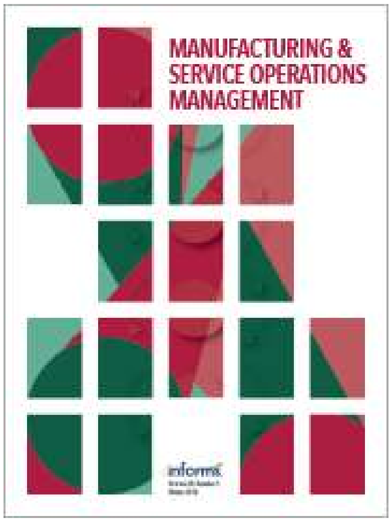

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20th Anniversary Invited Article

Industry 4.0: Opportunities and Challenges for Operations Management

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Abstract. Industry 4.0 connotes a new industrial revolution centered around cyber-physical systems. It posits that the real-time connection of physical and digital systems, along with new enabling technologies, will change the way that work is done and therefore, how work should be managed. It has the potential to break, or at least change, the traditional operations trade-offs among the competitive priorities of cost, flexibility, speed, and quality. This article describes the technologies inherent in Industry 4.0 and the opportunities and challenges for research in this area. The focus is on goods-producing industries, which includes both the manufacturing and agricultural sectors. Specific technologies discussed include additive manufacturing, the internet of things, blockchain, advanced robotics, and artificial intelligence.

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Keywords: additive manufacturing • internet of things • blockchain • robotics • artificial intelligence

1. Introduction

Mechanization, electrification, and computing each drove dramatic and disruptive progress in the production of goods and services. Industry 4.0, a term first coined by the German economic development agency GTAI, is so named to promote the idea that we are at the dawn of a new industrial revolution brought about by the emergence, advancement, and convergence of a number of technologies that enable an almost real-time connection between the physical and digital realms. This digital-physical marriage, driven by additive manufacturing (AM), the internet of things (IoT), blockchain, advanced robotics, artificial intelligence (AI), and other related technologies, "is gathering force [and will] be far reaching, affecting every corner of the factory and the supply chain" (McKinsey 2015b, p. 2). Individually and collectively, the technologies underlying the concept of Industry 4.0 hold the promise of reducing costs, enhancing flexibility, increasing speed, and improving quality, but more than that, Industry 4.0 offers the possibility of dampening the tensions inherent between these key operational priorities.

The operations management (OM) academic community must engage with Industry 4.0. From an educational perspective, we need to equip our students with the knowledge and skills required to manage the new operations and supply chain realities that will emerge. From a research perspective, we need to explore whether and how the technologies underpinning Industry 4.0 challenge our current understanding of operations, and more than that, we need to identify the novel and important operations questions that will emerge from the advancement and adoption of these technologies.

In this article, we discuss a number of Industry 4.0's foundational technologies, with the dual goals of (i) building awareness and understanding of Industry 4.0 in the OM community and (ii) encouraging OM research in this area by identifying opportunities and challenges. With those goals in mind, we will focus our attention on the operations implications of these underlying technologies and intentionally omit consideration of other potentially important domains, such as medical and financial applications. Furthermore, in keeping with the spirit of the term Industry 4.0, we will concentrate on tangible good production rather than service delivery. Of course, with the rise of product servitization, a trend that may well be accelerated by Industry 4.0, the distinction between goods and services is necessarily blurred at times. However, we explicitly omit consideration of smart operations in the public and retail sectors, because each is explored by other articles in this issue: the public sector is explored by Hasija et al. (2019), and the retail sector is explored by Caro et al. (2019). Within goods production, we consider both the manufacturing and agricultural sectors.

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As will become apparent, Industry 4.0 is not simply an umbrella term for a collection of disparate technologies. In fact, much of the promise of Industry 4.0 is in the potential interactions and synergies between subsets of these technologies; for example, advances in sensors and artificial intelligence has allowed for the development of collaborative robots that work alongside people. These synergies notwithstanding, we organize this article by technology and allude to their potential interactions as necessary. In what follows, we give a high-level overview along with research implications of the following technologies: additive manufacturing (Section 2), the internet of things (Section 3), blockchain (Section 4), advanced robotics (Section 5), and artificial intelligence (Section 6). Other relevant technologies are briefly discussed in Section 7. We conclude in Section 8 with some remarks on the impact of Industry 4.0 on operations strategy. We note that it is not the goal of this article to survey the nascent academic OM literature related to Industry 4.0, and therefore, any papers referenced are in no way intended to be exhaustive or representative.

