking production workers.

The Taylorist view has been challenged for many years, and is no longer as dominant in US manufacturing. (However, as we discuss below, elements of this view persist in legacy automation projects, and in low capability and trust among suppliers and workers.) An alternative "Pragmatist" view was described by John Dewey and its implications for production drawn out by Sabel. What follows draws a great deal from "lean" manufacturing or Toyota Production System, but also shares characteristics with German manufacturing and experiments in the 1970s and 80s in improving "Quality of Work Life" (Bushnell, 1994; Kochan, Katz, McKersie, 1986).[5] We note that pragmatists don't always practice the ideals described here;

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[5] Key differences include less interest in Germany in flexible boundaries between tasks: the German apprenticeship system produces deeply skilled tradespeople within relatively rigid occupational boundaries. Neither the German nor

managers in fact may put such pressure on workers that "lean production" becomes "anorexic", or is better called "management by stress" (Parker and Slaughter, 1988).

A key feature of the Pragmatist perspective is a view that knowledge is provisional; problems will arise, so it is important that assets (both human and physical) can be redeployed quickly (See Figure 3.) Rather than planning for long runs or large batches, it is best to have the goal of "one piece flow", among other reasons because parts may become obsolete over time and quality problems hard to identify when inventories are large (Womack, Jones, and Roos 1990).

Context is important in interpreting data; data alone don't explain how to fix a problem (Helper, Khambete and Boland, 2010). Knowledge close to the point of production is held to be very valuable; shop floor workers are the experts on the machines they run because they spend so much time observing them, and thus are key players in diagnosing quality problems (MacDuffie, 1997). Rather than separate planning and execution, the pragmatist view is that workers' knowledge can contribute to innovation and future production, as well as today's operations.

Figure 3 illustrates how these views about the nature of knowledge are associated with the interfaces and technologies both within firms (organizational architecture) and between firms (industry architecture). Response to problems or opportunities for improvement means that interfaces between tasks are frequently redrawn, so narrow specialization is not useful (Helper, MacDuffie, Sabel, 2000).

In this view, technology should serve the worker's ability to improve the process. "Jidoka" is a key concept in the Toyota Production System, a term translated as both

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the QWL programs share Toyota's (and other Japanese manufacturers) focus on reducing inventories and producing "just in time."

"automation with a human face" and "automatic line stop." The idea is that a worker is "freed" from watching the machine because it is designed to stop automatically (Narusawa and Shook, 2009). Both line workers and engineers should monitor the health of the process as they work, using all five senses – how does the process look, sound, smell, etc. (Helper and MacDuffie, 1997). Humans have much broader sensory capabilities than machines do, so people can give a much richer picture of what is occurring. Too much automation removes this knowledge – Toyota in 2014 actually removed some robots from its factories for this reason.[6]

Much knowledge useful for improving production is thus tacit, at least initially. Once people realize that a certain sound or indicator is important, this knowledge can be codified—standardized work instructions can be written to lay out in detail the best technique for doing a process step, and failure modes delineated. But this step of codification sets in motion another round of efforts to improve on the new standard, and tacit knowledge and a variety of perspectives are again important (Helper *et al*, 2000; Adler and Borys, 1996). That is, manufacturing, especially in the pragmatist paradigm, does not involve a worker pushing the same button on a machine every 20 seconds for 20 years. Rather, change is daily or weekly, as new products come in and new methods are invented. This process is most effective if the people doing the work are involved in the standardization because they know the details in a way that an observer, no matter how well-trained, cannot (Adler calls this process "Democratic Taylorism").

While there are many interesting angles to pursue when contrasting Taylorist and

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[6] According to Toyota Executive Vice President Mitsuru Kawai "We cannot simply depend on the machines that only repeat the same task over and over again. To be the master of the machine, you have to have the knowledge and the skills to teach the machine." Craig Trudell, Yuki Hagiwara and Ma Jie. "Humans Replacing Robots Herald Toyota's Vision of Future." Bloomberg. April 7, 2014 https://www.bloomberg.com/news/articles/2014-04-06/humans-replacing-robots-herald-toyota-s-vision-of-future; see also Jeff Rothfeder, "At Toyota, The Automation Is Human-Powered." September 5, 2017. https://www.fastcompany.com/40461624/how-toyota-is-putting-humans-first-in-an-era-of-increasing-automation

Pragmatist paradigms, the main implication of their existence for our research question is that they lead to very different views on how feasible it is for manufacturing plants to be able to separate the data that is generated by the production process – cycle times, defects, etc - from the context in which it was generated. Taylorists believe that human engineering can stabilize the environment to the point where recurring production cycles can be analyzed in batches and from a broad, statistical perspective. Conversely, Pragmatists believe that each production cycle has details that may yield important information on what is happening in the factory; properly cataloguing and analyzing such details requires shop-floor intervention. These differences in perspectives will have important implications for how organizational and industrial architectures and new technologies adjust to each other. An important factor in how industries get rearranged after a technological shock is the emergence of new types of firms that can challenge incumbents by pursuing new business models made possible by the new technology.

Auto Industry Background and Methodology

While Industry 4.0 affects all of manufacturing, we focus our attention on the automotive industry as this industry dwarfs other industries in the number of robots shipped annually. About half of U.S. robot shipments are to the automotive sector, and about 20 percent to the consumer electronics sector (Furman and Seamans, 2018). Automotive purchasers account for 39 percent of the stock of robots in the US, by far the largest sector (Acemoglu and Restrepo, 2017). In autos there were approximately 1,091 robots per 10,000 workers in 2012. In contrast, the average of all other industries was 76 robots per 10,000 workers (CEA, 2016).

There are several types of players in the auto industry. The automakers (e.g., Ford, Toyota, Volkswagen) design, market, and assemble cars. They preside over a supply chain that include large “first-tier” suppliers (suppliers who supply directly to automakers), who are in turn supplied by smaller second-tier suppliers, who are supplied by third-tier suppliers, etc. Automakers capture 70-80 percent of the market capitalization in the industry (Jacobides *et al*, 2016), though this figure overstates their share since many small suppliers are privately held. About 1.5 million people are employment in the U.S. auto parts sector, about four times as many as are employed directly by automakers (Helper, Miller and Muro, 2018).[7]

Automakers rely on a common set of suppliers, which is beneficial in that suppliers can specialize in narrow areas, such as automotive seating. Each automaker benefits from the reduced fixed costs and increased access to suppliers' experience making similar products for other customers. On the other hand, lead firms have reduced incentive to invest in upgrading the supplier's capabilities if that supplier may also use those capabilities to serve a competitor.

As described in the previous section, US automakers in the past used purchasing strategies that selected for suppliers with relatively low bargaining power. The Detroit Three used short-term contracts with many suppliers per part, and took complicated functions (e.g. product design and sub-assembly) in-house. In contrast, Japanese-owned automakers and their suppliers have emphasized more collaborative relationships. In recent years, US automakers have converged a bit toward Japanese practice (Planning Perspectives, 2017). However, a legacy of small, weak suppliers remains – a legacy that complicates adoption of modern automation practices. Data from a 2011 survey documented this weakness, including failure to adopt proven managerial techniques. One-third of auto suppliers have fewer than 500 employees, and fewer than half of these small firms have adopted quality circles (in which production employees

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[7] https://www.brookings.edu/blog/the-avenue/2018/07/02/why-undermining-fuel-efficiency-standards-would-harm-the-us-auto-industry/ Because of difficulties in assigning individual factories to industries, employment in auto parts is significantly underestimated; it is probably twice as large as presented in statistics based on the North American Industrial Classification System (NAICS). (Economic Report of the President 2013; Helper 2012).

gather regularly to troubleshoot quality concerns) and only two-thirds of them self-report that they consistently perform preventative maintenance. A quarter of small automotive firms employ no engineers. (See Helper and Kuan (2018) for information on survey methodology).

