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How will artificial intelligence and Industry 4.0 emerging technologies transform operations management?

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Abstract

Emerging technologies such as artificial intelligence, blockchain, additive manufacturing, advanced robotics, autonomous vehicles, and the Internet of Things are frequently mentioned as part of "Industry 4.0." As such, how will they influence operations and supply chain management? We answer this question by providing a brief review of the evolution of technologies and operations management (OM) over time. Because terms such as "Industry 4.0" do not have a precise definition, we focus on more fundamental issues raised by Industry 4.0 emerging technologies for research in OM. We propose a theory of disruptive debottlenecking and the SACE framework by classifying emerging technologies in terms of the functionalities they enable: sense, analyze, collaborate, and execute. Subsequently, we review the nascent but rapidly growing literature at the interface between digital technologies and OM. Our review suggests that one way to assess the value of Industry 4.0 technologies can be via their influence on adding revenues, differentiating, reducing costs, optimizing risks, innovating, and transforming business models and processes. Finally, we conclude by proposing an agenda for further research.

KEYWORDS

artificial intelligence (AI), business excellence, digital transformation, governance, Industry 4.0, information technology (IT), operations, supply chain management, strategy, blockchain, additive manufacturing, internet of things (IOT)

1 | INTRODUCTION

There is a saying that the only constant in life is change. Arguably the majority of changes in organizations and operations within the last few centuries have been brought about by technological changes and industrial revolutions (Johnson, 2010; Singhal, 2001). These technological changes often also bring about changes in organizational forms, governance processes, and how firms compete. For example, large modern multiunit enterprises were not needed in the pre-industrial world before the 1840s due to the use of traditional energy sources based on wind and animal power (Chandler, 1977; Landes, 2005).

Our goal in this article is to make sense of an emerging class of technologies that fuse the physical, digital, and biological worlds. These technologies are sometimes referred to as "Industry 4.0" technologies, which may have significant implications for industry transformations and firm survival (Agrawal et al., 2020). We begin by classifying Industry 4.0 technologies in terms of the functionalities that they enable. Subsequently, we review what we know about Industry 4.0, based on our review of articles in *Production and Operations Management* (*POM*), and then lay out an agenda for future research.

Industry 4.0 is an umbrella term originating from the practice literature that refers to a constellation of new technologies emerging from 2000 onwards that are expected to transform manufacturing and operations (Tang & Veelenturf, 2019). In academic literature and practitioner outlets, there is no single definition of Industry 4.0, nor is there a definitive set of associated technologies (Xu et al., 2018). For example, some practitioners identify the key technologies associated with Industry 4.0 as autonomous robots, simulation, the Internet of Things (IoT), cloud computing, additive manufacturing (AM), augmented reality, big data, and cybersecurity (Rüßmann et al., 2015). Following prior work (e.g., Olsen & Tomlin, 2020; Tang & Veelenturf, 2019), we focus on six key technologies under the broad umbrella of Industry 4.0: AM, the IoT, blockchain, robotics, autonomous vehicles (AV), and artificial intelligence (AI) and machine learning (ML).

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2 | THEORY OF DISRUPTIVE DEBOTTLENECKING AND THE SACE FRAMEWORK

One influential framework to characterize technologies and innovations is the lens of the theory of disruptive innovation (Christensen, 1992a, 1992b), based on research published in *POM* in the early 1990s, which makes a distinction between "sustaining" and "disruptive" innovations. Some argue that incumbents are usually good at managing transformations that pertain to sustaining or competence-enhancing innovations. More complex, however, are disruptive or competence-destroying innovations whose performance trajectory is typically below the current market needs and far below the performance trajectory of sustaining innovations. Typically, mainstream customers do not value these innovations; as a result, they initially have lower profit margins. We avoid using the "disruptive innovations" framing of technologies due to significant questions about their underlying ideas and key premises of this theory (King & Baatartogtokh, 2015; Tellis, 2006).

