Value Migration and Industry 4.0: Theory, Field Evidence, and Propositions[1]

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Abstract: Our paper offers several predictions about how Industry 4.0—the coordinated use of robots, sensors, AI, and other digitally-enabled technologies in manufacturing—will affect which firms and occupations capture value in manufacturing. We develop our insights using in-depth interviews with manufacturers that are part of the automotive value chain, including parts suppliers and automakers, and with integrators who provide robotics and other advanced automation to manufacturers. Among other findings, we highlight that value migration within firms likely affects whether and how value migration occurs across firms.

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1. Introduction

Innovation is a key driver of economic growth (Abramowitz 1956, Solow 1957, Romer 1990). Recent advances in artificial intelligence, robotics, and sensors will likely lead to many new innovations that contribute to growth (CEA 2016). In manufacturing, these technologies are collectively referred to as "Industry 4.0." However, there is often a large gulf between the time a new innovation is created and the time of its adoption.

In some cases, adoption of technology can be relatively straightforward and simple, particularly if the technology is a separable input that does not involve interactions with other inputs into a firm's production function. In other cases, it can be complex, as when there are complementarities, for example between the new technology, labor, and incentive structure (Bresnahan, Brynjolfsson, and Hitt 2002; Brynjolfsson and Milgrom 2013). Adoption of automation falls more in the latter category. It implies, at least to us, the use of a new technology that changes a firm's production process. To a firm adopting automation, the way in which a production process should change may not be clear, especially given complementarities within the firm, and may vary across firms depending on pre-existing organizational structures and the institutional environment in which they operate. Thus, firms may adopt new technologies in different ways. In the past, for example, Japanese, German, and American firms have adopted automation in different ways. For instance, in adopting computerized machine tools (CNC) German firms were more likely to combine the functions of programmer and machine operator, while American firms have typically separated them (Kelley). One might imagine, therefore, that Industry 4.0 will diffuse heterogeneously across different types of firms and sectors.

In this paper, we pull from observational data and historical literature to explore how Industry 4.0 will diffuse across firms and affect the creation and capture of value along value chains. We draw inspiration from a strategy literature on value creation and capture (Brandenburger and Stuart 1996), and from literatures on organizational architecture (e.g., Milgrom and Roberts) and industrial architecture (e.g., Jacobides). The industrial architecture literature describes how value "migrates" across firms and along a value chain over time. We argue that organizational architecture *within* firms—by which we mean the management practices within the firm, including the extent to which management views workers as partners to the production process, or as commodities—likely affects whether and how value migration occurs *across* firms.

Additionally, this paper explores the increasingly important role of "integrators" which intermediate between robotics firms and manufacturers.

We focus our attention specifically on the automotive sector for several reasons, including (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) the widespread presence within the US auto industry of two different industrial paradigms. We group these paradigms into two categories: mass production (an approach preferred by US manufacturers and which tends to view automation as a substitute for workers) and pragmatism (an approach preferred by Japanese manufacturers and which tends to view workers as complements).

The paper proceeds as follows. The second section provides background on Industry 4.0, robotics, and integrators. The third section provides background on the US automotive sector, including describing the different players along the value chain. The fourth section introduces existing literature on value creation, value capture, and value migration for both industry architecture (IA) and organizational architecture (OA). We then link IA and OA through a literature on industrial paradigms. The fifth section describes our findings from multiple site visits and interviews with automakers, parts suppliers, and integrators. The sixth section provides our propositions. The seventh section concludes.

2. Background on Industry 4.0, Robotics and Integrators

Industry 4.0

We focus on the recent rise in automation, including the use of robotics, AI, sensors, and other digitally-enabled technologies used in manufacturing that are collectively termed "Smart Manufacturing," "Industrial Internet of Things," or "Industry 4.0." In general terms, Industry 4.0 encompasses the increased digitization of the manufacturing world, and such digitization is driven by developments such as: the increased ability of sensors to collect data on all aspects of a production line, ranging from time elapsed between production stages to fine-grained detail on production outcomes that leads to heightened levels of quality control; the increased computational capacity to quickly analyze this huge amount of data and to make automatic production decisions based on these analyses; the increased ability to digitally connect machines within a factory so that information flows seamlessly among them, as well as to digitally connect production units to their upstream suppliers and to their downstream customers.

An important part of the Industry 4.0 vision is the idea that continuous collection and analysis of data in real-time will allow managers (both at middle and upper levels) to remotely monitor manufacturing operations and alter them as needed. For example, in a comment on its website on the emerging manufacturing paradigm, a large electronics and semiconductors firm states: "Remote monitoring, ideally, should be accessible anywhere (…). However, accessibility isn't the only part of remote monitoring systems (…). These systems have to allow business executives to not only see performance data, but also control operations. Remote monitoring systems can enable shutting on or off equipment or acknowledging and responding to an alarm."[2] In part, their decisions will be augmented by predictions from powerful software tools such as machine learning (Agrawal, Gans and Goldfarb 2018). This idea of remote monitoring and control is consistent with a mass production management philosophy, which is discussed in Section 4.

Automation has for over a century been a feature of manufacturing, but these new technologies differ in substantial ways from prior episodes of automation. Historically, production cells within a factory would go through the process of automation in isolation from one another. Now, however, Industry 4.0 enables management to integrate all the production lines into a coherent system within a "smart" factory, and even to integrate a group of factories and manage them using sophisticated "big data" analytic techniques. Thus, as described below, capabilities related to system integration are in high demand, and we expect these integrators to increasingly be at the forefront of the technological evolution of manufacturing, with important consequences for how value chains are structured. In principle, these technologies allow for the automation of the entire value chain, allowing it to be responsive in real-time to changes in demand.

There is much excitement about the prospect of Industry 4.0 to increase productivity, improve product quality, minimize disruptions due to labor shortage or other supply shortfalls, and meet changing customer demand. However, there are many reasons why adoption of these technologies may be slower than anticipated, including: the need to upgrade antiquated equipment

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[2] See, for example: Innovasic. "IoT enabling remote monitoring, enhanced plant automation control." Press Release. July 7, 2014. http://www.innovasic.com/news/industrial-ethernet/iot-enabling-remote-monitoring-enhanced-plant-automation-control/

and legacy technology; the need to adjust corporate or operational processes; the availability of workers with the requisite skills to operate the new technology; and fear of issues related to data privacy and cybersecurity.

We focus on these issues as they arise in the production of automobiles, and not in their use . That is, we focus on the *Industrial* Internet of Things, and do not discuss issues regarding autonomous vehicles. These distinctions are becoming blurred, as firms like Freightliner harvest data from their customer to not only offer them tips about how to increase fuel economy, but also how to improve the manufacturing of their products.[3] For now, however, our focus remains within the factory and production supply chains.

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. Robots are typically referred to as an "actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks [ISO]."[4] The International Federation of Robotics (IFR) provides annual, aggregated statistics of the number of robots shipped by country and by industry. Figure 1 provides estimated robot shipments by year, 2004-2016. The figure 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% between 2010 and 2016. The increase in robot shipments in the US was not as dramatic. Robot shipments to the US increased about 100% between 2010 and 2016.

This rapid increase is likely due to a combination of factors including a decrease in robot prices, an increase in robot functionality and flexibility, an increase in ease of use and interface, growing awareness of the potential cost-saving and/or value-added benefits provided by robots,

[3] Detroit. "Detroit Connect Analytics Delivers Fuel Economy and Safety Insights to Fleets." Press Release. September 1, 2016. https://demanddetroit.com/our-company/media/press-releases/detroit-connect-analytics-delivers-fuel-economy-2016-09-01
[4] ISO 8373, 2012, available at https://www.iso.org/obp/ui/#iso:std:iso:8373:ed-2:v1:en

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% between 1990 and 2005.

The dramatic change in ease of use of automation is apparent in some pictures we have taken during our site visits. For example, Picture 1 is a picture of an automated plastic injection mold machine at a medium-sized auto supplier plant in Michigan. The machine, which was built in 1980, has a number of dials, switches, and other controls that the machine operator would use to produce parts. Picture 2 is a picture of the user interface on a similar machine at the same plant built in 2017. The user interface is a touch-screen, similar to those used on smartphones and tablets, which the operator uses to control the machine. 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.

Figure 2 focuses exclusively on the US and provides an annual industry breakdown of the number of robot shipments. As indicated by the figure, approximately half of all robot shipments are to the US automotive sector, and about 20% to the consumer electronics sector. The Council of Economic Advisers (CEA) provides a breakdown of robots per worker in the 2016 *Economic Report of the President*. CEA's analysis shows that in the US automotive sector 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. The intensity of robots per worker in the US lagged that of Japan and Germany: in 2012, there were approximately 1,563 robots per worker in the Japanese automotive sector and approximately 1,133 robots per worker in the German automotive sector.

Integrators

An important part of this story of increased robot adoption is the crucial role played by robotics integrators. These are firms that sit between upstream suppliers of robots and automation technology and downstream customers – manufacturing firms which want to automate some part of their production process (see Figure 3). Much of what integrators do is 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, given that 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 if any 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” and in fact some large industrial equipment manufacturers such as Rockwell perform integrator-like functions as well. Amongst “pure-play” integrators, some are small 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% over the past 10 years.

3. Auto Industry Setting

Industry Background

While Industry 4.0 affects all of manufacturing, we focus our attention on the automotive industry. As indicated in Figure 2, this industry dwarfs other industries in the number of robots shipped annually. Acemoglu and Restrepo (2017) find that automotive purchasers account for 39% of the stock of robots in the US, by far the largest adopter (Acemoglu and Restrepo 2017).As Figure 4 shows, 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% of the market capitalization in the industry; this overstates their share since many of the smaller firms are privately held. Measured by employment levels, auto parts suppliers dwarf the automakers, most of whose employment is in motor vehicle manufacturing (and some in motor vehicle body manufacturing). Because of difficulties in assigning individual factories to industries, employment in auto parts manufacturing is significantly underestimated; it is probably twice as large as presented in the chart (Economic Report of the President 2013; Helper 2012).

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.

For reasons described in Section 4, 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 (Helper and Henderson, 2014).

Data from a 2011 survey by Helper (2012) documents this on-going weakness. Small-firm productivity growth is hampered by 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 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, 2017 for information on survey methodology). In the next subsection, we focus on survey results that shed light on how suppliers differ in terms of their approaches to managerial choices when facing technological change.