The 2011 survey asked plant managers whether they agreed with the following assertion: "We have found that use of Information Technology (IT) reduces the need for shop-floor workers to have analytical skill." Possible answers ranged from 1 (strongly agree) to 5 (strongly disagreed) – that is, the answers range from workers being substitutable to being complementary. Figure 4 shows the distribution of responses. Most managers saw IT and shop-floor analytical skill as complementary, but responses are widely distributed. Thus, this figure suggests that firms have different views on how technological change affects the knowledge requirements of a firm. The survey data shows that these different views are correlated with different managerial practices; plants where managers believe that workers and IT are complements pay higher wages, and enroll a higher percentage of their workforce in training for continuous improvement.

(Insert Figure 4)

To study how different managerial paradigms affected firms' practices regarding automation, we conducted multiple site visits (including plant tours) and phone interviews 2016 to 2018 (see Appendix). Below we draw on these interviews to help develop our framework to understand the impacts of Industry 4.0 on value creation and value capture in the auto industry.[8]

Digital Entrants

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[8] Our observations from these interviews fall into four themes: (1) why automate now (perceived labor shortage plus the emergence of integrators); (2) disparate views regarding the importance of tacit knowledge and the possibility of separating data from context; (3) the impacts of automation and how they are moderated by manufacturing paradigms; (4) the potential for value migration. See Appendix 1 for representative quotes from these interviews.

We begin by profiling the new players in the industry architecture, firms whose business models are made possible by the emergence of Industry 4.0. We group several types of firms, including robot manufacturers, integrators, and data analytics firms, into the category of "digital entrants." While some of these firms have been around for a long time—for example, Fanuc got its start in the mid-20th century in CNC devices[9]—they have become newly important to the manufacturing industry with the rise of Industry 4.0. Moreover, robot manufacturers tend to be "upstream" from integrators, which provide an interface between the robot manufacturers and manufacturing firms, but we group them all together so as to focus on the collective effect of these digital entrants on the distribution of value between upstream and downstream firms.

Robotics

Tracking the rise of "Industry 4.0" — or indeed any of the technologies that comprise it — is difficult, given both the lack of standard definitions and the lack of systematic data. To provide a sense of the rapid uptake of these technologies, we focus on robotics. We define a robot as an "actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks [ISO]."[10] Data compiled by Furman and Seamans (2018) from the International Federation of Robotics (IFR) indicates that annual shipments were relatively flat between 2004 and 2009 before starting to rapidly increase between 2010 and 2016. Worldwide robot shipments increased about 150 percent between 2010 and 2016, though only about 100 percent in the United States.

This rapid increase is likely due to a combination of factors including a decrease in robot prices, an increase in robot functionality and flexibility, improved ease of adoption and use;

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[9] https://www.bloomberg.com/news/features/2017-10-18/this-company-s-robots-are-making-everything-and-reshaping-the-world

[10] ISO 8373, 2012, available at https://www.iso.org/obp/ui/#iso:std:iso:8373:ed-2:v1:en

growing awareness of robots' potential benefits, and an increase in number and skill of robot integrators, which we describe below. Graetz and Michaels (2015) estimate that robot prices decreased 50–80 percent between 1990 and 2005.

The dramatic change in ease of use of automation became apparent to us during our site visits. For example, during a visit to a medium-sized auto supplier plant in Michigan we observed two vintages of automated plastic injection mold machines. The earlier vintage machine, which was built in 1980, had a number of dials, switches, and other controls that the machine operator would use to produce parts. The newer vintage machine, built around 2017, had a very different user interface; the operator controlled the machine by using a touch screen, similar to those found on smartphones. Advances in user interfaces and other technologies has made robots and other types of automated machinery much easier to program. In addition, the adoption of standards has made it easier to integrate these technologies with each other.

Integrators

Robotics integrators have played a key role in the increased diffusion of robotics. These are firms that sit between suppliers of automation technology and manufacturing firms which want to automate some part of their production process. Integrators adapt the robotic offerings of the upstream suppliers to the needs of the downstream customers by: diagnosing the customer's manufacturing requirements; designing a comprehensive plan for automation; installing and testing robotic and other equipment in accordance to this plan, and in accordance with established safety protocols; providing training to workers on the factory floor and to engineers; and providing ongoing maintenance and customer service. In principle, since much of the equipment is digitally enabled in some way, integrators could also offer data management, monitoring, or other advanced digital services. In practice, few integrators appear to offer these types of services at present.

There is much heterogeneity across the population of integrators. There is no set definition of “integrator”; some large industrial equipment manufacturers such as Rockwell perform integrator-like functions as well. Amongst “pure-play” integrators, some are one or two person businesses that have dedicated local customers, and that work on one or two projects at a time, whereas others are large enterprises with hundreds of employees and dozens of concurrent projects. Some integrators focus solely on product assembly and production line projects for customers, some focus solely on conveyance, sorting, and packing, and some do a bit of both. Integrators have been growing in importance in the US: they out-employ, outsell and outnumber robot suppliers by a margin of two to one (Green Leigh and Kraft, 2017). Membership of integrators in the Robotics Industry Association (RIA), which runs a certification program for integrators, has increased over 300 percent over the past 10 years.

Data analytics firms

The use of data analysis to improve production process is not a new development in manufacturing, since it goes back at least to Taylor (Bushnell, 1994). Yet, the emergence of Industry 4.0 represents a potential transformation in the use of data in manufacturing. The exponential increase in computing power available makes it possible to go beyond analyzing the operation of a single machine in isolation, allowing data analytics firms attempt to optimize manufacturing operations of the factory as a whole, even including suppliers. (McKinsey, 2011).

This breakthrough has led to a potential repeat of the specialization/convergence process that occurred in the machine tool industry as described in section 2. Some manufacturing firms are not developing a data analytics capability but instead contracting with specialist firms that mostly have never manufactured a single widget, but offer analytics services to manufacturers, such as: data storage and cleaning; profiling tools, which allow manufacturers to create a comprehensive inventory of their critical data; data mining tools, which enable manufacturers to identify dependencies and address potential problems at the cause; data analysis, including pattern identification and prediction of outcomes; visualization tools; and monitoring tools. [11]

Sight Machine, which was founded in Michigan in 2011 and a year later expanded to Silicon Valley, promises to use "artificial intelligence, machine learning, and advanced analytics to help address critical challenges in quality and productivity throughout the enterprise", through a platform that "enables real-time visibility and actionable insights for every machine, line, and plant throughout an enterprise"[12]. According to Crunchbase, it has raised US$ 30 million and employs 180 people. BEET Analytics Technology, which was also founded in Michigan in 2011, similarly proposes that its technology can "collect, process and present data down to the motion of each device of a production line", which would enable predictive maintenance and "maximize the capacity of existing assets by reducing the unplanned downtime and increasing the production throughput"[13]. Finally, start-ups are not the only "digital entrants": large, established manufacturers such as Rockwell, with its Connected Enterprise initiative, and Siemens are also offering data analytics services to manufacturers – with the important advantage that their own factories serve as training and experimenting ground for their analytics businesses. Kuka, a German robot maker, is rolling out an offering they call "manufacturing as a service", where Kuka guarantees uptime and other performance metrics if manufacturers follow Kuka's