We view technology as a way to enable certain functionalities, debottleneck activities, or help remove constraints. In other words, instead of a theory of disruptive innovation, we argue for a theory of disruptive debottlenecking, which views technology as instrumental in overcoming certain tradeoffs that prior generations of technologies had conventionally taken for granted. Some view Industry 4.0 as a natural culmination of Industry 1.0 (powered by water and steam and spurred by railroad networks), beginning from about 1760 to around 1840; Industry 2.0 (powered by electric power and assembly line production), beginning around 1900; and Industry 3.0 (powered by information technology (IT) and automation systems), beginning in the mid to late 1900s (Xu et al., 2018).

Figure 1 parses Industry 4.0 technologies in a historical context, mapping and contrasting them with previous generations of technologies (see Singhal and Singhal 2022a, 2022b for an insightful history of OM). We draw on prior work (Agrawal et al., 2020; Mithas et al., 2020) to parse emerging Industry 4.0 technologies in terms of the following functionalities: (1) the ability to sense the environment (*sense*), (2) the ability to analyze information (*analyze*), (3) the ability to collaborate with others within or across firms (*collaborate*), and (4) the ability to automatically complete tasks (*execute*).

The SACE framework captures the four functionalities: sense, analyze, collaborate, and execute. First, regarding "*sense*" technologies, pre-Industry 4.0 technologies used barcodes, whereas newer technologies make much greater use of RFID tags (Whitaker et al., 2007), quick response (QR) codes, and Internet-connected miniaturized sensors that talk to each other in real time, providing far more functionality in terms of the ability to track assets and people. Second, the prevalence of cloud computing and big data have enabled organizations to "*analyze*" data by deploying prescriptive and cognitive analytics using advanced machine learning and AI technologies. There is a clear shift from descriptive and predictive analytics that were more prevalent in the pre-Industry 4.0 era, often enabled by business intelligence tools and customer relationship management systems (Mithas et al., 2005; Saldanha et al., 2017), to more advanced analytics enabled by big data technologies. New algorithms and software learn continuously and improve themselves, raising hopes of significant breakthroughs across manufacturing and service sectors (Kissinger et al., 2021; Mithas et al., 2019; Parker et al., 2016). Third, significant enhancements in Internet connectivity and 5G technologies are enabling digital platforms, blockchains, and smart contracts. These technologies are creating new possibilities to *"collaborate"* across firms and value chains. By contrast, previous generations of enterprise systems created significant efficiencies in collaboration within firms for the most part and sometimes also enabled partnerships with suppliers and customers around the world as reflected in the outsourcing and offshoring of operations (Bardhan et al., 2006, 2007). Finally, with respect to "*execute*," additive manufacturing (AM), robotics, and autonomous vehicles open up new possibilities for *executing* and delivering new efficiencies in manufacturing, warehousing, and logistics operations.

3 | WHAT WE KNOW: INDUSTRY 4.0 AND OPERATIONS MANAGEMENT (OM)

We searched the Scopus database using keywords related to the six Industry 4.0 technologies in this paper by restricting the search to the UTD-24 list of journals (see Figure 2).[1] *POM* was among the top three journals in terms of published papers on the six technologies of interest; it alone was responsible for nearly 11% of papers related to Industry 4.0 technologies, the majority of which appeared recently or are forthcoming. We next review and discuss the *POM* papers that study each of the key Industry 4.0 technologies and their impact on operations and other issues.

3.1 | Additive Manufacturing (AM)

AM, also known as 3D printing, has several advantages over traditional manufacturing. For example, AM can make more complex products, offer more product variety through tailored production, enable localized production, and shorten production and delivery lead times. AM is generally more economical for making low-volume products but can be costlier for large-volume products. Overall, the use of AM is not likely to completely replace traditional manufacturing any time soon, whether it be in factories or demand locations (stores and warehouses). When used in factories, AM replaces the traditional mode of production. When used in demand locations, AM also changes the supply chain structure by removing the shipping operations needed in the supply chain with the traditional production mode.