2. Additive Manufacturing

AM, also known as three-dimensional (3D) printing, is a process that takes a digital 3D representation and produces the associated physical object layer by very thin layer, joining the layers as it goes along. Although there are many AM technologies (material jetting, powder bed fusion, and vat polymerization for example), the high-level AM process flow is common across these technologies. The initial 3D digital model is converted into a digital .stl file format that is then virtually sliced into a set of flat horizontal-layer models. These digitally sliced layers form the instructions for the AM "machine" to produce the object layer by layer. Oftentimes, a finishing step is required after the object is removed from the machine. AM has been heralded as a revolutionary technology with enormous consequences for operations management. Why? Let us consider the operational priorities of quality, flexibility, speed, and cost.

AM enables the production of complex shapes and internal geometries unattainable by traditional manufacturing methods. For products in which shape drives performance quality, AM alleviates the manufacturability constraints facing design engineers. A by-now famous example is the fuel nozzle for GE's LEAP aircraft engine. GE engineers developed a new nozzle tip design that was key for improved fuel efficiency, "but there was a problem. The tip's interior geometry was too complex [and] was almost impossible to make" (Kellner 2017). GE was, however, able to produce the new design using an AM technology, and now, it manufactures the nozzles using production-scale AM at a factory in Alabama.

An AM machine is indifferent to the shape that it is instructed to produce, and therefore, it does not require a new setup when switching between the production of objects that differ in their geometries. Subject to space constraints, some AM machines can simultaneously produce different objects. As such, AM technologies are inherently flexible and in their theoretical limit, eliminate manufacturing diseconomies of variety.

New product design is an iterative process, whereby provisional designs are refined based on prototype testing. Commercial production begins after the design is finalized. With traditional manufacturing methods, production of prototypes is time consuming, and commercial production may require the development of new product-specific tooling and equipment. Because AM is flexible, prototyping is rapid, and commercial production does not need to wait for product-specific resources. Therefore, speed to market is greatly enhanced.

For similar reasons, the upfront cost of production is also reduced, because product-specific manufacturing investments are not required. All else equal, a lower upfront cost reduces the sales volume required to break even, thus allowing profitable production of low-volume products. Assembly-related variable costs can be reduced by designing products that require fewer component parts. In a different AM application, GE engineers developed a new turboprop engine that was assembled from a dozen parts rather than 855 components as was the case in the older version.

The promised quality, flexibility, speed, and cost benefits of AM may lead to fundamental changes in operations strategies. Instead of mass production of a limited variety of products concentrated in a small number of factories, geographically distributed low-volume production of highly customized products becomes increasingly attractive. Taken to its natural limit, geographically distributed low-volume production may evolve to personal fabrication, whereby consumers locally print their purchased design on demand. It is not inconceivable that, for some products, the operations strategy of mass production of limited variety may give way to one of customized production by the masses. That is, the entire architecture of the supply chain may change.

Service parts for uptime-critical industrial assets (turbines, for example) offer a compelling case in point for geographically distributed low-volume production. Service part demand is highly unpredictable in the timing, location, and part required, and therefore, inventory storage is expensive. Locating AM machines close to assets will enable rapid on-demand printing of the required service part, with a resulting uptime improvement and inventory reduction. This vision is becoming a reality, with Siemens claiming to be the first to commercially print spare parts on demand for large gas turbines (Müller 2016).

The promise of AM notwithstanding, a number of significant disadvantages currently limit its applicability. Complex geometry is not the sole determinant of product quality. Strength, size, materials, product uniformity, and many other characteristics matter. AM still faces challenges on these characteristics. Different materials require different AM technologies, and this limits the flexibility of AM machines and their ability to produce multimaterial products. Although the new product development time is fast, the AM production cycle time is typically slower than traditional manufacturing methods, with postprocess finishing sometimes being the bottleneck. Additionally, although the upfront cost of production is low, the per part variable cost of AM production is often high because of high input material costs. However, it should be noted that AM can be attractive from a sustainability perspective, because the quantity of material wasted in production can be substantially lower.

These speed and cost limitations matter a great deal at scale production, with the result that AM is currently more attractive than conventional methods only at low production volumes. As a case in point, HP announced a new AM technology intended for mass production and entered a partnership with auto component manufacturer GKN in 2018 "to deploy HP Metal Jet in their factories to produce functional metal parts for auto and industrial leaders including Volkswagen" (HP 2018). However, according to Volkswagen, "the sweetspot of 3D printing technologies is not in giant numbers of vehicles [and] there's a better use case for specialty parts" (SCDigest 2018). Indeed, the HP printers are currently intended only for production of cosmetic pieces, such as customizable car key rings and name plates (SCDigest 2018).