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[11] See e.g., https://www.liaison.com/blog/2017/09/20/big-data-analytics-tools-manufacturing-industry/

[12] https://sightmachine.com/company/

[13] https://www.crunchbase.com/organization/beet-analytics-technology#section-overview. BEET has also taken the route of entering into an alliance with a leading robot maker to offer customers the combination of hardware and data analysis in a single package: https://www.prnewswire.com/news-releases/kuka--beet-sign-value-added-reseller-var-agreement-620341993.html

instructions precisely, instructions based on Kuka's predictive analytics about tool wear, etc.[14]

As production becomes more automated, data becomes easier to capture (it is automatically captured by the equipment). By promising to turn this data into useful information, analytics firms compete more effectively and may capture an ever-greater share of the value in supply chains. This possibility was borne out in our interviews, which found that integrators appear to play a prominent role in small suppliers' decision to automate. Automation seems feasible to these firms now, not just because of the declining cost of the physical assets themselves, but also the declining costs of integrating those assets with existing technology and the ease with which the new technology can be programmed and controlled[15]. As one supplier explained to us: "Automation is much more doable for a small firm like ours now – [we] don't have to program in assembly language and there are integrators to help us." Recall that firms adhering to the Taylorist philosophy pursue solutions with standardized, simple interfaces (Figure 2). Integrators appear to have a lot of appeal to firms following this philosophy, as contracts can be explicit and division of labor clearly separated. Thus it is likely that the benefits of automation are now particularly salient to firms adhering to this philosophy, thanks in part to the work of integrators. However, some baseline level of in-house capability is needed to make automation successful. An integrator told us of a customer of his, a third-tier supplier to Honda that pays its workers $8/hour and has no maintenance department; the automated equipment he installed broke quickly.

The integrators that we interviewed serve both large and small customers. For example,

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[14] Presentation at Center for Automotive Research Management Briefing Seminar, Traverse City MI August 2018.

[15] An additional push into automation comes from the perceived difficulty of finding workers; Our interviewees consistently said they are unable to find enough production workers at the going wage ($12-15 per hour, plus benefits), and believe that raising the wage would not increase the supply.

one integrator we visited was building a robotics cell for a small family-owned parts manufacturer, as well as multiple robotics cells for a large US automaker (among many other projects). This integrator reported that the automaker had provided detailed technical specifications and that the automaker's in-house electricians and robot technicians would service the robotics cells once they were installed on the customer's site (as opposed to the integrator performing these functions, which sometimes is the case with smaller manufacturers).

The growing role of integrators in serving manufacturers both large and small may be evidence that a condition that enables a shake-up of the industry architecture – namely, technological change that allows new players to enter the value chain – has started to take root.

Digital Entrants and Value Migration in the Auto Industry

Differing views on the separation of data from context and the role of tacit knowledge

Many academics and consultants are optimistic about the potential for data analytics to drive the future of manufacturing in a way consistent with the technical convergence view. MIT engineering professors proposed a vision of "distributed manufacturing": "In a world of fragmented production, when a company needs a part, it does not build a factory. Rather, it taps into a national network portal and places a computer-aided design (CAD) description of the part it desires, and the numbers it needs, on the portal. ... Just as we email Word or PDF documents today to the likes of Kinko's, designers can email IGES or ProE files to manufacturers." (Berger, 2013, chapter 6).

Our interviewees with experience on factory floors were much less sure that such easy transfer of data would be feasible or desirable (see quotes in Appendix Table B). We listened to a discussion of this topic at an industry reception in December 2017 between a veteran purchasing director at a Japanese automaker (Terry) and a recent engineering graduate (Vijay):

> Vijay: “This big data stuff is really exciting! New companies like Beet can use data analytics – you [a manufacturer] could give them data from 20,000 sensors and they could figure out why you’re having quality problems, where the bottlenecks are. With machine learning, soon machines can fix themselves, change out their own tools just before the old one is likely to break.”
>
> Terry: “I’m not so sure about this. You can’t just take the data by itself—you have to see where it was generated. There’s a saying in Toyota, “machines can’t learn, only people can.” We do “monozukuri” workshops with our suppliers to improve the process. We get our product designers and engineers to the shop floor, to see the gemba. We always start with having the production associate describe the process, because they know it best. There’s stuff that is not obvious to the engineer, like this machine heats up and then it makes the hole too big, or this machine gets condensation dripped on it.
>
> Vijay: But you could put heat sensors on the machine — with machine learning, machines can now learn.
>
> Terry: Yes, that’s a good idea. But if you wait until the whole set up is perfect, you’re going to have a lot of idle time, a lot of dollars sitting around. It’s better to start with something and then improve it later, and you can always learn more about the process. How would you kaizen[16] a robotic cell remotely? We are currently looking to reduce the cycle time of a plastic molding process, where we have a robot insert a nut into the mold cavity. We know that we can speed things up by not having the robot go all the way back to its base each time – move the nuts very close to the mold, and have the robot arm go only a very short distance from the nuts to the mold. We also don’t need to have the mold open all the way each time – just enough so the robot has enough clearance to get in there. How can you know how close you can get things without being there? Even when they’re setting up a line, our engineers will be out there with old refrigerator boxes to create a cheap mock-up of how things are going to look — when you do that, you see a lot more than with CAD.

This conversation illustrates several of the key points of our literature review: the importance of context (“go and see”) for the Toyota person and the desire to start quickly with something and then improve it over time. The engineering student, in contrast, believed strongly in the power of data (abstracted from its industry context) to improve performance, consistent with a view that there is a technical convergence of skills related to “Industry 4.0” (data analytics and integration of automated equipment).

We saw evidence of the interplay between tacit knowledge and standardization when we

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[16] “Kaizen” is a Japanese word meaning “continuous improvement.”

visited a tool and die shop. We watched a computer-aided design (CAD) programmer use 3-D software to design a die that would be used to turn a flat piece of metal into the outside of a car door. A key issue in this kind of situation is “springback,” the tendency of metal to return to its original shape after it has been stamped. With traditional steel, the CAD program models springback automatically. However, in the last 10–20 years, the types of materials used have proliferated: automakers now specify aluminum, magnesium, or one of many types of “advanced high strength steel.” Because these materials are new, CAD programs don’t yet have a model of how they will react to the complex forces in a die. The programmer we talked with had designed dies in the pre-CAD days and had an intuitive sense of how the material would react, though iteration was required. Gradually he developed rules of thumb, and sometimes sent corrections to the CAD software developers, who would incorporate his information into their models. Although this process was fairly ad hoc, it meant that standards were improved, and then automakers raised the bar in terms of process control required, which meant tacit knowledge came back into play.

Impact of automation on work and the moderating role of manufacturing paradigms

In our interviews, we explored the impact of automation on the numbers and skills of both production workers and of engineers (see quotes in Appendix Table C). Increased interest in automation at suppliers typically leads to an increase in engineers in-house, despite their reliance on integrators. The in-house engineers were needed to define the project the integrators were to be hired to work on, select the company to do the integration, and monitor their work. A forward-thinking supplier of about 50 people hired a controls engineer at the start of an automation push that began in 2013. But for other engineering skills, they rely on integrators: “There are three skills we need for 200 hours per year. No one person has them all, and by going outside I can get state-of-the-art expertise, not state-of-our-employee's expertise," the process engineer said. He sent a technician to learn how to do the robot programming needed to adjust for tool wear, but that is the extent of the firm's robot programming capability. In the auto industry robots need to be re-programmed only when a model is refreshed or changed (several years). "We are top-heavy right now – too much staff for our level of sales. But we will be growing our sales significantly with the business we've already booked and won't be adding more engineering slots," the CEO told us.