In most cases, the cost of 3D printers is still too high to adopt AM in demand locations such as stores; however, mass

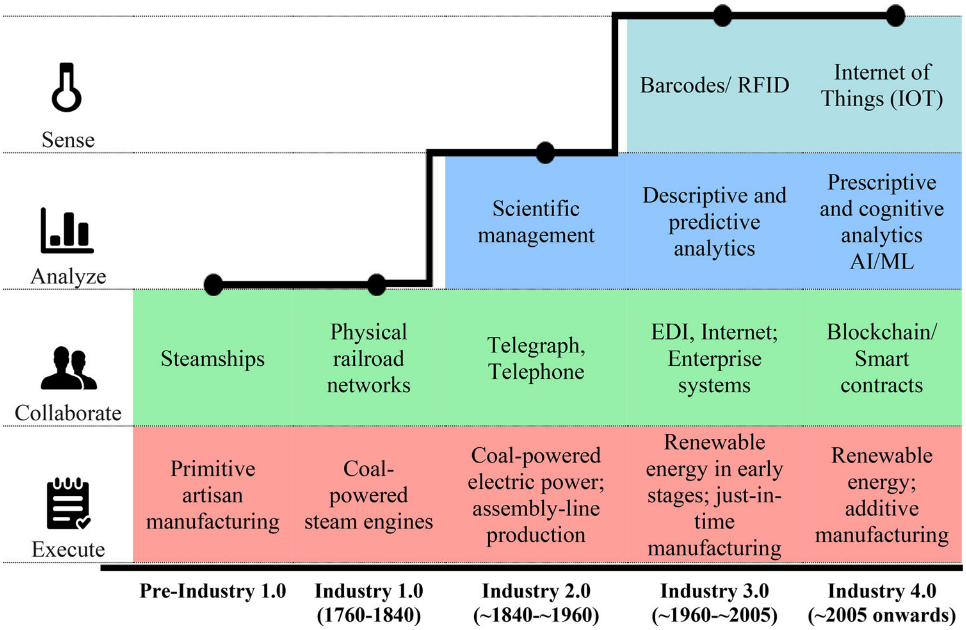

FIGURE 1 Industry 4.0 technologies and their functionalities in a historical context. AI, Artificial Intelligence. See Table A1 in Appendix A of the Supporting Information for further details mapping the SACE framework with the emerging technologies, including how complementary management innovations amplify the impact of technologies.
Notes: RFID, radio-frequency identification. ML, machine learning. EDI, electronic data interchange. AI, artificial intelligence. [Color figure can be viewed at wileyonlinelibrary.com]