Perhaps because maintenance and repair operations (MRO) are seen as a natural early application of AM, it has also been an area of recent OM research. Song and Zhang (2018) model a hybrid multipart MRO system in which spare parts can be stocked or 3D printed on demand, and they find that the value of 3D printing is increasing in the part variety (as measured by the number of parts) and decreasing in the part criticality (as measured by the part's outage or backorder cost). Motivated by a Royal Netherlands Army peacekeeping mission and the fact that AM-produced parts in the field may be of lower quality, Westerweel et al. (2018) explore a dual-sourcing service part system in which regular spare part orders can be filled after a lead time, but AM can be used to on-demand print temporary replacement parts. Knofius et al. (2019) explore how the part consolidation potential of AM influences overall lifecycle costs when spare parts management is taken into account. AM aside, the MRO space has undergone significant change over the past 20 years, with original equipment manufacturers, such as Siemens and GE, eager to take on an increasing role in the profitable after-market service business. The implications of AM for MRO contracting and supply chain structures may be profound and therefore, merit future research.

Away from the MRO space, the flexibility benefits of AM in terms of upfront product line design have been the subject of recent research. Dong et al. (2016) examine the impact of flexibility economics on assortment planning (i.e., which product variants to offer), and they find that, compared with traditional flexible production technologies with variable capacity cost that grows in product variety, the adoption of AM, with variable capacity cost that is invariant to variety, leads the firm to provide more variety. Sethuraman et al. (2018) explore the personal fabrication potential of AM in the context of a monopolist firm that sells a product design to customers who can then use AM to produce the product at a quality of their choosing.

D'Aveni, a strategy scholar who has studied and written extensively about AM, claims that

> We're headed toward an assembly-less world where there are no supply chains because everything's made together at the same time in one product build-up or printing job. Such a future is not without its challenges. For starters, companies will face difficulties adjusting to the new manufacturing reality, where purchasing components and sub-assemblies disappears, and the R&D department will reign supreme. (Blanding 2018)

Whether such a future comes to pass any time soon, this vision presents opportunities and challenges for the OM academic community.

3. The Internet of Things

A sensor detects and/or measures some property of the environment in which it is deployed and translates its input into an electrical signal that can be processed by electronic circuitry. According to a report from Deloitte University Press (Holdowsky et al. 2015), the average price of a sensor fell by over 90% between 1992 and 2014 (from $22.00 to $1.40), and microprocessor clock speeds increased by a factor of 991 (from 29 million to 28,751 million Hz) over the same timeframe. This confluence of cost reduction and processing speed increase, along with advancements in measurement and communications technologies, have enabled the vision of a vast array of interconnected sensors on machines, people, and products coupled with intelligent controllers, broadly defined, that can take actions based on real-time sensor readings: in other words, the IoT.

Whereas in the past, decision makers operated somewhat in the dark, lacking full information on the current state of their relevant environments, communication between sensor-enabled devices promises to enhance the information quality and information completeness available to decision makers (Saghafian

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et al. 2018). By quality, we mean the accuracy or precision with which some nominal property is measured. By completeness, we mean that, by combining sensor measurements of different local attributes, one can build system-wide state information. Crucially, the vision of real-time communication in the IoT will enhance the timeliness associated with this information quality and completeness. Indeed, "the strategic significance of the IoT is born of the ever-advancing ability to break that [darkness] constraint, and to create information without human observation, in all manner of circumstances that were previously invisible" (Holdowsky et al. 2015, p. 5).

A McKinsey report estimated that, by 2025, the economic impact of the IoT would be in the trillions of dollars, with the majority of this impact attributed to operations applications in the areas of inventory, maintenance, worker productivity, and optimization opportunities (McKinsey 2015a, pp. 111–112). McKinsey is far from alone in projecting profound implication for operations. It is the information completeness, quality, and timeliness promised by the IoT that are the foundation of such projections.

There is an echo of recent history in this heralding of information-driven improvements to inventory management. Radio-frequency identification (RFID) tags and readers promised a revolution in the tracking and monitoring of inventory as it flowed through a supply chain because RFID enables high-quality (i.e., accurate) and timely (no periodic auditing delay) inventory records in a way that barcoding cannot. Industry's excitement about the potential of RFID was soon followed by a surge of OM research that explored the benefits of inventory record accuracy and real-time visibility of the inventory pipeline progress (see, for example, Heese 2007, Lee and Özer 2007, Gaukler et al. 2008, and others). Evaluating the benefit of perfect inventory information—a common, if often implicit, assumption in the traditional inventory literature—can be done by developing a policy that accounts for information inaccuracy or delay and then comparing it with a perfect information benchmark policy (see DeHoratius et al. 2008 for an example). If accuracy and timeliness of inventory information were the only operational benefits of the IoT, then prior RFID-related research has already answered many of the related research questions.