Many of the smaller suppliers are now considering adopting automated technologies such as robots and machine vision systems (cameras used to automate inspection). Our recent interviews focused on these smaller firms. We visited two automakers and eight auto parts suppliers in which we spoke at length with engineers and senior management and did plant tours. Over the course of

2016 and 2017, we visited three industry trade groups and spoke with individuals who interact with integrators or manufacturers on a regular basis, and we visited one small robotics manufacturer, one mid-sized robotics integrator, and one very large integrator. We spoke with two other suppliers, three other integrators, and one industry association by phone. We also attended two trade shows, an industry conference, and an industry reception where we spoke with multiple manufacturing managers and data analytics firms.

Auto Industry Survey Data Results

One question on the 2011 survey elicited how much firms' managers believe IT is complementary to/substitutable for shop-floor workers' analytical skill. More specifically, the 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. Using descriptive analysis, we examine how firms' answers to this question vary across how they answer two other questions: "What is the average wage (not including benefits) at this plant for unskilled and semi-skilled workers?"; and "About how many employees at this plant have received some formal training in Continuous Improvement methods?" In other words, we want to know if there is a statistically significant difference (at the 95% level) between the number of firms that consider workers to be substitutes or complements and how much these firms pay workers, as well as how many of these workers are encouraged to receive Continuous Improvement training.

Figure 5 shows the distribution of responses to the question of whether firms view shop-floor worker skill to be complementary or substitutable to the adoption of IT. Most managers leaned towards viewing them as complementary.

Figure 6 shows how answers to the complementarity versus substitutability question correlates to how much firms pay their unskilled workers. While the small sample of firms that answered both questions makes it harder to discriminate between alternatives in a statistically significant way, nevertheless we do see a general correlation between firms that consider shop floor worker skill to be complementary to IT to those paying their workers higher wages.

Finally, Figure 7 shows how answers to the complementarity versus substitutability question correlate to the percentage of employees receiving Continuous Improvement Training in each firm. Firms that consider shop floor worker skills to be complementary to IT enroll higher percentages of employees in Continuous Improvement training.

Thus, these graphs show descriptive evidence that not only do firms have different views on how technological change affects the knowledge requirements of a firm, but also that these different views are correlated with different managerial strategies, particularly when it comes to human resources (Section 4 presents the different managerial theories behind these views). Such evidence must be taken into account when theorizing whether and how automotive suppliers, and other firms in general, will adopt new automation technologies.

4. Industry Architecture, Organization Architecture, and Drivers of Value Migration

What drives firms to automate? The starting point we adopt for answering this question involves understanding how that decision affects how firms create and appropriate value. In this section, we first define our key terms: value creation, value migration, industry architecture, and organization architecture. We then briefly describe two factors—technology and strategy—that affect how value migrates within industry and organizational architectures.[5]

Both students of industry architecture (IA) and students of organizational architecture (OA) argue that exogenous technology forces and firm strategy drive how these architectures evolve. However, most authors look at the evolution of IA and OA separately. We follow this practice by first looking separately at the impacts of firm strategy and technology on IA and OA. We then introduce a discussion of "industrial paradigms" that we argue links industry architecture and organization architecture.

Value Creation and Industry Architecture

[5] In the interests of brevity, we omit other factors that affect architectures. A key omission is that of public policy, which has significant impacts on both industrial architecture (through factors such as antitrust law, R&D subsidies) (Jacobides and Winter 2005) and organizational architecture (through factors such as rules regarding unions, subsidies for training, even rules about the ways that pension funds may be invested) (Osterman; Lazonick).

Brandenburger and Stuart (1996) use a cooperative game theory framework to understand how distribution of value along the value chain is determined by bargaining among the players, with firms trying to play one supplier off against another and customers doing the same to firms. The explicit distinction between value creation and value appropriation is considered to be one of the main advantages of this framework (Ryall 2013, Gans and Ryall 2017). The term "industry architecture" describes "who does what" and "who takes what" along a value chain at a point in time. (Jacobides, MacDuffie and Tae 2016). The concept of *value migration* refers to changes in value appropriability along the value chain, over time, which can occur due to a change in the "industry architecture" (Jacobides, Knudsen and Augier 2006).

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 – in other words, what could be connected to an IBM-compatible system (Jacobides and Tae 2015). However, an effort to improve time-to-market led IBM to decide to bet on modularity, and it subsequently relinquished control over the operating system and the microprocessor. Microsoft and Intel, which had acquired control of these two main components, had the incentive to make their offerings compatible with all the other products in the value chain. As described by Curry and Kenney (2003): "Microsoft gladly qualifies other MPUs [microprocessors] to run its software such as the new Transmeta MPU, while Intel is anxious to support other operating systems such as Linux. Because lower prices encourage greater sales, every firm would like the overall price of a PC system to drop; their only wish is that the cost reduction occurs at other segments in the value chain." Thus, while IBM was busy fighting off competitors in its own segment (namely other OEMs 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 (Jacobides, Knudsen and Augier 2006). The result of increased modularity and the emergence of an open architecture was the waning of the dominance of OEMs in the industry architecture, with suppliers such as Intel and Microsoft gaining significantly more importance. Figure 8A below, taken from Jacobides and MacDuffie (2013), demonstrates how value migrated over the years in the computer industry (value being measured as market capitalization).

Shapers of industry architectures: Technological convergence.

A technological shock 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 manufacturing 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 a growing 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 in the cutting of 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. Additional breakthroughs in fields such as material shaping and forming, properties of materials, and continuous chemical processes, allowed for the emergence of new instances of the specialization/convergence phenomenon:

activities such as materials analysis and testing and the production of measurement and control instruments moved away from firms that were also the end-users, and were taken up by newly formed specialists.

Shapers of industry architectures: Strategic action

As the personal computer industry example illustrates, firms are not mere spectators in the industry architecture shaping process, passively observing the interplay of technological change, final industry arrangement, and value capture (Jacobides 2005, Ferraro and Gurses 2009). For one, firms and industry associations spend considerable amounts of resources trying to manipulate rules and regulations that affect their industry through lobbying and other practices. Beyond that, firms can engage in strategic management maneuvers 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/mobility of the components that are required in their production process (Jacobides, Knudsen and Augier 2006).

The strategies mentioned above 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 metrics and faster development time. In response, these automakers attempted to shift to a new paradigm of how to organize production in the sector, 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 and 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. By gaining control of key modules, the mega-suppliers could develop industry-standard components, which would lead them to be able to command higher margins and increased sales. OEMs initially were not attuned to this risk; they intended to emulate the example of the computer sector, which was seen 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, Macduffie, and Tae, 2016).

Eventually the OEMs did realize that this change in industry architecture was costly for them. The OEMs then decided to reverse course and deny suppliers the ability to produce standardized components across customers. 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, as indicated in Figure 8B.

Value Creation and Organizational Architecture

Economists have in recent decades begun to look "inside the black box" of the firm, to understand how firms transform inputs into outputs. 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). Milgrom and Roberts (1990, 1995) point out that organizational decisions in functional areas are highly complementary. For example, a firm that uses flexible manufacturing equipment (such as CNC) is likely to have shorter product development times and more highly skilled workers than a firm that uses specialized, inflexible machinery. There are important literatures outside economics that we draw on as well. The "labor process" literature argues that capitalist managers have incentives to develop and adopt technology in such a way as to de-skill workers on the shop floor.

An example of how organization architecture in our sense affects adoption of new technology is the case of CNC (Computer Numerical Control) Machine Tools. Machine tools cut away metal to make a highly precise, durable component. Traditionally, machine tools were operated by highly skilled machinists, who determined how to make a component. The machinist decided what sequence of cuts a machine should make, decided 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, 1993 and 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,[6] with significant pay differentials. Even taking into account the pay differentials, integration of programming and operating was associated with higher productivity. Noble argues that a desire to reduce worker bargaining power led management to choose the less-productive path.

Shapers of organizational architectures: external technology

An extensive literature argues that technological change is one of the main drivers 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, adopting practices such as the elimination of piece rates, giving workers authority for scheduling machines, and increased lateral communication and teamwork.

Shapers of organizational architectures: firms' strategy

A host of articles and books advises firms on how to reorganize to improve performance. Managers should choose practices that are complementary to each other, for example, by adopting flexible work practices if they adopt flexible equipment (Milgrom and Roberts, 1995). A literature on "high-road" practices argues that increasing worker skill while adopting a marketing strategy

[6] 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.

of frequent new-product introductions allows firms to be profitable while paying a higher wage (Osterman, forthcoming). There is evidence that firms actually adopt policies in complementary ways For example, Aral, Brynjolffson and Wu (2013) find that the adoption of human capital management software is greatest in firms that have also adopted performance pay and human resource analytics practices.

Linking industry architecture and organizational architecture: Industrial paradigms

The philosophy of "mass production" underlay much of US manufacturing prowess 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 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 in favor of smaller lot sizes, more experimentation, and a greater role in decision-making for shop-floor employees (Kenney and Florida, 1993; Adler, Goldoftas and Levine; Bergren, 1994).

Table 1 summarizes these differences, and their implications for the design and use of automation. The table shows correlations across practices, but does not attempt to determine which factors are the driving forces that cause the other factors. In some perspectives, views about the nature of knowledge are primary; in others, desired power relations (especially over workers) drive other decisions (Noble, 1978; Braverman, 1972).

A key enabler of mass production was a view that the environment is stable. Firms could make predictions about technology, markets, and demand that enable long-term plans and investments to pay off. Various policies can promote this stability, including for example government actions to manage aggregate demand through fiscal and monetary policy (Piore and Sabel, 1984). In such an environment, investing in high fixed costs to enable low variable costs made sense, because products could be run long enough to amortize the fixed costs. Since operations were stable, it also made sense to design a fixed division of labor with workers specializing in narrow tasks. The value of specialization meant that it also makes sense to have a planning function separate from operations (Chandler, 1978). 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.)

These 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). Both suppliers and workers were considered interchangeable. Suppliers competed fiercely against each other for work based on competitive bidding; contracts were explicit, to enable "apples–to-apples" comparisons of bids. Contracts with workers were also explicit; due to worker organizing it became difficult to fire workers, but companies did not take advantage of the knowledge of their long-tenure workers (Helper and Henderson, 2014).