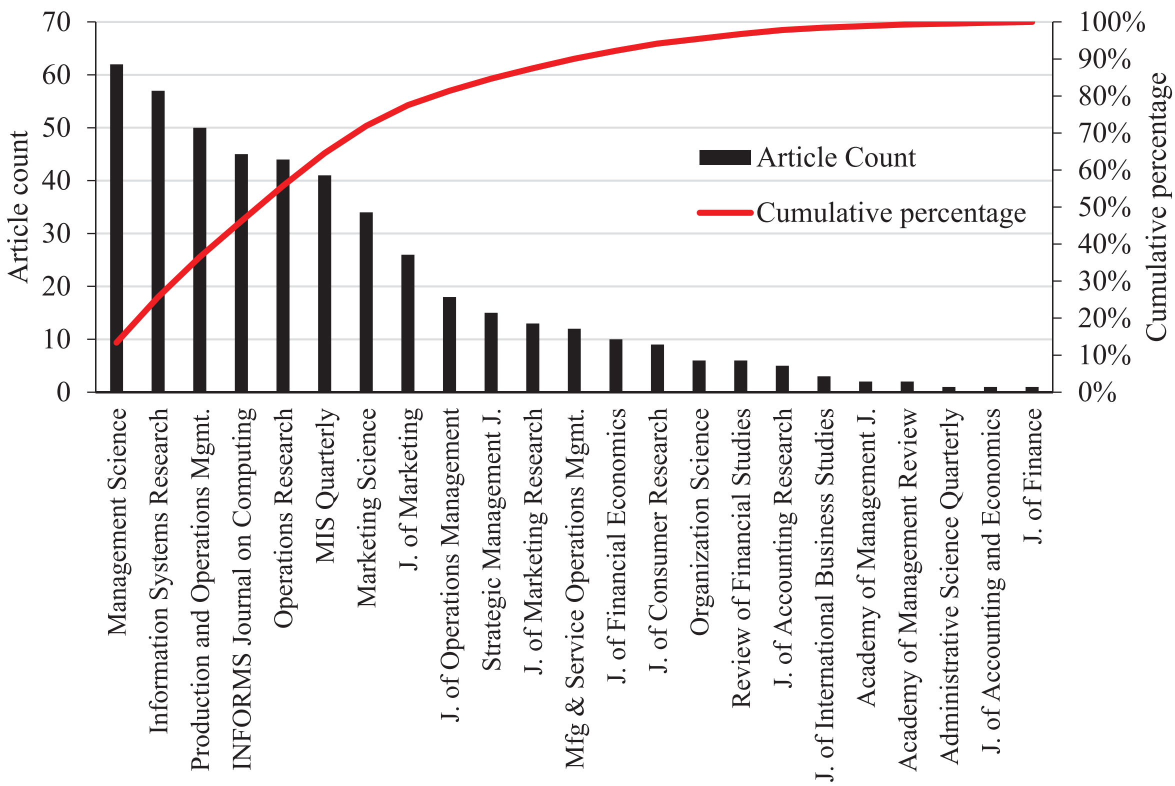

FIGURE 2 Pareto analysis of premier business journal publications on emerging technologies.
Note: Figure 2 shows a Pareto analysis focusing on the 463 papers published in 23 of the top UTD-24 business journals since 1983 (*Accounting Review* did not have any articles related to the six Industry 4.0 technologies).
[Color figure can be viewed at wileyonlinelibrary.com]

customization could occur in stores once this cost is low enough. Chen et al. (2021) study scenarios in which both factories and stores utilize AM. They investigate the impact of AM on product offering, pricing, and inventory decisions under the two scenarios. Westerweel et al. (2021) consider the scenario when AM is used in demand locations to satisfy spare parts inventories and study inventory-related issues.

3.2 | Drones, robots, and autonomous vehicles

Drones, advanced robots, and autonomous vehicles can change the way firms manage warehouses, inventory, and shipping in the supply chain. First, drones can be used in logistics to conduct last-mile delivery; inspect and assess the security and maintenance of logistics assets such as highways, warehouses, and terminals; and conduct aerial reviews of inventory and pallets inside warehouses and distribution centers. The potential benefits of drones include reduced labor costs, reduced transportation costs, the seamless integration of warehouse management systems, and improved customer service. Perera et al. (2020) study the impact of a drone delivery system (DDS) on a retailer's extant logistics parameters, for example, the number of customer-facing delivery centers (last-mile warehouses) it uses and the delivery lead times it offers. The authors show that as drone technology matures and becomes more cost-effective, delivery networks will become increasingly decentralized while delivering products at faster speeds. Although perfect delivery customization, under which each demand location is offered a customized delivery guarantee, is theoretically feasible under a DDS, it may not be practical to implement such a finely differentiated delivery strategy. Bravo et al. (2019) design a method to solve a path planning problem that arises in applying unmanned aerial vehicles (UAVs) in humanitarian relief to search for victims in disaster-affected areas.

Second, advanced robotics enable retailers such as Amazon and JD to automate their warehouse operations and order fulfillment processes. Robots can substitute human labor, resulting in higher productivity and lower operational costs, albeit with a significant upfront investment in developing algorithms for storage and scheduling decisions in automated warehouses (Wang et al., 2021a; Yuan et al., 2019). Finally, turning to autonomous vehicles (AVs), AVs have the potential to make mobility more affordable, sustainable, and accessible. Naumov et al. (2020) study the impact of autonomous passenger vehicles and pooling on consumer mode choice and its effect on the performance of road and public transit systems. They show that the well-intentioned move to promote pooling may have the unintended consequence of triggering a public transit death spiral, leading to both worse public transit quality and more (rather than less) traffic congestion. They argue that the deployment of autonomous vehicles and pooling can accelerate the transition to sustainable urban mobility but only when accompanied by policies that make driving less attractive. Compared to driverless cars, less talked about are autonomous commercial trucks, which may have an enormous impact on the shipping industry. Self-driving trucks can leave a warehouse at any time, drive all day and night, and deliver products to local distribution centers more quickly and with fewer issues.