In general, the introduction of automation led to increased skill. For example, the process engineer quoted above said, "When a worker is running a robotic cell, it takes more skill than before. They have to make sure that the robot is supplied with material, they have to stage the parts, and they make sure the process is continuing to run. When it's down, they do low-level trouble-shooting, they have to do the beginning of the re-start process. Now they have a bit of their time they have to manage to get all this done – it's not just standing at the machine pushing a button." The CEO said, "It takes several days [for an experienced operator] to learn to run a robot cell and this makes it more important to have the same person there every day, and so turnover and absenteeism become more important."

In some ways, the introduction of automation decreased skill. Machine vision is now quite cheap; in calendar 2017 this firm has gone from having no machine vision to having 10–12 cameras inspecting parts. They report that "Now that we have cameras, the worker doesn't inspect anymore – they just pack the good ones. The machine decides go or no go." Although the machine reduces the worker's exercise of judgment, inspection is a tedious and high-stakes task.

In some cases, the impact on skill varied based on complementary investments/institutions, as suggested by our distinction between Taylorist and Pragmatist paradigms. As one medium-sized manufacturer reported: “In our German plant, all the machines are operated by technicians – they can set up the machines as well as run them. Here in the U.S., technicians set up the machines, and operators run them. They can do a lot more set-ups and faster de-bugging in Germany.”

Comparing Figures 2 and 3, recall that firms with different management philosophies approach their relationship with labor differently. In the Taylorist model, workers are typically seen as “inputs” in which case we would expect that automation would be used to replace workers. In the Pragmatist model, workers are typically seen as partners, as in the German example above.

Pragmatist manufacturers emphasized to us the importance of understanding the context in which the data was generated, and the importance of having frontline workers as partners in this endeavor. Even simple data collection could go wrong. At one highly automated firm a manager told us, “Sometimes the sensors go bad – about once a week a sensor will tell us the product is defective when it really isn’t. Then we have to check things out manually –it’s really great if you have an experienced operator who’s seen this before”. Data interpretation is also much easier when an experienced worker can help interpret the sensor data. The sensor may actually be capturing what is happening with the machine next to it, or is reacting to having condensation from the roof dripping on it.

We saw some nascent examples of how Industry 4.0 techniques could be developed in a way that enhanced worker capabilities. Equipment and software design could focus on intuitive user interfaces (such as heat maps rather than columns of numbers or programming interfaces that require precise and non-intuitive syntax). In some automotive plants, unionized skilled tradespeople run a 3D printing room, where they design and print replacement parts for production equipment, drawing on their years of experience of the key failure modes of such parts, and on social networks that alert them to possibilities for the new, additive technology.

More generally, this variation across the two management philosophies reinforces the notion that we would expect to see heterogeneity in terms of the link between automation and the role of workers. While there is no evidence available yet on how these two management philosophies' approach to labor relations interact with industry architecture and value migration, in the following section we advance propositions on how these interactions could play out.

Value migration

Is the process of value migration is already in motion? Will digital entrants become the new "Intel inside" the auto industry, dethroning the automakers even when the siren song of modularity could not? There is some evidence that a shift in value may be starting, as we discuss below and in Appendix Table D).

First, we are seeing examples of integrators becoming responsible for a significant portion of the manufacturing process – in particular, those parts of the process that become automated and optimized via data analytics. A manager at one integrator states: "[An integrator] allows customer to focus on their core business, which is not robotics or automation." Thus, it seems likely that much of the value generated from the application of automation and analytics to production could be appropriated by integrators. This likelihood is probably increasing to the extent customers are willing to outsource to integrators the knowledge required to set up and maintain a "smart manufacturing" unit, which would be more likely for firms pursuing the Taylorist philosophy. Put simply, the less customers know about their operations, and thus the less they know how to optimize them, the more integrators can do it for them and not only charge more for it, but also leverage the knowledge spillovers accrued from accumulating data and experience to other settings. Moreover, it seems that it is Taylorist firms that are more at risk.

In the few instances where Industry 4.0 is becoming a palpable reality, different players in the value chain are already haggling over one of the main causes of value migration: data. In these settings, data on production is continuously generated by machinery equipped with sensors. A manager from one integrator made it clear that robot manufacturers have their eyes set on the customer-generated data: "Fanuc continues to capture data on its equipment when it's used by GM (and other customers I think)."

Similarly, an industry association staffer highlighted the conflict that could arise over who controls the data: "Who controls the data that automation throws off is going to be an important discussion. You could imagine the integrator or the robot manufacturer owning the data, doing predictive analytics, and making a guarantee that if the process is run a certain way that there will be a certain amount of uptime."[17] In fact, these conflicts are already starting to take place: a manager at another integrator reported a disagreement that occurred between his company and a robot manufacturer they work closely with. The disagreement was over who would have control of the data collected in the cells implemented by the integrator that used robots from the supplier in question. The two firms eventually figured out an agreement where both would benefit from the data, using it to set up a joint consulting operation.

Despite signs of growth, customer demand for Industry 4.0-based manufacturing environments is still in its very incipient stages. In the words of a manager at an integrator: "We

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[17] This business model would be similar to Kuka's proposed "manufacturing as a service" described above.

don't do any 'big data industry 4.0' stuff … The industry is trying to standardize but it's not there yet." According to David (1990), this is a common occurrence in the history of technological adoption. While describing the context of electricity adoption, he offers: "At the turn of the century, farsighted engineers already had envisioned profound transformations that electrification would bring to factories, stores and homes. But the materialization of such visions hardly was imminent. (…) Certainly, the transformation of industrial processes by the new electric power technology was a long-delayed and far from automatic business" (p. 356). David asserts that this delay can be attributed to the unprofitability of replacing existing plants and equipment, and that the acceleration of adoption had to wait for the physical depreciation of capital and a capital formation boom that accompanied a climate of macroeconomic expansion in the 1920s. While determining whether the same process applies to our context would require a more thorough investigation, it can be argued nonetheless that it is a plausible hypothesis.

The fact that, as the quote points out, Industry 4.0 is not yet a standard means that integrators are not yet in a position to appropriate as large a share of the value generated in the supply chain as we hypothesize could be the case in the future. Consequently, automakers and parts suppliers still do not see integrators as threats to how much value they capture.[18]

Propositions

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[18] Industry analysts are aware of this possibility however. McKinsey advises traditional automakers to adopt Industry 4.0 ("the next generation of lean production") as one of four strategies to avoid losing out in consumer markets to "technology players." Despite this warning, the use of the term "lean" (sometimes a synonym for the Toyota Production System), their description of an Industry 4.0 success at an automaker echoes more Taylorist than Pragmatist in its assumption that data collection and use does not involve people in any way worth mentioning: "By applying advanced analytics and in-line automated quality management to a metal-machining process, it boosted overall productivity by more than 30 percent, reduced scrap by 80 percent, and shortened process time by 50 percent. The company fitted computer-numeric-control machines producing crankshafts with Internet of Things sensors to extract and monitor performance data and developed an algorithm to analyze this data in real time to detect and immediately correct quality deviations. In addition, it analyzed the data to optimize tool positioning to increase throughput." (Aboagye, *et al.*, 2017)

How will the development of Industry 4.0 shape, and be shaped by, management paradigms, organizational and industry architectures? In this section, we hypothesize possible scenarios for the automotive industry. Because these are propositions about yet unrealized possible states of nature, the data needed to test these predictions will not come along for a few years. Nevertheless, the propositions are useful as a framework to think about how the interplay of technological and strategic factors affects the evolution of such a transformative social phenomenon as automation.