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. The data needed to run a business was held to be transferable across industries, with managers receiving MBAs that are 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).[7] At suppliers, due to their customers' price-squeezing tactics discussed earlier, automation is less common, and robots remain relatively 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 mass production view, top management at automakers can design duties for suppliers and shop-floor workers; deep skill 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

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

workers; the box below shows an example of how this played out in the case of Computer Numerical Control (CNC) machine tools (see Appendix). Similarly, executive functions remained with the lead firm (the automaker in this case); automaker-designed components were sent out for competitive bid. This 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, 2017).

The mass production view has been challenged for many years, and is gradually being overtaken by the pragmatist view in many US factories. (However, as we discuss below, elements of this view persist in legacy automation projects, and in low capability and trust among suppliers and workers.) The "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).[8] It is also the case that pragmatists don't always practice the ideals described here; 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's important to be sure that assets (both human and physical) can be redeployed quickly. (See Table 1, second row.) 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, 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

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

contribute importantly to innovation and future production, as well as today's operations. 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, automation 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 "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.[9]

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, MacDuffie, Sabel, 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"). However, we saw this involvement in only one of the suppliers we visited. This company (German-owned) used software

[9] 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

to upload the updated work instructions directly to computer monitors above the workstations. Since workers in the same cell would be assembling products over the course of a day, it was helpful for them to be able to refer to the updated instructions. In contrast to the typical process of having laminated sheets of paper at the workstations and in the office, the computerization ensured that management and workers shared the same updated instructions.

5. Evidence

We draw evidence from a series of interviews conducted on the phone and during site visits to over a dozen manufacturing plants, integrators, industry associations, and trade shows, as documented in greater detail in Section 3 above. Our observations from these interviews and site visits fall into four themes: (1) why automate now; (2) the difficulty of integrating and importance of tacit knowledge; (3) the impacts of automation; (4) the role of value migration. Quotes from these interviews and site visits that align with these themes are detailed in Tables 2A – 2D. We discuss the themes and highlight a few exemplary quotes in each case below.

Why Automate Now?

The decision to automate and the timing of such automation came up ofteni. As indicated in Table 2A, the comments centered on the cost of automation falling, especially because of the role of integrators, and also around the existing skill base and availability of labor.[10]

One theme that came up during all of our site visits was the difficulty of hiring and retaining workers. Automation was typically described as a partial solution to this problem. At the same time there was little discussion of the need to increase wages to retain workers or to hire higher quality workers.[11] Firms say they are unable to find enough production workers at the going wage

[10] While we do not dwell on it here, automation was also described as a useful way for a firm to grow quickly to meet growing customer demand. We also observed some cases in which customer demand was used as an explicit justification for investing in automation. As one integrator noted “Some [manufacturers’ demand] get[s] hot, need automation as the company grows. Automation comes into play when [the manufacturer] can’t keep up because volume reaches a critical mass.”

[11] There appear to be heterogeneous reasons for the labor shortage. One plant was located in an area of rural Michigan with close to 3% unemployment rate, indicating a real shortage of labor. We also heard from an integrator

($12-15 per hour, plus benefits), and believe that raising the wage would not increase the supply. "People are using robots not to replace workers, but to fill positions they can't fill any other way."

It was rarely the case that plant managers or integrators would describe automation solely as a means to substitute for labor, however. Automation was often seen as a way to improve product quality and increase value-added. As noted by one integrator "Sometimes the project is to replace workers, sometimes it is to increase value-added." Not all suppliers are undertaking automation. Some firms lack capability 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, meaning that the automated equipment he installed broke quickly.

Integrators appear to play a prominent role in the decision to automate. For small manufacturers this appears to be tied not just to 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. As one small parts 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." Again, referring to the Industry Architecture column of Table 1, recall that firms adhering to the Mass Production philosophy pursue solutions with standardized, simple interfaces. 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, the integrators that we interviewed and visited serve both large and small customers. For example, 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 large US 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). Again referring to Table 1, integrators appear to have a lot of appeal to firms following a Mass Production philosophy, as contracts can be explicit and division of labor clearly separated.

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that several of his customers were considering automation as a way to address worker absences due to the opioid crisis.

Finally, the growing role of integrators may be evidence that a condition that enables a shake-up of the industry architecture – namely, technological change that allows for the entrance of new players in the value chain – has started to take root.

Difficulty of Integrating; Role of Tacit Knowledge

Many academic engineers and consultants are quite optimistic about the potential for data analytics to drive the future of manufacturing, in a way consistent with the technical convergence view. For example, 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), as indicated by quotes in Table 2B. 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[12] 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 — you see a lot more than with CAD.

This conversation (which really did occur) 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 visited a tool and die shop. We watched a CAD[13] 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 type 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 this information into their models. Although this process was

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[12] "Kaizen" is a Japanese word meaning "continuous improvement."
[13] CAD is "computer-aided design."

fairly ad hoc, it did mean 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.

In our interviews, we explored the impact of automation on the numbers and skills of both production workers and of engineers (see quotes in Table 2C). 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 3 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. Since they are in the automobile 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, 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 Mass Production 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."

Referring to the column on Industry Architecture in Table 1, recall that firms with different management philosophies approach their relationship with labor differently. In Mass Production model, workers are typically seen as "inputs" in which case we would expect that automation would be used to "replace workers." In the Pragmatism model, workers are typically seen as partners, as in the German example above. 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.

Value Migration

Does the data show whether the process of value migration is already in motion? Are firms in the value chain responding strategically to this possibility? There is some evidence that the processes we have hypothesized could become/are becoming a reality in time, as indicated by some of the quotes in Table 2D. Firstly, integrators are starting to become 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 any value that could be generated from the application of automation and analytics to the manufacturing process 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 Mass Production philosophy outlined in Table 1. 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 firms pursuing a Mass Production philosophy 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 sources of value migration: data. In these settings, data on production is continuously generated by machinery equipped with sensors. The 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, a member of an industry association highlights the future 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." 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 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. Whether the same process applies to our context will 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.[14]

6. Propositions

While it may be true that Industry 4.0 is not fully a reality yet, the expectation is that it will become one in the next few decades. How would this development shape organizational and industry architectures where manufacturing plays a big role? In this section, we hypothesize possible scenarios for the automotive industry, which is traditionally manufacturing's representative sector. Because these are propositions about yet unrealized possible states of nature, naturally 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 indicated in Figure 3, robotics manufacturers interact with upstream parts suppliers and downstream auto manufacturers via robotics integrators. In principle, integrators provide physical

[14] 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 mass production than pragmatism 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)

integration of advanced automation as part of a manufacturing production line and also value-added data service, including managing data produced by the automated production line. The latter is at the heart of what people have in mind with Industry 4.0, but our field research has revealed little attempt on the part of integrators, or data analytics firms, to perform such a function. However, either integrators or data analytics firms could start to provide such services in the future, shifting the industry architecture.

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. 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 data analytics firms that operate across industries gain prominence in the value chain.

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.

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.

Efficiency does not necessarily determine industry architecture, as our examples above showed. (before Toyota's competition forced them to change, US automakers successfully protected profits from suppliers by inefficiently designing a market with small, weak suppliers; this strategy promoted automaker profits at the expense of total value creation.). Below we look at some factors besides efficiency that may affect where value is captured. By centralizing the capabilities required for modern manufacturing, could integrators become the "kingpin" of the automotive supply chain to the detriment of automakers' and suppliers' share of the pie? We graphically depict this idea in Figure 9. This leads to our third proposition:

> *P3: Integrators could start to provide data analytics services, allowing them to capture more value from auto manufacturers and parts suppliers.*

On the other hand, and akin to what Jacobides *et al* described in their case study, automakers and component manufacturers could perceive integrators 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 issues of organizational identity and framing – self-perception affects what managerial actions are taken and what capabilities are pursued. 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 integrators, as depicted in Figure 10, and leads to our next propositions:

> *P4: To the extent that auto manufacturers start to see integrators as threats to auto manufacturers' profits, then we expect that auto manufacturers will try to develop internal automation capabilities.*

> *P5: To the extent that parts suppliers start to see integrators as threats to parts supplier profits, then we expect that part suppliers will try to develop internal automation capabilities.*

Alternatively, if automakers decide to invest in automation and data analytics capabilities and suppliers decide to not do so, the former could use increased visibility into the latter's operations to reinforce their lead role, leading to more value for the automakers relative to parts suppliers, as indicated in Figure 11.

P6: To the extent that auto manufacturers develop internal automation and data analytics capabilities and/or partner closely with data analytics firms, they will acquire increased visibility into parts suppliers' operations.

Another scenario is also based on Jacobides and Winter (2005). According to them, a second factor in determining changes to IAs is how changes in the knowledge development process affect the roster of potential entrants in an industry. In the banking case, the increased importance of data management practices led to the entry of firms such as EDS and IBM, which began to export their capabilities to a previously unexplored market. Similarly, firms that possess the general purpose manufacturing capabilities associated with modern automation, such as integrators, could increasingly encroach into markets that were previously the domain of manufacturing specialists. Nevertheless, both manufacturers and integrators could stop short of generating and appropriating the potential value associated with the optimization of production derived from the systematic collection and analysis of data on all stages of the production process, which plays a big part in the Industry 4.0 vision. This would leave room for a new potential entrant to the industry – data analytics firms could capture significant value in the chain.

Perhaps part of the reason why integrators have not yet started to offer value-added data services to their customers is that they lack the technical capabilities to do so. As highlighted elsewhere, much of the success of AI and machine learning is driven by the ability to harness large datasets (Agrawal, Gans, Goldfarb 2017). These datasets are controlled by large cloud-computing companies such as Amazon (AWS), Google, and Microsoft. It is possible that these firms, with their control of data and expertise using AI and machine learning to harness the data to generate insights, will ultimately capture much of the value, as indicated in Figure 12. This leads to our seventh proposition:

P7: To the extent that automation capabilities on the part of integrators, auto manufacturers and parts suppliers start to rely on data analytics firms, then we expect that data analytics firms will capture more value from integrators, auto manufacturers, and parts suppliers.

In another possible scenario, robot manufacturers would integrate vertically into the integration business, which would require them to go beyond their current standardized production and attempt to increase the customization of products to consumers. This would lead to more value for the robot manufacturers, relative to other parts of the value chain, as indicated in Figure 13.

P8: To the extent that robotics manufacturers start to vertically integrate into more integration- and data-analytics type work, then we expect that they will capture more value from integrators, auto manufacturers, and parts suppliers.