Although RFID technology plays a role in the IoT, sensors[1] enable much richer information to be gathered. Not only can a firm have timely and accurate data on inventory levels, but also, ubiquitous sensors allow it to have timely and accurate information on the state of the local environment in which any particular unit of inventory or processing asset resides. Moreover, the real-time connectivity associated with the IoT means that this rich local information can be translated into rich system-level information. In the food industry, IoT-enabled monitoring of "temperature, humidity, and other environmental conditions of perishable foods" across the supply chain is seen as an opportunity to "improve buffer inventory" (Shacklett 2017).

The sizing of inventory buffers—although a dominant focus in the history of OM research—is far from the only concern of an operations manager. The real-time execution, continuous improvement, and upfront design of the operating system are equally important, and the completeness, quality, and timeliness of information envisioned by the IoT have the potential to dramatically impact these aspects. "General Motors, for example, uses sensors to monitor humidity to optimize painting; if conditions are unfavorable, the work piece is routed to another part of the plant" (McKinsey 2015a, p. 68). GE sees the IoT as enabling real-time optimization not only within a facility but also, across networks of assets and facilities, "allowing optimization ... to find the most efficient system level solution" (Evans and Annunziata 2012, p. 11). In agriculture, multiple sensors deployed across a field enable precision application of pesticides and water based on the local conditions of individual parcels within the field or even at the individual plant level. Condition-based maintenance (CBM) of operational assets, whereby repair and replacement decisions are made based on current asset conditions rather than planned inspections or unplanned outages, has received significant practical and academic attention long predating the emergence of the IoT (e.g., Wijnmalen and Hontelez 1997). However, the ubiquitous and connected sensors in the IoT—coupled with advanced predictive analytics—are making CBM a key IoT application area (McKinsey 2015a).

The recent emergence of digital twins offers a glimpse into the potential of IoT-enabled operations. A digital twin is "a sensor-enabled digital model of a physical object that simulates the object in a live setting" (Parrott and Warshaw 2017, p. 3). The crucial aspect here is the "live setting"; that is, it is not simply a static digital representation of an object before use, but it is a dynamic representation of the object that evolves in use. Real-time sensor measurements across a range of elements enable a system-level representation of a complex asset (e.g., a turbine) or indeed, an entire production system. The physical world has a dynamically coupled representation in the digital world, and this data-rich environment can enable operations managers to uncover previously unknown relationships between system conditions and outcomes. This understanding can drive continuous improvement in defect reduction, uptime, and other key performance indicators of the existing system while also generating improved manufacturability design ideas for future products and factories.

"Digital twins exist at the nexus of physical engineering, data science, and machine learning" (GE 2016, p. 2), and this holds true for IoT-enabled operations more broadly. Distilling the vast data generated from sensors into actionable knowledge will be a formidable challenge. Real-time, data-rich, system-level optimization within and across networks of factories and assets will require algorithms that can solve extremely large problems almost instantaneously. Such difficulties offer ample research opportunities in the realm of data analytics and optimization methods.

OM research has already extensively explored the value of inventory information (see the RFID discussion above) and the value of forecast information sharing in a supply chain (e.g., Lee et al. 2000, Aviv 2002). Therefore, viewing IoT-enabled operations as information-rich ones, one might conclude that the interesting research questions have already been explored. This would be an unfortunate conclusion. IoT-enabled operations will deliver a much broader array of production- and logistics-relevant data, opening up questions as to what types of data are most useful, how the data should be best used, and how data ownership in interfirm production systems (e.g., servitization of processing assets) would be best configured. That is, the IoT will lead to a wide variety of research questions related to the design of the processes and procedures for managing operations and supply chains.

4. Blockchain

With extensive data now available through the IoT, there is a desire to store such data in an accessible yet secure fashion. One possible solution to this storage problem is blockchain. Although blockchain technology has been surrounded by significant hype, there do seem to be solid operational use cases for the technology (e.g., Babich and Hilary 2019).

A blockchain is a distributed and secure ledger. It is distributed in the sense that it can be accessed and written to from any (possibly authorized) location, and its data are stored on a peer-to-peer network (i.e., not in a central location). It is secure, because after a block has been added to the chain, it cannot be altered unilaterally. It is a ledger, because it stores information. Many people are familiar with digital currencies, such as bitcoin, which use blockchain technology. However, it is blockchain's other applications that will likely be of more use to operations managers.