As described above, digital entrants (be they integrators, robotics manufacturers or data analytics firms) interact with upstream parts suppliers and downstream auto manufacturers. In principle, digital entrants provide physical integration of advanced automation into production lines and manage data produced by the automated lines. The latter is at the heart of what people have in mind with Industry 4.0, but our field research has revealed only nascent efforts by digital entrants to perform such a function thus far. However, they are starting to provide such services, potentially shifting the industry architecture, especially for Taylorist manufacturers.

In this process, much of the value generated in the production process could go from being derived from the specific capabilities (often highly tacit) that each industry requires and that belie the competitive advantage of manufacturers, to being derived from the mastering of general purpose manufacturing capabilities associated with modern automation – more specifically, the management and optimization of interconnected automation cells within plants, firms, and entire supply chains. This is a scenario where the development of Industry 4.0 technology will be such that firms operating under the Taylorism paradigm will gain prominence over firms operating under the Pragmatism one. The location of bargaining power in the value chain has implications for the total amount of value created in the industry.

P1. To the extent that data can be usefully separated from its context, total value creation in industry will be higher if digital entrants that operate across industries gain prominence in the value chain, relative to manufacturers.

To the extent that large datasets are not available (or not sufficiently enlightening), then process improvement depends crucially on a deep understanding of the individual manufacturing processes that generated the data. Accordingly, this is the scenario where Pragmatism becomes the most relevant paradigm for manufacturing under Industry 4.0.

P2. To the extent that a detailed understanding of a manufacturing process is helpful for understanding the data generated by that process, total value creation in industry will be higher if manufacturers retain prominence in the value chain, relative to digital entrants.

Akin to what Jacobides *et al* (2016) described in their case study, automakers and component manufacturers could perceive digital entrants as threats to their current share in the value distribution of the industry. If so, the prediction that follows is that these firms will develop internal general-purpose automation capabilities so as to prevent a market for integrators from fully flourishing. Jacobides and Winter (2005) describe how a firm’s decision to acquire new capabilities and redefine its scope is highly contingent on organizational identity and framing – self-perception affects what capabilities managers pursue. If banks consider themselves to be strictly banks, they are less likely to try to expand their data-processing and IT capabilities than banks that see themselves not only as banks, but as information processors and data handlers. Firms that have a broader self-perception are thus willing to draw on techniques from different sectors than banking *per se* in their capability development process. Analogously, manufacturing firms that begin to see themselves also as, for lack of a better term, “technology firms,” would be more likely to invest more in the emerging manufacturing technologies, thus relying less on integrators. In this scenario, automakers and suppliers increase their value appropriation to the detriment of the digital entrants, leading to our next propositions:

P3: To the extent that manufacturers see digital entrants as threats to profits, then we expect manufacturers will develop internal automation and data analytics capabilities.

Additionally, if there is asymmetric investment in technology by downstream or upstream manufacturers this could increase visibility from one part of the supply chain into other parts of the supply chain, which shift value from one set of firms to another. For example, automakers could use increased visibility into upstream parts suppliers operations to reinforce their lead role, leading to more value for the automakers relative to parts suppliers.

P4: To the extent that manufacturers develop internal automation and data analytics capabilities, they will acquire increased visibility into the operations of other manufacturers in the supply chain, leading to a shift in value toward the data-savvy manufacturers.

We expect the technological shock of Industry 4.0 automation to differentially affect firms depending on their management paradigm. As noted above, a key tenet of Industry 4.0 is the increased connectivity of equipment used in a production line within a plant and also increased connectivity of plants to each other along the value chain. To the extent that manufacturing plants along a value chain are organized according to a pragmatist paradigm, they are already coordinating with each other. Thus, we expect that layering additional connectivity on top of this will not shift value away from the manufacturers.

In contrast, manufacturing plants that are organized according to a Taylorist paradigm have less managerial coordination along the value chain. We therefore expect that layering additional connectivity on top of this will be disruptive, potentially shifting value away from the manufacturers. In particular, under the Taylorist paradigm, the interfaces between firms or production processes are relatively standardized and simple (as indicated in Figure 2). While this standardization may allow for quicker automation, it is not clear that it provides an opportunity for the manufacturers to capture any added-value from the automation. The manufacturers have few established relationships, tacit knowledge, or trust with suppliers or customers, providing an opportunity for any other type of firm to enter and establish these relationships. Thus, we would expect that third party providers of automation services—be they robotics firms, integrators or data analytics firms—to capture much of the value.

P5: When responding to the technology shock of Industry 4.0 automation, manufacturers are likely to create and capture more value if they operate according to the Pragmatist paradigm (compared to using the Taylorist paradigm).

So far, we have considered technological developments to be exogenous to firms' strategies. Firms simply would react to what is the state of technology at any point in time – or, more precisely, to what they perceive to be the state of technology at any point in time, since the concept of "current state of the technology" is a fuzzy one to economic agents, who are cognitively limited in their ability to exactly pin down the possibilities offered by technology. However, the extent to which technology develops, including the feasibility of separating data from context, is also somewhat endogenous to the efforts and strategies of firms. Taylorist firms can "impose their beliefs" on how technological processes develop over time, in a way that more separation is created due to their efforts. Conversely, "Pragmatic" equipment design would place more emphasis on user-friendly user interfaces, so even people without special training (such as frontline workers) can help collect and analyze data.

P6: Firms will attempt to influence the development of Industry 4.0 technology in the *direction of the manufacturing paradigm they subscribe to.*

8. Conclusion

Our paper develops a framework that links organizational and industry architectures to value creation and value capture. We then use this framework to offer several predictions about how the adoption of Industry 4.0—the coordinated use of robots, sensors, AI, and other digitally-enabled technologies in manufacturing—will affect which firms capture value in manufacturing. We use our framework to argue that the effect of Industry 4.0 on value creation and capture will depend critically on a firm's management paradigm, and particularly how this paradigm influences views about the nature of knowledge in the firm.

Existing literature describes value migration across firms as potentially resulting from changing industry architecture. We build on this literature by highlighting that value migration *within firms* likely affects the nature of value migration *across firms*. We describe two industrial paradigms currently in use in the automotive sector, Taylorism and Pragmatism, which we believe will lead to different patterns of value migration. If factory owners develop ways of automating that capitalize on their greater access to the context in which production data is generated, they will be better able to prevent value from migrating to "digital entrants" that offer automation consulting and data analytics. Manufacturers can do this by adopting an organizational architecture that empowers shop-floor workers to combine their local knowledge with digital tools. Conversely, to the extent that digital entrants develop a more abstract version of these tools that they spread across industries, then these entrants will capture more value.

We develop our insights using in-depth interviews with firms in automotive value chain. We focus on the auto industry because of (i) its importance to the US economy as a whole, (ii) its intensive use of robots relative to other industries, which lead us to believe it will be an early adopter of Industry 4.0, and (iii) its history of different industrial paradigms. We have focused on issues that arise in the production of automobiles, and not in their use, precluding a discussion of the implications of autonomous vehicles for industry and organizational architectures (see Appendix 2 for discussion of this issue). Compared to other industries, the auto industry has high volume and moderately high precision requirements.