Finally, as indicated in Table 1, manufacturing firms tend to follow different management paradigms, and we expect this to impact the amount of value they are able to create and capture from automation. 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 mass production 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 mass production paradigm, the interfaces between firms or production processes are relatively standardized and simple (as indicated in Table 1). 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. Rather, 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.

P9: Manufacturers are likely to create and capture more value if they operate according to the pragmatist paradigm (compared to using the mass production paradigm).

7. Conclusion

Our paper offers several predictions about how Industry 4.0—the growing use of robots, sensors, AI, and other digitally-enabled technologies in manufacturing—will affect value creation and value migration in manufacturing, particularly in the auto sector. 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, which we believe will lead to different patterns of value migration.

We focus on the auto industry for several reasons, including (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 specifically focused on issues that arise in the production of automobiles, and not in their use, precluding a discussion of autonomous vehicles, their uses, and implications for industry and organizational architecture in other sectors of economy. 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 implication for other manufacturing sectors. We hope our propositions will inform future research into the auto industry, Industry 4.0, and value migration. A useful task for future research will be to explore conditions under which our results do or do not generalize, and other boundary conditions.

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Table 1: Industrial Paradigms: Implications for Automation

	Nature of Knowledge	Organization Design	Ideal Boundaries	Equipment Design	Equipment Use	Industry Architecture
Mass Production	Environment is stable Abstraction is valuable	Division of labor Separate planning and execution	Fixed to allow specialization within tasks Contracts are explicit	Monuments Low automation at suppliers	Few, large changes [hare]	Standardized, simple interfaces Suppliers, workers seen as interchangeable Suppliers, workers lack trust, capability
Pragmatism	Knowledge is provisional Problems will arise Context is important in interpreting data	Cross-training Frequent cross-task, cross-hierarchy discussion is useful Integrate planning and execution	Permeable to allow discussion among tasks Contacts are relational	Light, small	Frequent small changes [tortoise]	Discussions assumed shared knowledge Suppliers, workers have capability and incentive to participate in joint problem-solving

Table 2A: 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 2B: 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]
<u>New Skills Needed/Lack of Capabilities</u> “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]
<u>Opportunities for Learning/ Protecting Knowledge</u> “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 2C: Impacts of Automation

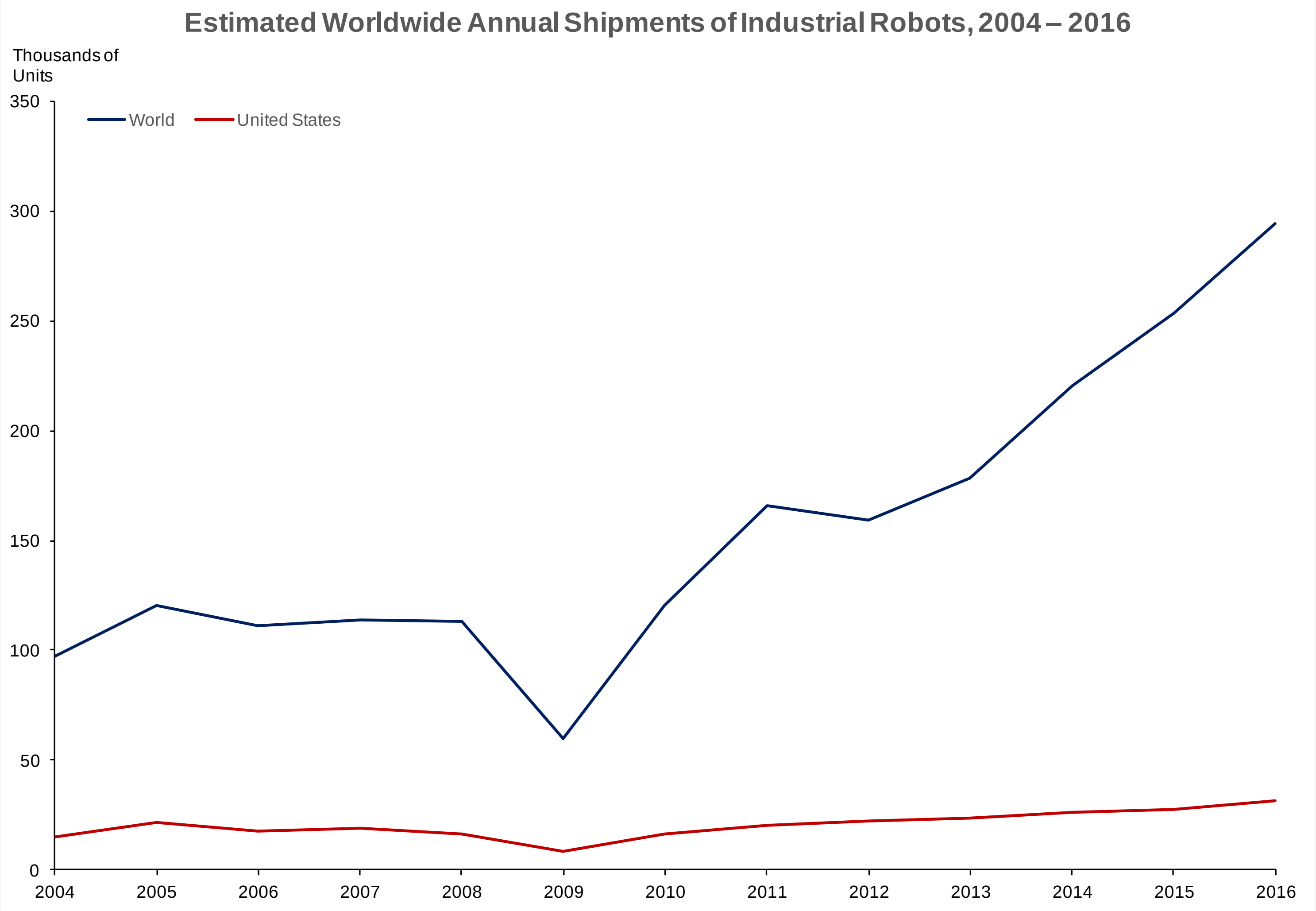
Replace Workers “Sometimes the project is to replace workers, sometimes it is to increase value-added.” [Integrator 1, 10/20/2017] “But the robot won’t take breaks, get tired, join a union. It can work three shifts – so it should pay back in less than a year” [CEO, Small supplier 1, 11/30/2017] “You 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 2D: Value Migration

<u>Not Yet Happening</u> "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]
<u>Some Shift in Roles</u> "[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]
<u>Capturing Data</u> "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]

Figure 1



Source: International Federation for Robotics.

Figure 2

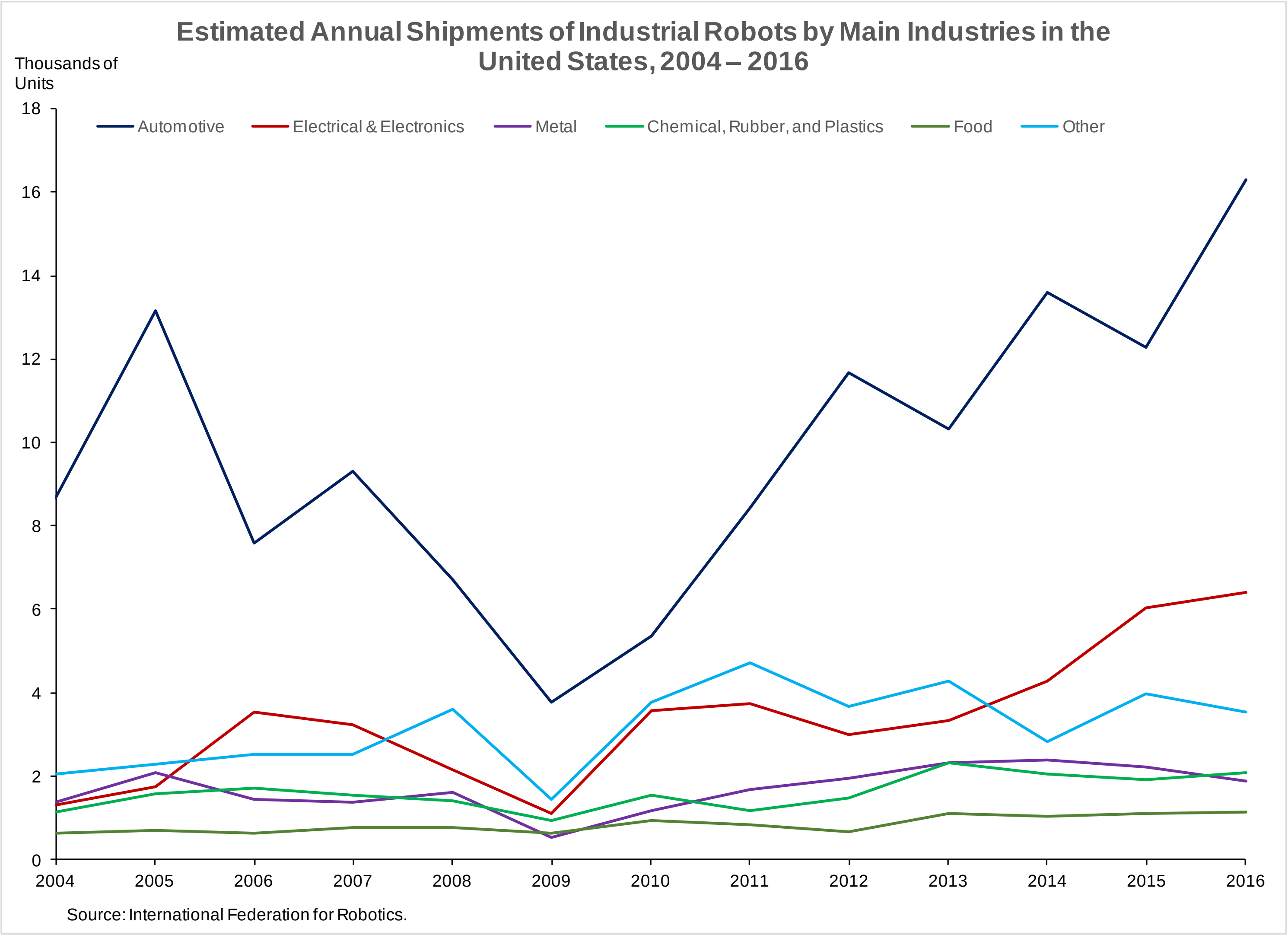

Estimated Annual Shipments of Industrial Robots by Main Industries in the United States, 2004 – 2016
Thousands of Units
18
16
14
12
10
8
6
4
2
0
Automotive
Electrical & Electronics
Metal
Chemical, Rubber, and Plastics
Food
Other
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Source: International Federation for Robotics.