Blockchain allows information to be kept on the entire history of a product as it travels along the supply chain. Although this can also be done through a central database, such as those provided by enterprise software companies (e.g., SAP and Oracle), its distributed nature provides greater flexibility. With a blockchain, there is no need to allow third-party access to commercially sensitive systems. Furthermore, anyone in the supply chain can upload information to the chain, and they do not need to be directly connected to some centralized "owner."

Although the information is secure after it is in the chain, there is of course no magic guarantee that only factual information will be uploaded. Blockchain suffers from the same "garbage-in-garbage-out" danger of any information system. However, there is one important difference in this regard. Blockchain information can be entirely digitized. That is, information can be uploaded automatically from IoT sensor data. As long as the sensors are accurate, the information in the blockchain will also be accurate.

To make this concrete, consider the following possible future for the kiwifruit supply chain from New Zealand to China. Suppose that each fruit is automatically tagged with a micro-RFID tag on picking. Every time that the tag passes a reader, location and timestamp information is uploaded to the chain. In addition, suppose that, after packed, a temperature monitor is attached to the tray that the kiwifruit sits in. Then, every time a reader is passed (e.g., when loading and unloading from the shipping container), the full history of the temperatures that all of the fruit in the tray have experienced is uploaded to each of the fruit's chains. A buyer in China might scan the tag and then, have access to a website that translates the blockchain information into useable information. Where was the kiwifruit grown? How old is it? What temperature extremes has it been exposed to? How likely is it to be at its optimal eating point?

All of the technology to make this scenario a reality currently exists. The only stumbling blocks would be the insertion of the micro-RFID on (manual) picking and the reading of the chip by the Chinese consumer. However, currently, fruits are tagged at packing with individual stickers, and pallets of kiwifruit are given RFID tags; therefore, it is not a very large jump to individualized RFID tags. Also, although scanning of tags might involve a ramping up of phone technology, Chinese consumers are used to scanning quick response (QR) codes (2D barcodes) to learn more information about a product (or to pay for that product). Tray-level QR codes linked to a blockchain could be implemented without delay.

The level of information described above is unprecedented. It would allow for product recalls to be handled extremely efficiently. It would also increase product (particularly food and pharmaceutical) safety and decrease fraud. As long as effective methods could be devised for inputting the information, it could significantly increase the accountability of the supply chain.

In particular, it should allow visibility of whether ethical standards have been adhered to in the production and distribution of the product.

Another important application for blockchain, beyond information storage, is the availability of so-called "smart contracts." These are contracts that are automatically triggered based on some externally verified event. For example, payment could be authorized as soon as the container reaches customs. More interesting is if smart contracts are combined with detailed supply chain information. For example, the kiwifruit transporter's payments could depend on the maximum and minimum temperatures experienced by the fruit during transit. Although effective contracting is a relatively mature area within OM, smart contracts seem to offer a whole range of coordination mechanisms not previously considered.

A final important benefit of blockchain is the elimination of intermediaries. Much of the current role of distributors and freight forwarders is information based. With blockchain, many of those roles can be eliminated. Furthermore, if governments embrace the technology, then customs' processes may be able to be significantly simplified. However, all of these efficiency gains rely on a level of standardization within the industry. If multiple competing blockchains develop (as they likely will) and if they are made proprietary (as could easily happen), many of the efficiencies may be lost.

We see a number of research opportunities stemming from blockchain's likely impact on the processes and procedures surrounding the supply chain. First, if blockchain fundamentally changes the structure or the power relationships in supply chains, then these new configurations will need to be analyzed. Second, as discussed earlier, smart contracts would seem to provide a significant opportunity for more effective and sophisticated coordinating contracts. Third, as mentioned for the IoT, the quantity of data available through blockchain is a level of magnitude not considered in most operations models.

5. Advanced Robotics

Manufacturing automation is not new, and production system robotics are already highly sophisticated. The concept of a "lights-out" factory, in which processing is almost entirely carried out by robots, has been around for decades. Over 15 years ago, "in one of Fanuc's 40,000-square-foot factories near Mt. Fuji, robots [were] building other robots at a rate of about 50 per 24-hour shift [running] unsupervised for as long as 30 days at a time" (Null and Caulfieldt 2003). Nevertheless, robotics technology is rapidly advancing in ways that may have profound implications for factories, agricultural production, field service management, and distribution logistics.

Conventional robots in a factory reside within protective metal cages that ensure physical separation from workers under normal operation. This is not only because the nature of the work carried out by robots (welding, for example) is often inherently dangerous. It is also because we have not been able to equip robots with sufficient intelligence to dynamically adapt and adjust to an ambiguous and rapidly changing local environment. The motion of human workers is not fully predictable, and therefore, separation is required to maintain a tightly controlled operating environment for the robot. Recent advances in sensor technology and artificial intelligence are enabling a new generation of robotic technologies that can be deployed alongside human workers.