Despite this focus, we believe that our results will likely have implications for the causes and consequences of value migration and diffusion of “smart” production technologies such as Industry 4.0 in other sectors, including both manufacturing and services. For example, Komatsu collects data on how its construction industry customers use its equipment, aggregates it, and feeds it back in terms of advice about the most energy efficient way to lift a load with a backhoe; the company has set up an open platform for its customers, with potential implication for industry architecture. Similarly, hospitals struggle with questions of organizational architecture, such as the extent to which expert systems or the judgment of physicians or nurses should be the basis for deciding on diagnosis and treatment. Both construction firms and hospitals risk losing value given the increasing role of digital entrants in their industrial architectures.

The technological advances that we study have implications for labor in a wide variety of occupations. The notions that a computer can substitute for labor, or that a plant can be completely automated and monitored from a distance, rely on a similar assumption: that data can be understood even though it has been separated from the context in which it was created. This is a strong assumption, especially given prior research on the complexity of technology adoption when there are complementarities, for example between the new technology, labor, and incentive structures (Bresnahan, Brynjolfsson, and Hitt 2002; Brynjolfsson and Milgrom 2013).. Thus, we believe our paper provides a useful counterpoint to the doomsday scenarios sometimes described in the popular press that robots will take all the jobs. Our predictions suggest that this need not be the case, or at least that the extent to which robots will substitute for jobs will depend critically on the nature of the firm’s managerial philosophy regarding the nature of knowledge and the desired interfaces with labor.

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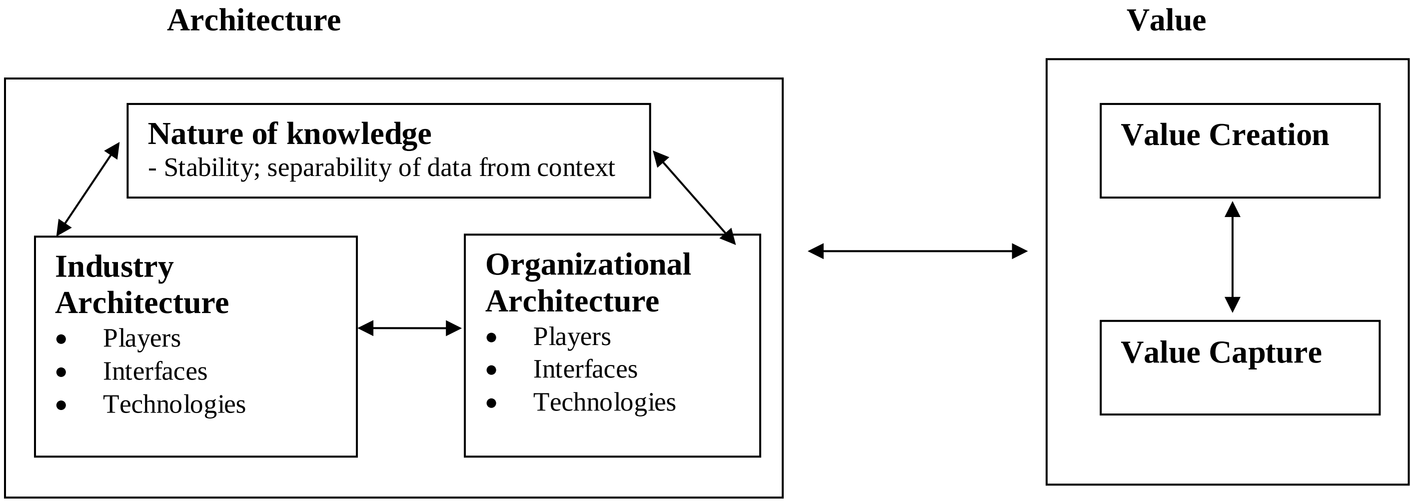