Figure 3

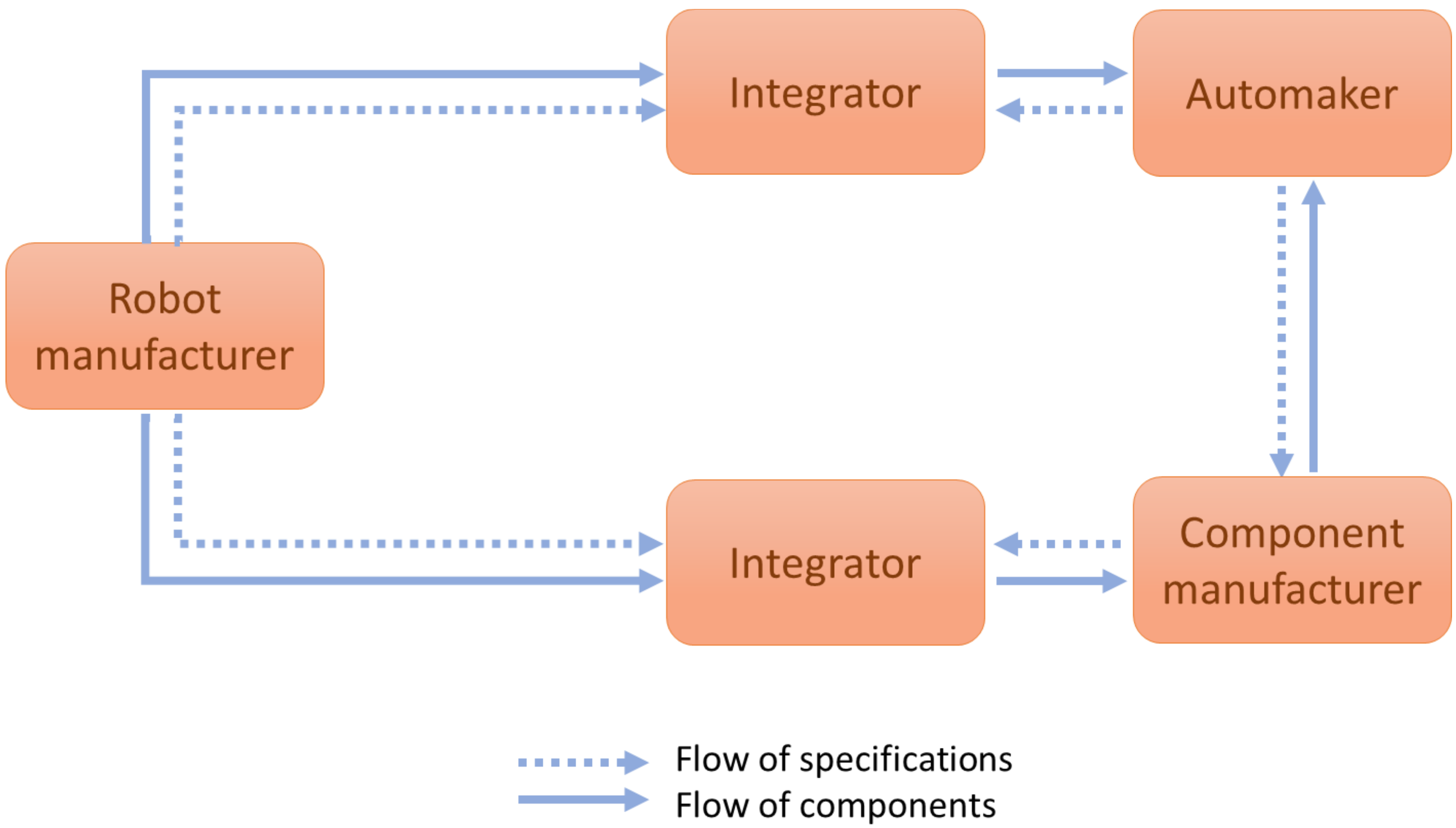
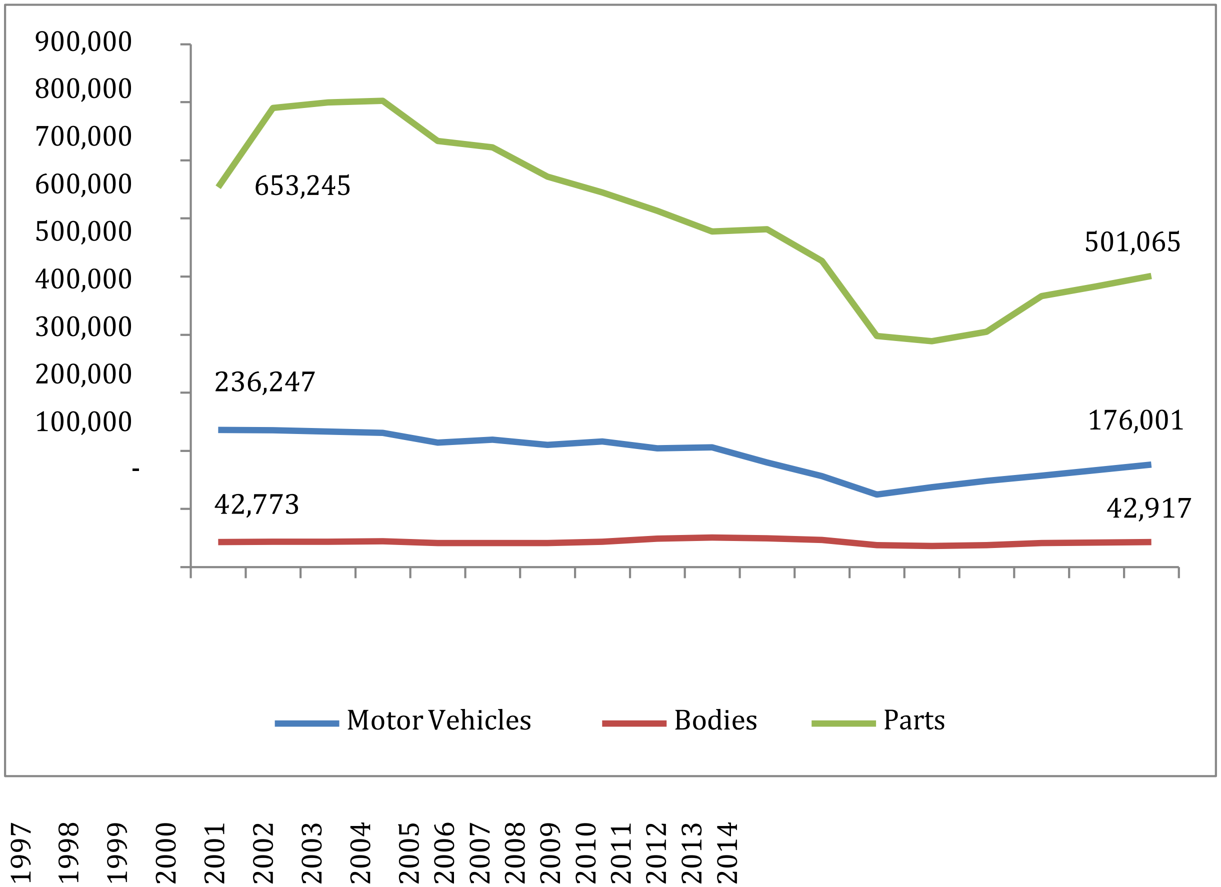
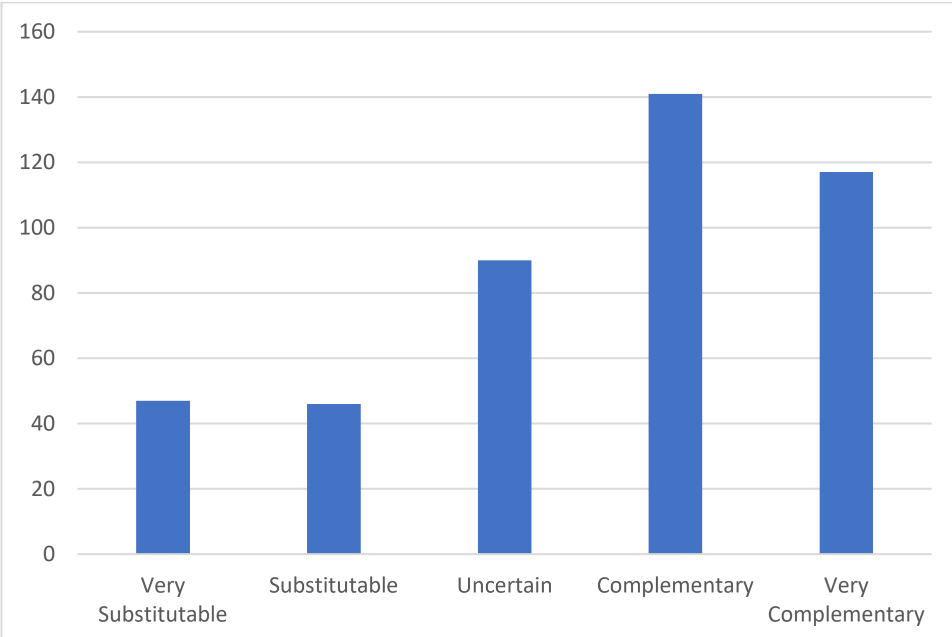

Integrator
Automaker
Robot manufacturer
Integrator
Component manufacturer
Flow of specifications
Flow of components

Figure 4: U.S. employment: motor vehicles, parts, and bodies (1997–2014)



Source: US Census, compiled in https://www.usitc.gov/publications/332/employment_changes.pdf