These collaborative robots, often referred to as "cobots," are being rolled out in real production settings. BMW, for example, now has robots working alongside human workers on its assembly line in Spartanburg, South Carolina, with the motive for one such deployment being to automate a manual task that could cause repetitive strain injury. Interestingly, "existing industrial robots could perform this work, and do it much more quickly, but they could not easily be slotted into a human production line because they are complicated to program and set up, and they are dangerous to be around" (Knight 2014, p. 67). Exoskeletons are also being used to further blur the lines between human and robotic workers.

Ongoing advancement and development of collaborative or interactive robotics are, of course, active fields of research in computer science and engineering. Studying the adoption, acceptance, and application of cobots in production (and indeed, service) settings would seem like a natural line of inquiry for the OM field, especially for those interested in behavioral operations management. The vision—which is to some extent already a reality—of humans and robots working alongside each other raises questions of how such systems should be designed and managed. Answering those questions will require an understanding of how workers perceive and interact with robots in repetitive processing settings.

Although perhaps less interesting from a novel OM research perspective, advancements in robotics are also changing the economic rationale for investments in factory automation. Purchasing and installing robots have long been expensive and time consuming: "robots deployed on factory floors today require teams of specialists who have in-depth expertise for installing (the robots as well as the safety systems), calibrating, and programming them to perform the manufacturing tasks. Typically, this setup takes weeks and costs a multiple of the purchase price of the robot itself" (Intel 2015, p. 1). Traditionally, automation of a processing activity was driven by a desire for variable cost reduction (when labor is expensive), quality improvement (when a robot can repeatedly execute the task with more precision than a person can), or safety (when the processing environment is dangerous or the task is physically onerous). The significant upfront cost and configuration time meant that robots were attractive for high-volume repetitive operations but that they were not attractive for low-volume operations or operations requiring flexibility in terms of volume or mix of work (because robot capacity was fixed and was not easily reconfigured or repurposed). Newer generations of robots, from ABB, iRobot, Motomon, and others, are becoming cheaper and perhaps more important, more easily configured for a range of different tasks, thereby alleviating their conventional flexibility disadvantage. The factory of the future will look very different as cheap, configurable, and collaborative robotics become increasingly available.

Robotics are also taking off in the production of agriculture. According to Jordan (2018), "about 60 percent of the romaine lettuce and half of all cabbage and celery produced by Taylor Farms are harvested with automated systems." Although automatic harvesting of more delicate fruit, such as berries, is further off, advanced robotics are also being used to assess ripeness, pack produce, and hoe weeds. The trade-offs involved in such technologies are likely to be very similar to those found on the factory floor.

The effects of advances in robotic technology are being felt outside of the farm and factory as well. Great strides are being made in the automation of vehicles and the use of drones. Automated guided vehicles have been in use in factories for decades. However, sensors and related technologies are now reaching the point that such vehicles can become autonomous and freed from predefined paths. For example, "thousands of students at George Mason University will have another dining option at their disposal: on-demand food delivery via an autonomous robot on wheels" (Holley 2019). Autonomous vehicles are projected to have a large impact on transportation networks and supply chains (e.g., Olsen and Parker 2019).

Drones or unmanned aerial vehicles are another robotic technology that is fast becoming ubiquitous. They can be used to survey remote locations, deliver small items (such as pharmaceuticals), monitor assets, and spray crops. Larger drones that carry passengers also seem to be on the horizon (Associated Press 2016). Drones are being used for lights-out inventory counting and inspection of oil pipelines to name just two common operational tasks. They may lead to new transportation optimization formulations (e.g., Agatz et al. 2018). The opportunities for OM research seem similar to those for autonomous land vehicles.

In summary, the cost, flexibility, speed, and/or quality of various robotic technologies are improving, with collaborative robotics being a key trend. Furthermore, robotic transportation options have the potential to significantly affect supply chain design.

6. Artificial Intelligence

Like Industry 4.0 itself, AI is a term that does not have one precise definition. Traditionally, AI has meant the mimicking of human intelligence using computers, but recently, the term has begun to encompass "analytics" and "big data" also. Indeed, it is often used simply to indicate that a computer rather than a human is engaged in problem solving, a perspective that readily fits the OM mindset. Borrowing a framework from analytics, we can categorize AI industrial applications as being descriptive, predictive, or prescriptive.