Figure 1: Value and Architecture: General Case

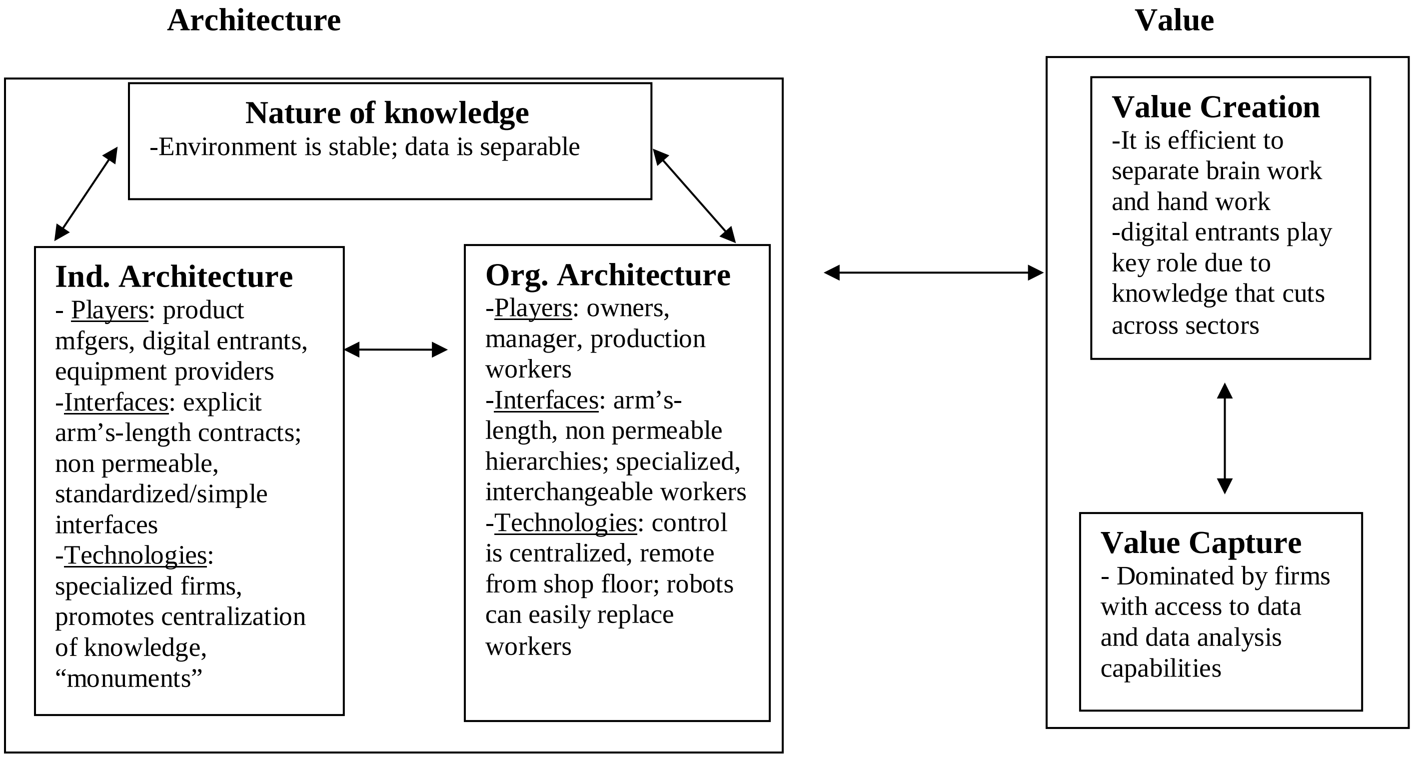


Figure 2: Value and architecture - Taylorist case of automation

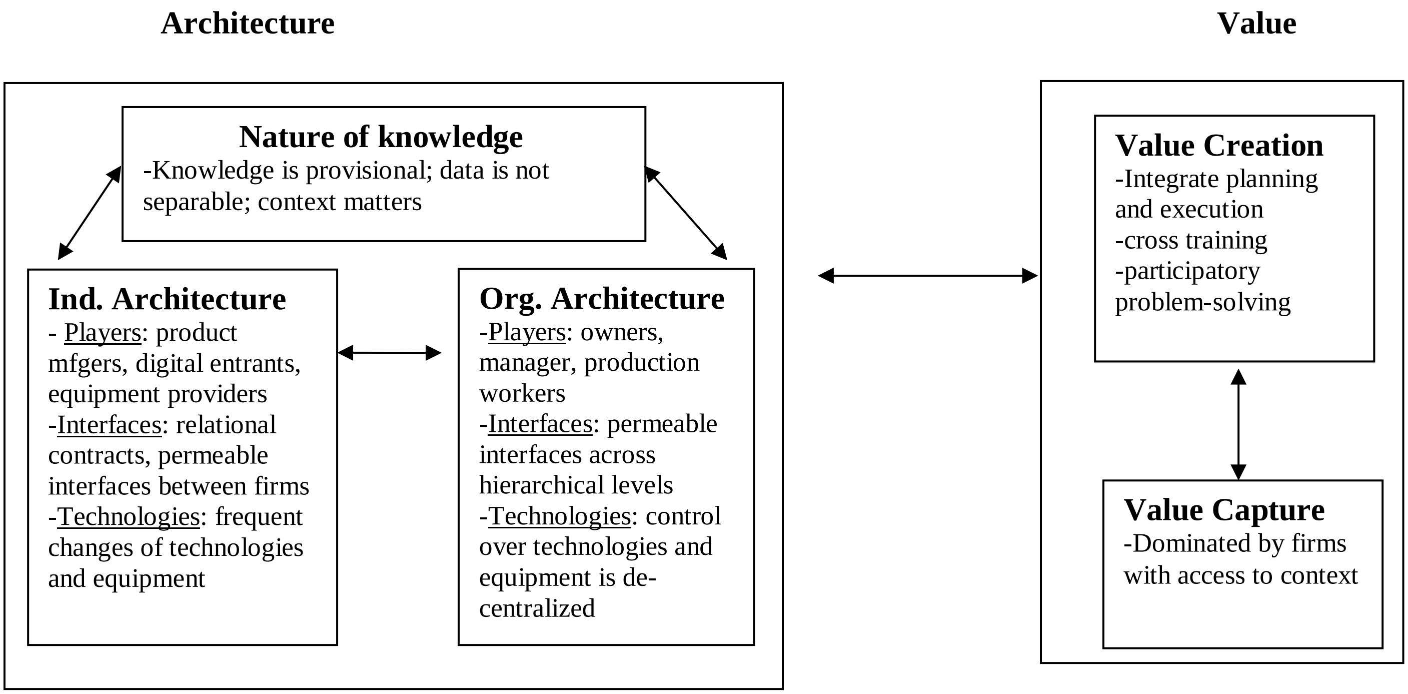
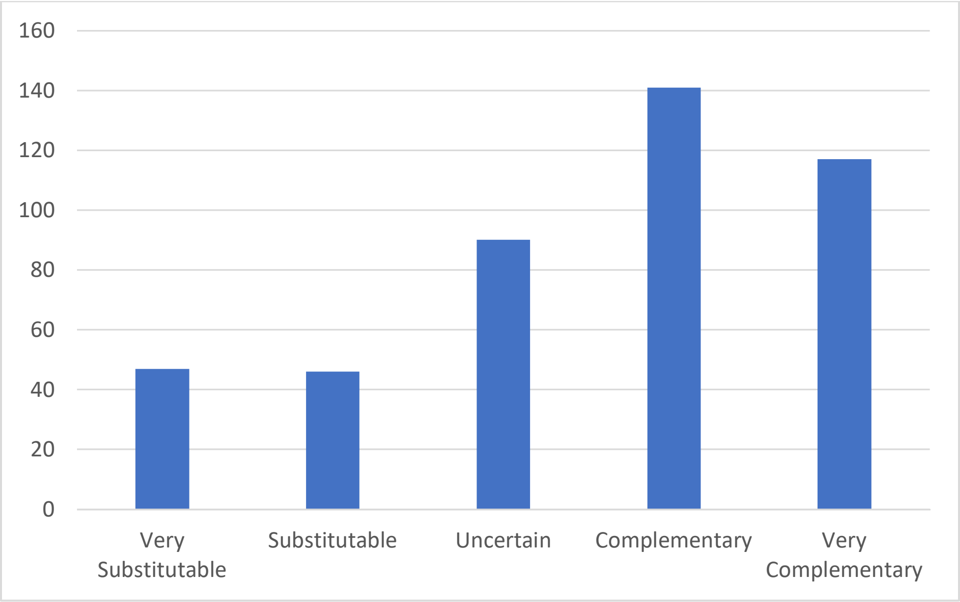


Figure 3: Value and architecture - Pragmatist case of automation



Firm responses to: " 'We have found that use of Information Technology (IT) reduces the need for shop-floor workers to have analytical skill.' Strongly Agree, Agree, In Between, Disagree, Strongly Disagree?"

Figure 4: Heterogeneous views of labor across firms

Supplemental Appendices Follow

Appendix 1: Interview Methodology and Quotes

As part of our study, we conducted multiple phone interviews, site visits and plant tours during 2016 to 2018. We talked with firms representing each part of the Industrial Architecture, and with employees in each part of the Organizational Architecture. We identified firms through industry directories and trade association membership. In particular, representatives from the Center for Automotive Research (CAR), a non-profit automotive research organization based in Ann Arbor, Michigan, and from the Robotics Industry Association (RIA), a trade group of robotics suppliers and integrators based in Ann Arbor, Michigan, were particularly helpful in arranging interviews and site visits. We deliberately chose firms that represented a variety of approaches to the question of whether automation substitutes for or complements worker skill. We were able to check for representativeness of our interview sample by examining the 2011 survey data (see Helper and Kuan (2018) for additional details on the 2011 survey), which had a 35 percent response rate and was broadly representative of the national distribution.

All plants we contacted were located in the United States; some were owned by German or Japanese parents. Our site visits included two automakers, 13 auto suppliers (i.e., upstream from automakers), a small robotics manufacturer, two mid-sized robotics integrators, and one very large robotics integrator. We also met in person with three industry trade groups, three technical assistance organizations, and conducted telephone interviews with one other automaker, four other auto parts suppliers, three other integrators, one industry association and staff members of two unions. We also attended two trade shows, three industry conferences, and an industry reception where we spoke with representatives from multiple manufacturing and data analytics firms. We spoke with owners of small companies; executives of large companies in engineering, purchasing, marketing, and human resources; technicians, skilled tradespeople, and production workers (both union members and not). Interviews started with open-ended questions about the automation process in their firm, with follow-up questions on: their views on reasons for adopting robots and other new technologies; how employees and the production process adapted to these new technologies; how these new technologies affected the firm's relationship with customers and suppliers; and interviewees' views on the promise of the Industry 4.0 paradigm. Representative quotes from our interviews have been gathered together in the tables that follow.

Table A: Why automate now?