Figure 5



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 6

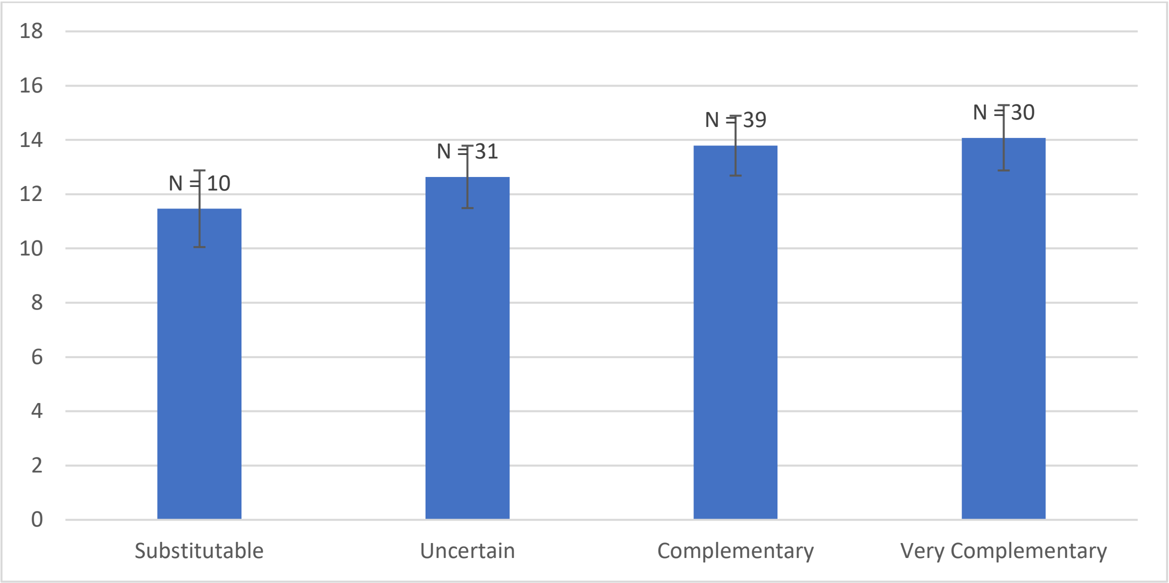
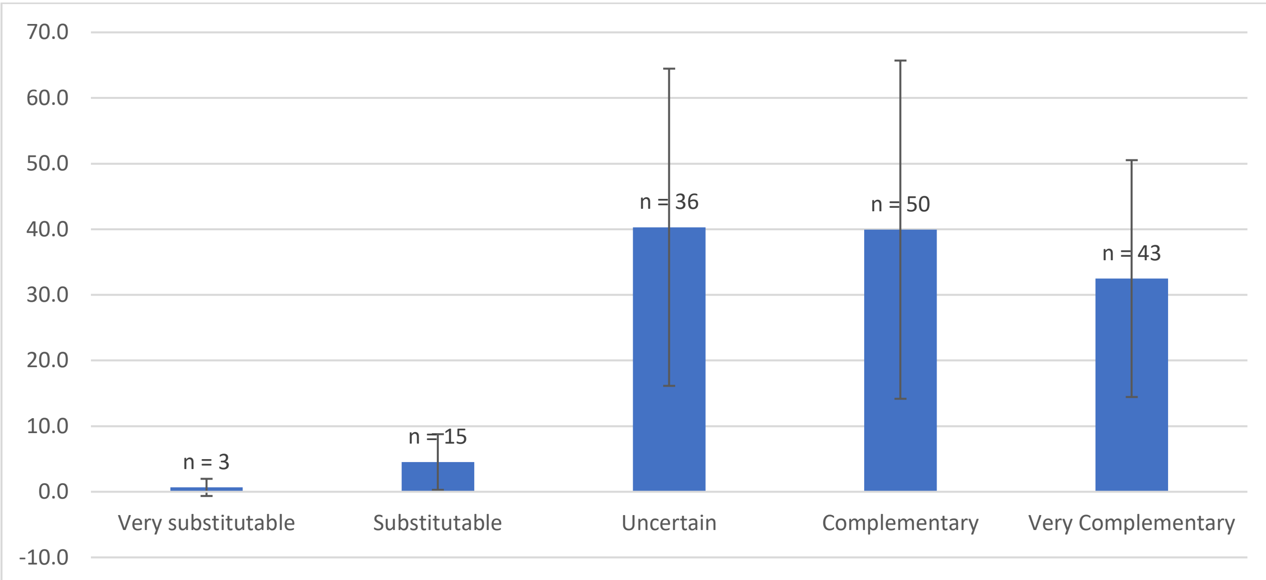

18
16
14
12
10
8
6
4
2
0
N = 10
N = 31
N = 39
N = 30
Substitutable
Uncertain
Complementary
Very Complementary

Figure 7



70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
n = 3
n = 15
n = 36
n = 50
n = 43
Very substitutable
Substitutable
Uncertain
Complementary
Very Complementary