Workers that inspect, pick, or sort products must continuously recognize different objects and categorize them correctly. This is mentally fatiguing, and errors can result in defects going unnoticed or products being picked or placed incorrectly. AI that recognizes images or objects can augment workers' categorization skills or alternatively, enable robots to automate these types of pattern recognition tasks. As discussed in Section 3, sensor-enabled operations will generate vast amounts of data that can be mined using AI techniques to uncover previously unknown relationships between processing conditions and outcomes, and this information can then be used to improve process design and control. In agriculture, facial recognition is being developed to allow "farmers with large herds to know as much about the behavior of individual cows as farmers with small herds do" so that milk yield can be improved (Owen 2018). Such applications are descriptive in the sense that AI is describing an existing state (of an object or processing relationships) and is not necessarily predicting future outcomes or prescribing actions.

Of course, after cause-and-effect relationships are at least partially understood, then benefits can be gained by predicting future outcomes and prescribing current actions based on those predictions. Predictive AI has become a key focus of durable asset manufacturers, such as GE and Siemens, because condition-based maintenance is dependent on accurate estimates of future failure times. This requires sensors that deliver continuous data to a computer but also, advanced algorithms that predict remaining life based on current and past sensor readings. Prescriptive AI, whereby operational actions (or at least recommendations for actions) are generated by software, is not especially new; manufacturing and supply chain decision support systems (DSSs) have existed for decades. What is new is the increasing adoption of machine learning techniques to generate these prescriptions. (Advances in machine learning also underpin the increasing use of descriptive and predictive AI.)

Whereas prescriptive OM models traditionally set up the objective and solved for the optimal decision using some appropriate algorithm, with machine learning, the computer uses training data and statistical techniques to learn how to make good decisions without relying on a specific underlying model. There are also hybrids to this approach, where the algorithms are given some guidance but not the entire model (see, for example, the dual-sourcing application in Gijsbrechts et al. 2018). Because machine learning in OM is the focus of the article by Mišić and Perakis (2019) in this issue (and also discussed somewhat by Song et al. (2019) in this issue), we do not elaborate further here and refer the interested reader to those articles.

AI also goes hand in hand with advanced robotics. According to Roose (2019), although

> [i]n public, many executives wring their hands over the negative consequences that artificial intelligence and automation could have for workers . . . in private settings . . . these executives tell a different story: They are racing to automate their own work forces to stay ahead of the competition, with little regard for the impact on workers.

Indeed the founder of the Chinese e-commerce company JD.com has been quoted as saying "I hope my company would be 100 percent automation someday." As noted earlier, human workers have traditionally been more flexible but slower than robots, but with advanced robotics and smart AI, that trade-off seems to be changing.

From an OM research perspective, AI presents ample opportunities for algorithmic development either in general purpose methods or in specialized applications. The complexity and scale of the problem and the speed of solution are likely to be distinguishing features of future work. From a behavioral perspective, just as with robotics, AI introduces an interaction between humans and technology. In particular, workers will become more reliant on AI-generated recommendations, and this raises interesting questions as to how best to manage this worker-machine interface. There is an emerging literature in organizational behavior on algorithm aversion (Dietvorst et al. 2015, 2016), and there is one in OM studying the interaction between human workers and DSSs. For example, both Caro and Saez de Tehada (2018) and Sun et al. (2019) show that adherence to such DSSs can be low but that it can be improved with changes to either how it is presented or the algorithmic prescriptions. In general, we would expect AI to have a significant impact on a large number of operations and supply chain processes.

7. Other Technologies

Although we have focused on the core technologies of AM, IoT, blockchain, advanced robotics, and artificial intelligence, other emerging technologies are also relevant to Industry 4.0.

Augmented reality (AR)—in which the physical world is enhanced with digitally generated visual or other sensory information—has applications not just in entertainment but also, in industry. GE is experimenting with AR as a means to drive productivity and quality by "projecting the work instructions onto the parts and [using] sensors to monitor the assembly and give feedback to the operator. . . . The system signals the operator immediately if an error occurs or guides them to the next step" Kellner (2018). Anecdotal cases of AR use by Boeing, GE, and "several other firms show an average productivity improvement of 32%" (Abraham and Annunziata 2017, p. 5).

In a similar vein, although Google Glass was not a consumer success, wearable AR glasses have found applications in manufacturing: "with Google Glass, [the worker] scans the serial number on the part she's working on. This brings up manuals, photos or videos she may need. She can tap the side of headset or say 'OK Glass' and use voice commands to leave notes for the next shift worker" (Shamma 2017). Other applications of industrial wearable technology include devices aimed at reducing posture- and movement-induced injuries and those aimed at tracking worker exposure to hazardous materials.