Skill Base; Labor "In our German plant, operators do a lot more with the automation, because they are better trained than they are here." [Supplier 2, 10/20/2017] "The 'opioid issue' is hitting some of my customers. The issue is whether labor will be there every day." [Integrator 1, 10/20/2017] "Sometimes the project is to replace workers, sometimes it is to increase value-added." [Integrator 1, 10/20/2017]
Growth or Specific Need "Some customers get hot, need automation as the company grows. Automation comes into play when customer can't keep up because volume reaches a critical mass." [Integrator 2, 10/23/2017] "For most of our members, automation is driven by a specific product [e.g., winning a large order], even if the automation is flexible. For contract manufacturers, automation is a much harder sell." [Supplier trade association technical director, 10/10/2017]. "The majority of applications are catered to customers' unique needs." [Integrator 2, 10/23/2017]

Costs of integration falling "Automation is much more doable for a small firm like ours now – don't have to program in assembly language and there are integrators to help us" [Small supplier 1, spring 2017]

Table B: Automating is harder than anticipated (still a role for tacit knowledge)

Simple Coordination "Firms don't want to call a robot guy, a press guy, a controls guy – they want to make one phone call". [Supplier trade association, technical director, 10/10/2017].
New Processes "Adding data and sensors is a big change from the traditional black art of tool and die." [Technology trade association director, 10/30/2017] "Automation is adopted gradually by clients, so they can become more comfortable and have more ideas of how it can be applied." [Integrator 1 10/20/2017] "We'll have to present the foam pads to the robots differently than we do now – get the pads on a roll instead of the strips we do now. … The robot will be slower." [Engineer, Small supplier 1, 11/30/2017]
New Skills Needed/Lack of Capabilities "Have to learn by doing; physical ability is part of it. Its like a sport, you have to learn certain moves." [Tool and die shop owner, 10/26/2017] "When a worker is running a robotic cell, it takes more skill than before. They have to make sure that the robot is supplied with material, they have to stage the parts, they make sure the process is continuing to run. When it's down, they do low-level trouble-shooting, they have to do the beginning of the re-start process. Now they have a bit of their time they have to manage to get all this done – it's not just standing at the machine pushing a button." [engineer]. It takes several days for an experienced operator to learn to run the cell. This makes it more important to have the same person there every day – so turnover and absenteeism become more important [CEO, small supplier 1, 11/30/2017]. "Workers are unskilled, and stamping is esoteric, it requires many specific skills that

cannot be taught in any way other than by doing (CNC is an exception). It takes 8 years to become good at it, including the apprenticeship. Some steps of stamping can be programmed in CNC, but the final steps that cannot." [Tool and die shop owner 10/26/2017] "Cost of the robot is 20-30% of the cost of the system. Use of integrators is driven by lack of internal resources – firms cut engineering resources during the crisis. Companies believe integrators offer them something they can't do on their own. Even larger companies have outsourced integration, though some of them still have that capability internally." [Technology trade association staff 11/10/2017]
Opportunities for Learning/ Protecting Knowledge "We like to do one learning job per year to 'push the envelope of what we know.'" [Integrator 1, 10/20/2017] "Knowledge around one plant is transferable to other plants. We pick up 'tips and tricks'" [Integrator 1, 10/20/2017] "We try to internalize as much knowledge as possible and not outsource it to suppliers, so we can access it faster." [Supplier 2, 10/27/2017]

Table C: Impacts of automation

Replace Workers "Sometimes the project is to replace workers, sometimes it is to increase value-added." [Integrator 1, 10/20/2017] "But the robot won't take breaks, get tired, join a union. It can work three shifts – so it should pay back in less than a year" [CEO, Small supplier 1, 11/30/2017] "You can program robots easily –just put them in teach mode and move the arm where you want it to go. But, robots are dangerous, slow, can't pick up much (5kg) – want to see what OSHA says." [Technical director, supplier trade association, 10/10/2017]
Change Role of Workers [Pointing out the person who was displaced when they put in the additional label maker] "Now she's a lead – makes sure the material is there – sometimes she pushes the pallet herself, sometimes she gets someone else – makes sure the people are there to run the job. She's much happier, gets paid more…. Now, we need her because the process is not under

control. Really we shouldn't need a lead to expedite things [CEO, Small supplier 1, 11/30/2017]

"Now that we have cameras, the worker doesn't inspect anymore – they just pack the good ones. The machine decides go or no go." [Engineer, Small supplier 1, 11/30/2017]

New Management or Customer Ideas

"[Blue light] is a 'terrible invention' it allows end user to demand more from us in terms of matching certain tolerances of detail, even for stuff that doesn't matter – it can be in tolerance when it leaves our die, but out of tolerance once welded – steel is floppy" [Tool and die shop owner 10/26/2017]

"We spend a lot of money 'chasing tolerances that don't matter'" [Tool and die shop owner, 10/26/2017]

"New data systems like Plex mean we [top management] can do a lot of things ourselves. The CFO and I did a deep dive into costs on individual products – before we would have had to ask cost accountants to spend a week figuring this out, we would have had to ask a guy to go out on the floor and count parts to see where we were with production and inventory." [CEO, Small supplier 1, 11/30/2017]

Table D: Value migration

Not Yet Happening

"We don't do any 'big data industry 4.0' stuff" … "The industry is trying to standardize but its not there yet." [Integrator 1, 10/20/2017]

"Problem with centralized data-mining is that it might be impossible to establish causality if many goods are being produced and there are time lags." [Director, Large integrator 3, 10/12/2017]

"Assumption that integrators reduce the need for programmers is fair. Also, systems have become much more user-friendly."]Integrator 1 10/20/2017]

Some Shift in Roles

"[An integrator] allows customer to focus on their core business, which is not robotics or automation." [Integrator 2, 10/23/2017]

“Many integrators started out because of outsourcing from auto manufacturers.” [technology trade association staff 11/10/2017]

Capturing Data

“Fanuc continues to capture data on its equipment when it’s used by GM [and other customers I think].” [Integrator 1, 10/20/2017]

“Who controls the data that automation throws off is going to be an important discussion. You could imagine the integrator or the robot manufacturer owning the data, doing predictive analytics, and making a guarantee that if the process is run a certain way that there will be a certain amount of uptime.” [Technology trade association]

Appendix 2. Autonomous Vehicles: Implications for our analysis

This paper studies how the emergence of new technologies affects value creation and value migration in the automotive industry. Our analysis was oriented towards the value generated by manufacturers and how it could change going forward—i.e., focused on production. . Yet, new technologies will also play a large role on the demand side of the industry, bringing about important changes to how cars are consumed. The acronym CASE, standing for Connected, Autonomous, Shared and Electrical, encapsulates what this new era would consist of, leading to the emergence of new business models (such as “personal mobility as a service”) that will have significant repercussions to how value is created and shared among incumbents and entrants. Given the relevance of these changes to the demand side, why focus on the production side? We argue that industry analysts themselves have showed that, despite the excitement over the new opportunities being created on the demand side, manufacturing will still be a significant locus for competition over profits in the next few decades.

For example, according to the Boston Consulting Group, by 2035 human-driven cars will still represent 77 percent of new car sales, and the personal car will represent 82 percent of on-road passenger miles. Therefore, while CASE is obviously the major growth vector in the industry for the next 20 years, in the larger scheme of things it would still take several decades to become the dominant paradigm for car usage, if it ever does. Additionally, BCG estimates that the industry profit pool will grow from $225 billion in 2017 to $380 billion in 2035, with profits available in the production of classic components staying relatively stable (going from $67 to 70 billion), profits from on-demand mobility growing to a similar level at $76 billion, and profits in the production of AV components growing to $26 billion. (Note that since BCG's research focused on CASE, these figures underestimate new profits that will arise from the manufacturing of classic components and vehicles.) Overall, these numbers point to the continued relevance of the production side, be it for CASE production or not, to the competition for profits.