Figure 8A

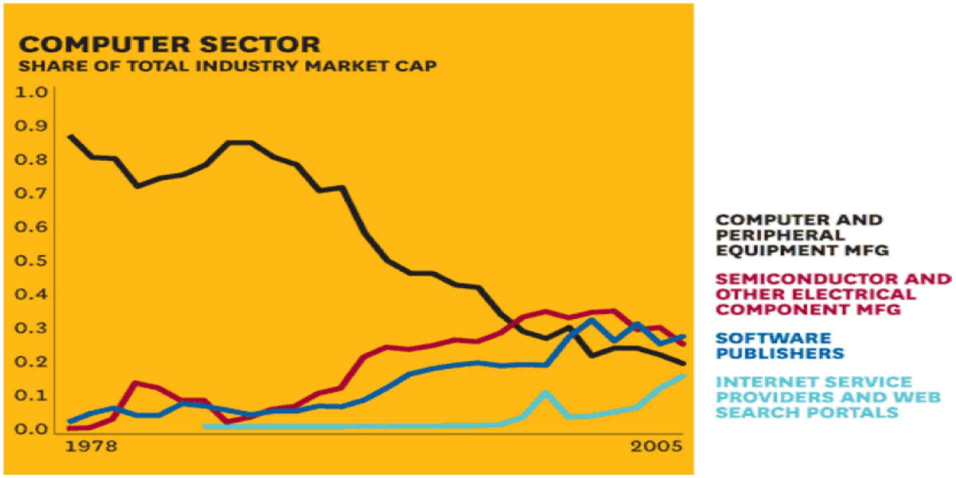


Figure 8B

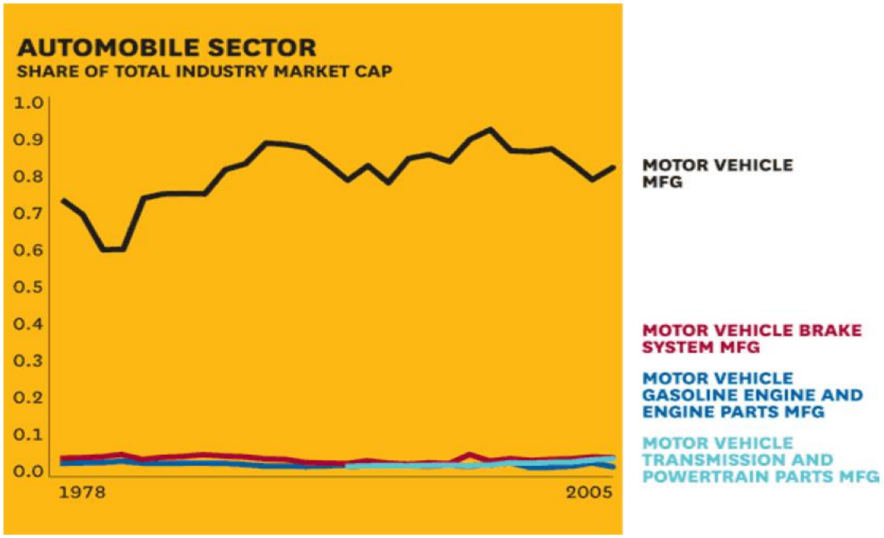
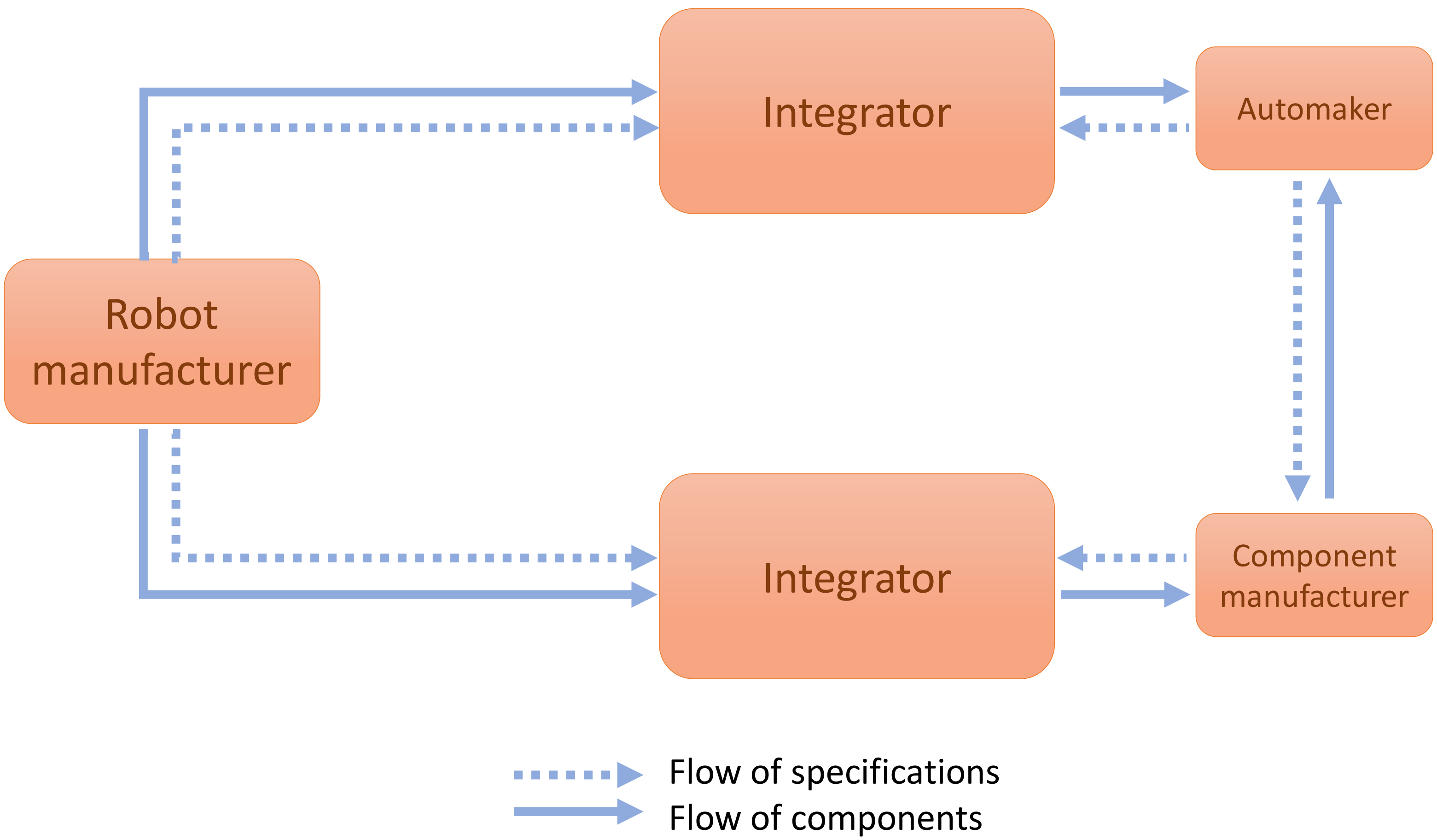
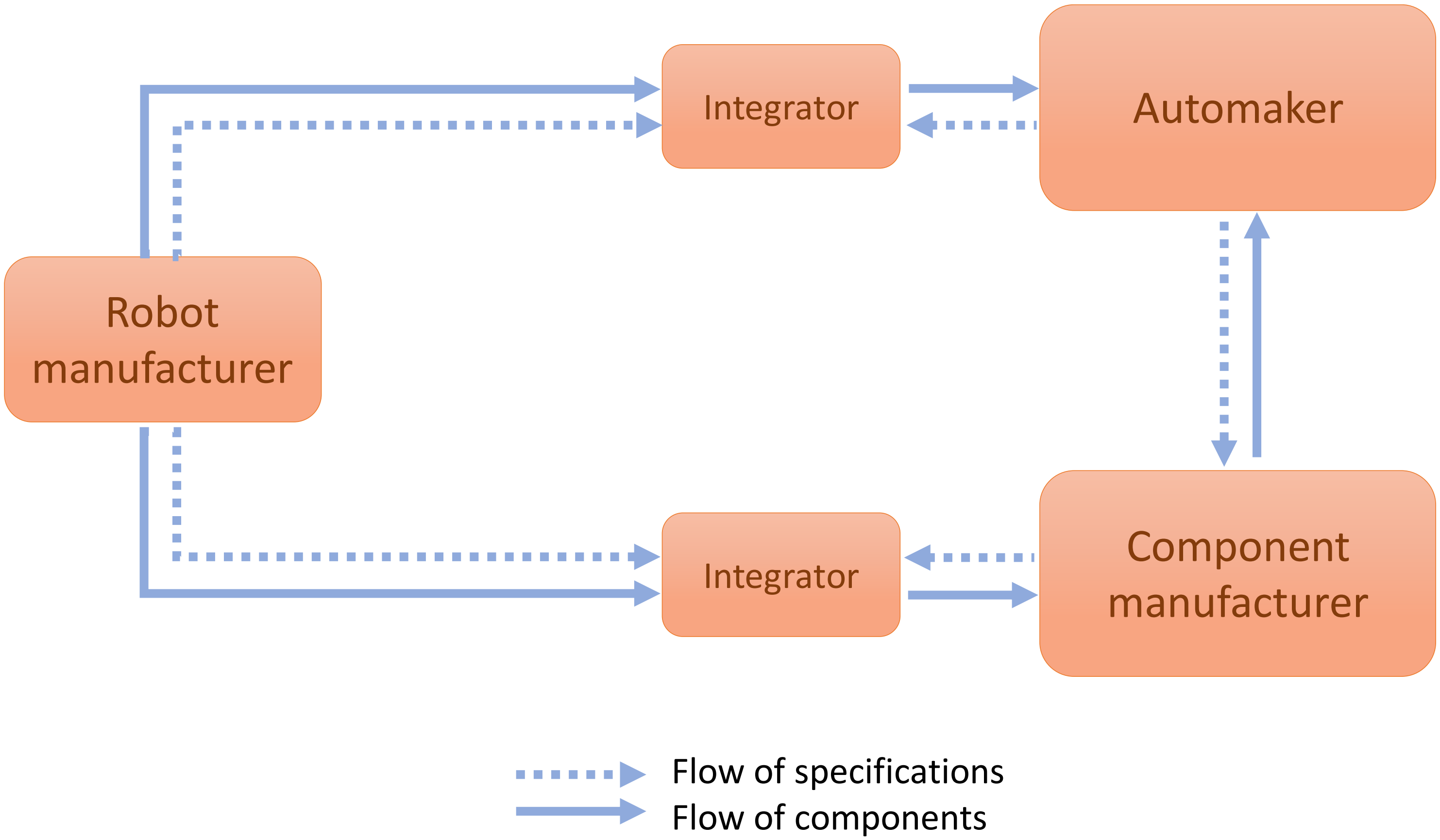


Figure 9



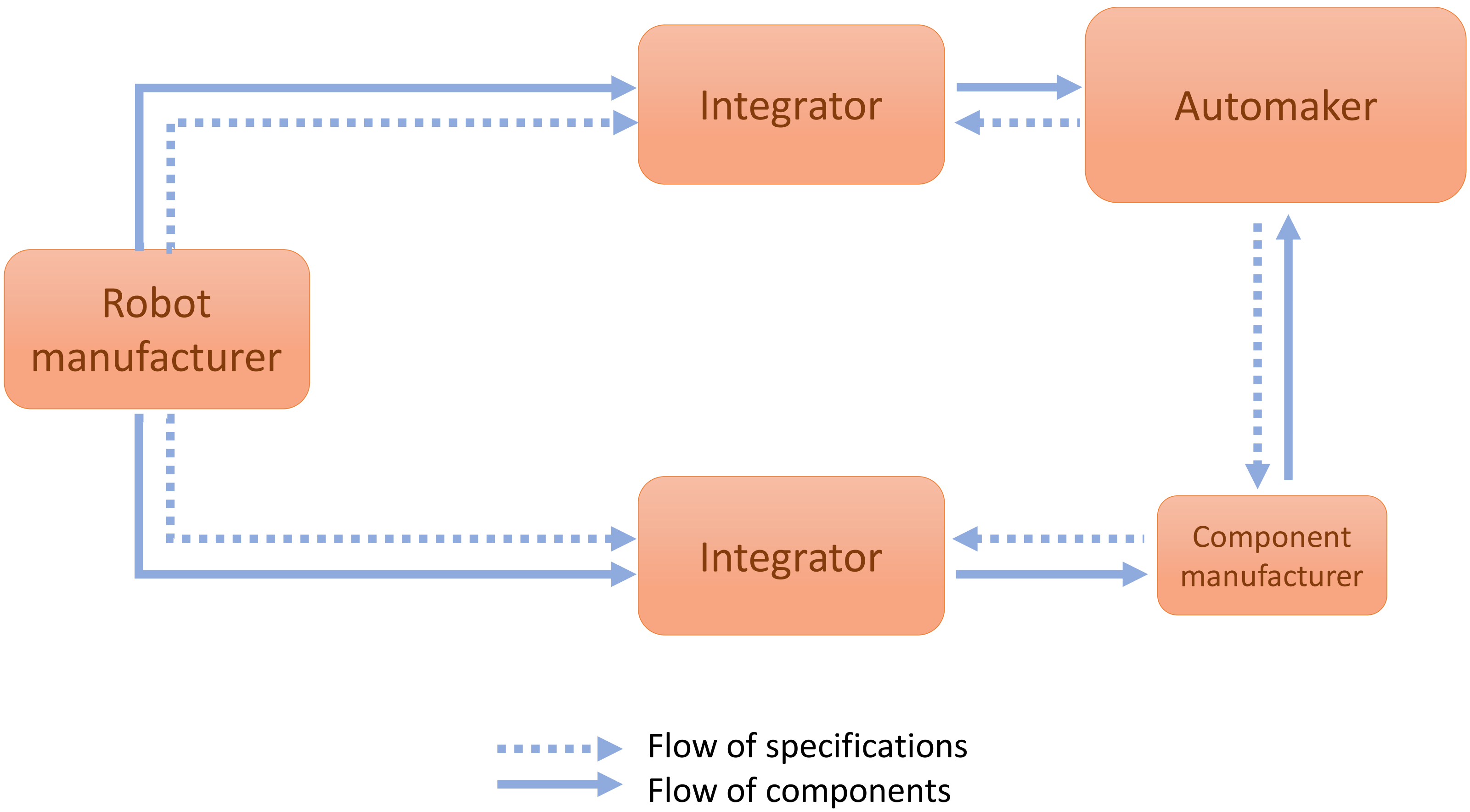
Integrators would capture greater value share if they started to provide data analytics services.