Along with progress in sensor technology and AI, innovations in material science (such as the thin, strong, transparent, and highly conductive material graphene and "smart materials" that can adjust their properties in a controlled fashion in response to external stimuli) are likely to drive advances not only in wearable devices but also, in "smart" products that have embedded intelligence that can be exploited during both production and use.

The term Agriculture 4.0 is sometimes used as an analog to Industry 4.0 (e.g., De Clercq et al. 2018). However, there is another dimension to Agriculture 4.0, namely agricultural-specific technologies and high-technology foods . For example, vertical farming and genetic engineering are two key technologies in this sphere. In addition, laboratory-manufactured and bioprinted animal and plant proteins are growing in popularity. Venture capital flooding into the agriculture technology sector (protein, food, and seed and crop technology) was U.S. $25 billion in 2015, and the Agricultural Development Bank of China has allocated at least 3 trillion yuan (U.S. $435 billion) by 2020 to the modernization of China's agriculture industry (Bosworth 2016).

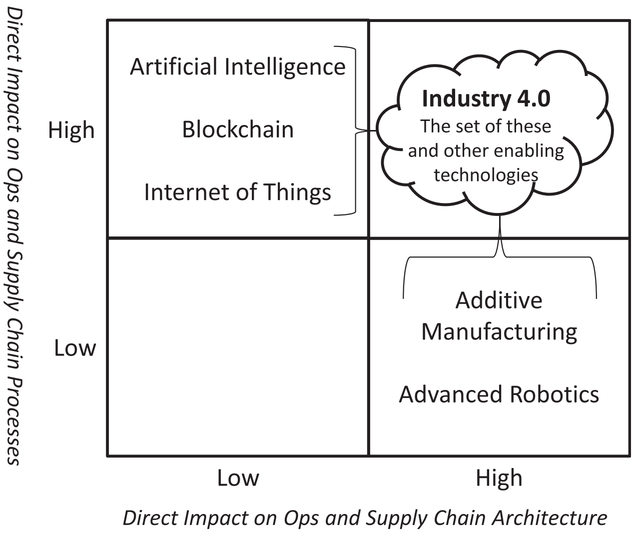
8. Conclusions

One hierarchical view of operations and supply chain strategy is that a natural tension exists between the competitive priorities of cost, flexibility, speed, and quality, and although all are important, a firm cannot be best in class on all four priorities and must, therefore, choose between them. Overall business strategy (e.g., which customers to target and what do they value) helps the operations function make this choice. The ranking among priorities then drives both the design of the tangible architecture of operations (i.e., the degree of vertical integration; the capacity and type of production, transportation, and MRO assets; inventories; and the geographic distribution of these various elements) and the design of the intangible processes and procedures that orchestrate the flow of goods and information through this operations and supply chain architecture.

As we have already discussed, the technologies underpinning Industry 4.0 can either in isolation or in combination improve one or more of the four priorities. More intriguingly, Industry 4.0 may alleviate some of the tension between the priorities and thereby, enable new customer value propositions. Crucially, Industry 4.0 creates new design possibilities for the operations architecture and its associated processes. Certain technologies, the IoT for example, will directly impact the processes for managing the operations and supply chain architecture and thereby, indirectly influence architectural choices. Others may directly influence the architecture but the processes only indirectly. Figure 1 categorizes technologies by their potential for direct impact on architecture and processes. However, as reflected in the figure, the key to Industry 4.0 is that it is not an individual technology. Instead, it is a synthesis of these related technologies. We can, therefore, anticipate that Industry 4.0 will have a profound impact on both the architecture and process dimensions of operations strategy.

AM and cheap/configurable robotics reduce the minimum efficient scale required for economic production and promote flexibility and speed of production

Figure 1. Potential Impact on Operations Strategy



launch. Cobots, AI, wearable devices, and AR can elevate (or eliminate) the role of human assets. The IoT, blockchain, and digitization enable remote and real-time monitoring, diagnosis, control, and optimization within factories and across geographically dispersed assets. A globally distributed and agile network of production assets that can dynamically and rapidly adjust and reallocate activities becomes possible.

It is promises such as these that make many believe that the marriage of the physical and digital worlds that is Industry 4.0 will have a revolutionary impact on operations and supply chain management. The OM community should engage with this vision to both understand the implications and limitations of Industry 4.0 and to help develop the concepts and techniques that will further drive its potential and adoption. We hope that this article will prove to be useful as OM researchers look for opportunities and challenges in this space.

Endnote

[1] For ease of exposition, we will use the term sensor to describe both the sensor and any associated controller that drives action based on the sensor reading.

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