Figure 10



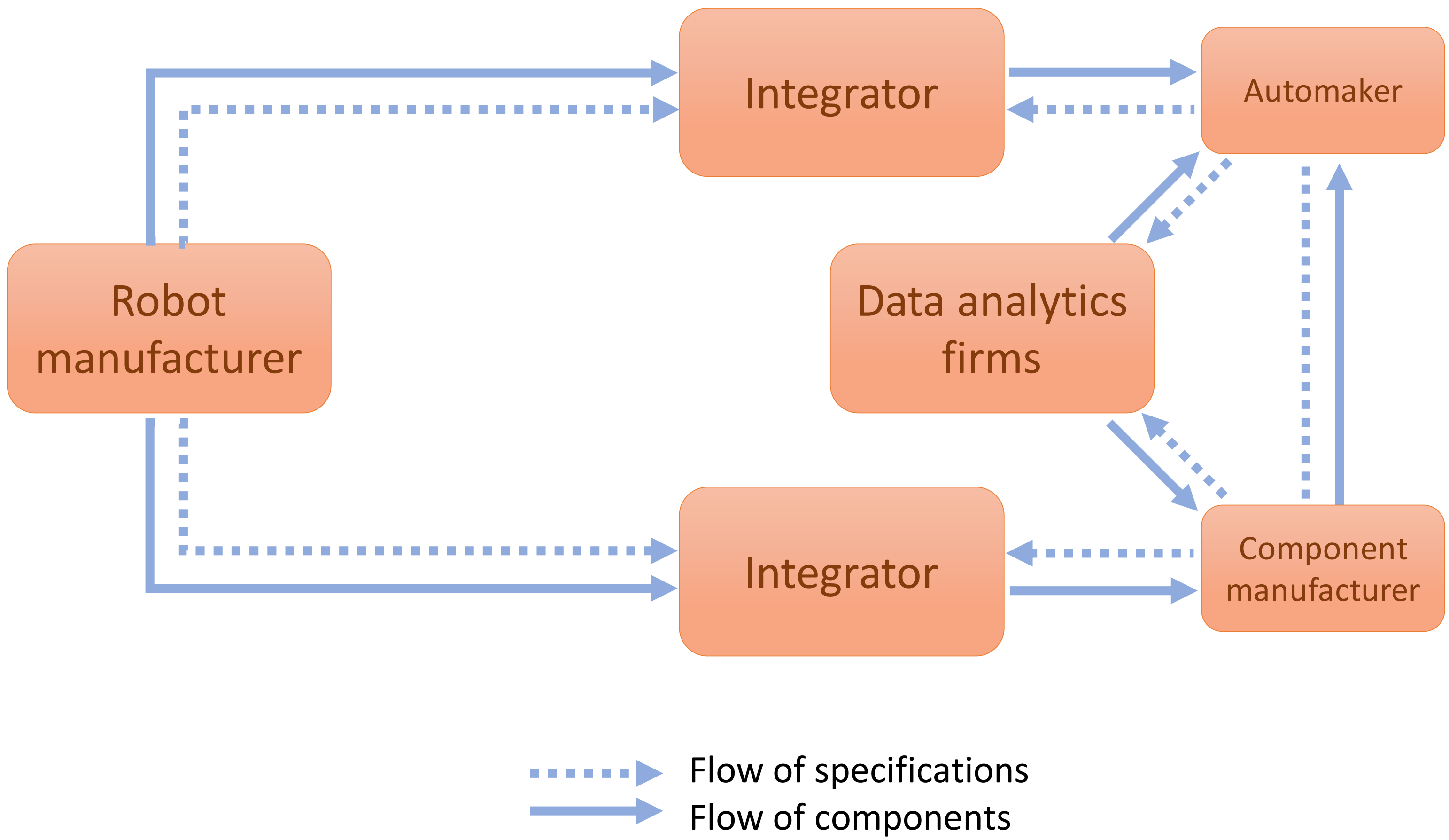
Automakers and suppliers would capture greater value share if they started to provide data analytics services.

Figure 11



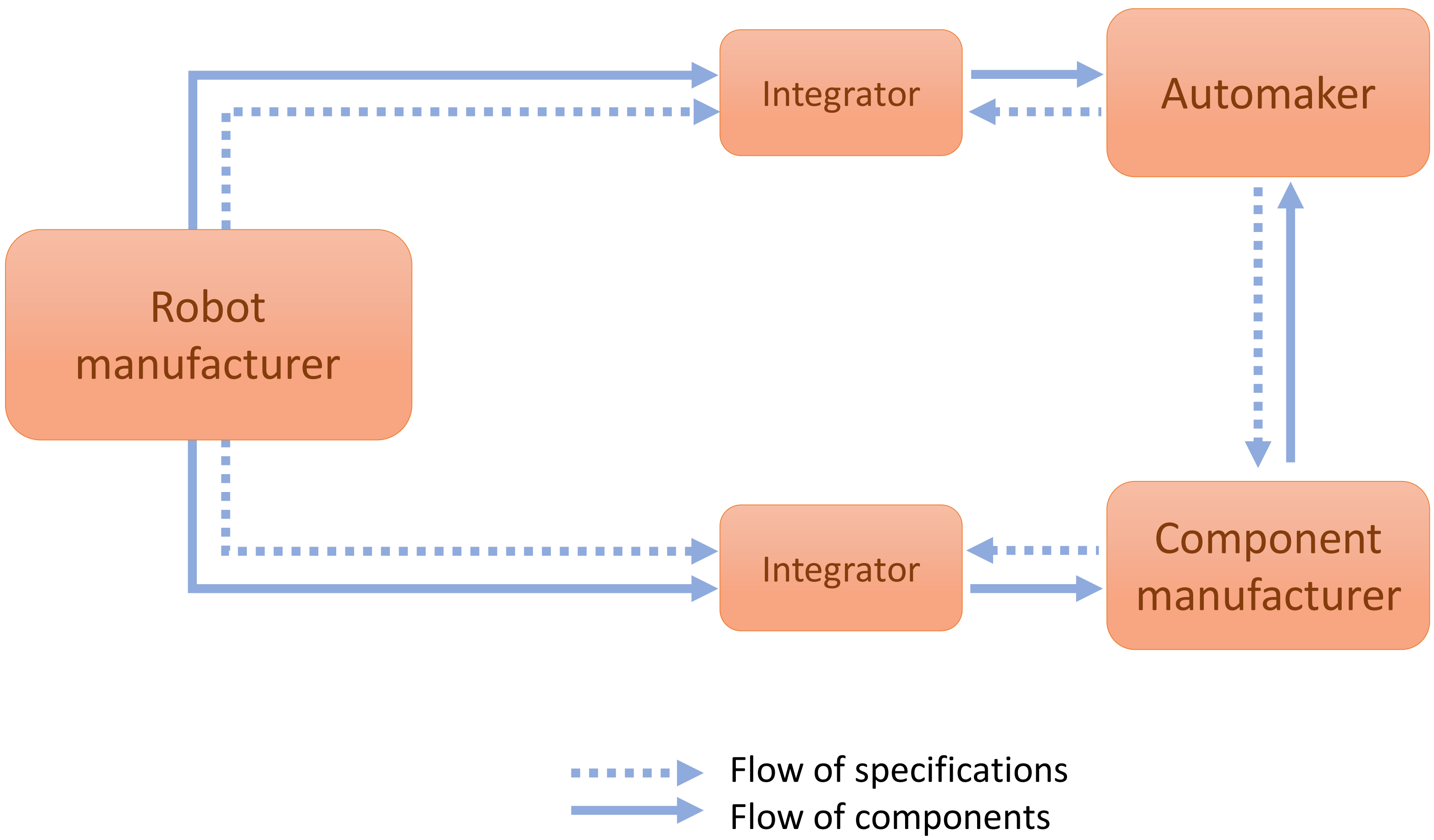
Automakers would capture greater value share if they started to provide data analytics services and suppliers did not.

Figure 12



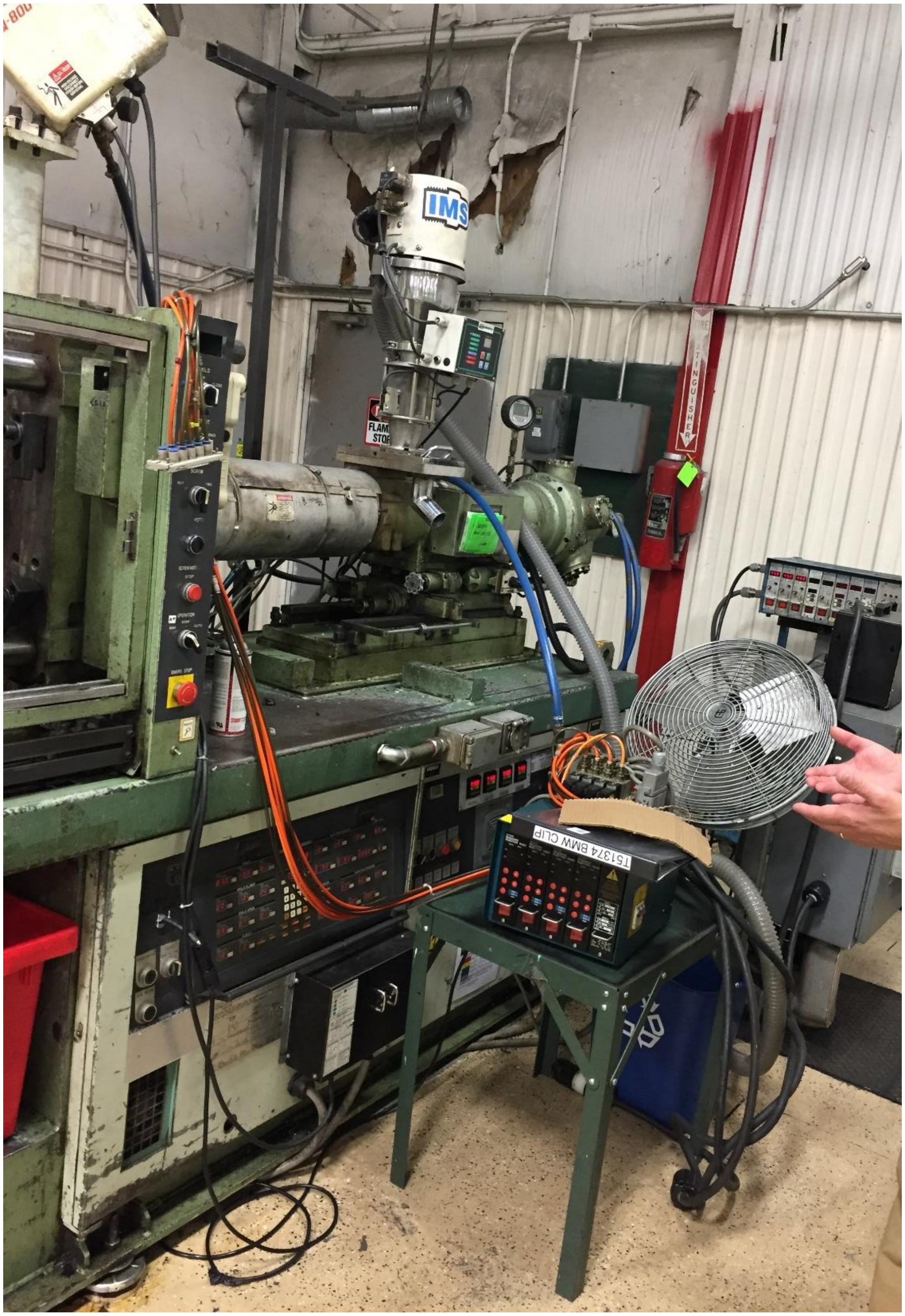
Data analysis firsm would capture greater value share if they started to provide data analytics services.

Figure 13



Robot manufacturers would capture greater value share if they started to provide data analytics services.

Picture 1: Knobs and Dials on Older Manufacturing Equipment



Picture 2: Graphical User Interface on Modern Manufacturing Equipment