3.3 | Artificial Intelligence (AI), big data, and machine learning

Published papers in *POM* that study AI and related technologies (e.g., big data and machine learning) can be classified into two streams of research: (i) research that studies how AI innovation impacts company performance and (ii) research that studies how AI, Big data, and machine learning can be used as algorithmic tools to make better decisions. Two *POM* papers (Li et al., 2021; (Li & Li, 2021) study the impact of AI innovation on company performance. (Li & Li, 2021) conduct an empirical study on the impact of AI innovation, represented by the AI-related patents that a company owns, on the relationship between corporate social responsibility (CSR) and idiosyncratic risk (IR). It is known that CSR can negatively affect IR, while beyond a certain level, it acts in the opposite direction, exhibiting a U-shaped relationship. Their study shows that AI innovation flattens the U-shaped curve, weakening CSR's positive impact on IR. This result indicates that AI innovation is not always beneficial. (Li & Li, 2021) study the AI automation of the retailer's order decision in a decentralized supply chain comprising one supplier and one regretful retailer. They show that replacing human decisions with AI automation could worsen companies' performance.

Turning to how AI and related tools can be leveraged to design better algorithms for operational decision-making, Lau et al. (2018), Chang et al. (2021), and Zhu et al. (2021) study how big data and machine-learning techniques can be used to better forecast demand and make predictions. Cohen (2018), Swaminathan (2018), Ellis et al. (2018), Geva and Saar-Tsechansky (2021), and Yang et al. (2021) discuss how AI and other data-driven tools can be used to make better pricing, inventory, humanitarian operations, and service operations decisions. Helm et al. (2016), Hopp et al. (2018), Queenan et al. (2019), and Nenova and Shang (2021) argue that big data analytics can enable better decisions in healthcare.

3.4 | Blockchain

A blockchain is a distributed—decentralized—ledger and a digital system for recording transactions among multiple parties in a verifiable and tamperproof way (Babich & Hilary, 2020). Conventional transaction systems such as ERP systems and even newer technologies such as RFID tags do not reliably allow all parties involved in a supply chain transaction to see all relevant information flows, inventory, or money. A blockchain system eliminates blind spots and enables transparency and traceability in the supply chain.

When blockchain recordkeeping is used, assets such as units of inventory, orders, loans, and bills of lading are given unique identifiers, which serve as digital tokens. Additionally, participants in the blockchain are given unique identifiers or digital signatures, which they use to sign the blocks they add to the blockchain. Every transaction step is then recorded on the blockchain as a transfer of the corresponding token from one participant to another.

The potential benefits of blockchains in supply chain management include: (i) enhanced transparency and traceability and (ii) increased supply chain efficiency and speed due to a higher visibility of inventory flows in the supply chain, which makes lead times more predictable, and hence reduces supply chain uncertainties. Hastig and Sodhi (2020) argue for OM research on implementing supply chain traceability systems by identifying business requirements and the factors critical to successful implementation. Wang et al. (2021b) design and implement a blockchain-enabled data-sharing marketplace for a stylized supply chain. They demonstrate how a blockchain can be used to overcome impediments in supply-chain data sharing (such as distrust, privacy concerns, data misuse, and the asymmetric valuation of shared data between entities) and provide a detailed tutorial with a step-by-step implementation for how to set up such a data exchange prototype using Hashgraph. Pun et al. (2021) and Shen et al. (2021) study the effectiveness of blockchain as a signaling tool for product authenticity. Pun et al. (2021) consider a market with a manufacturer and a deceptive counterfeiter. The manufacturer can signal product authenticity either with blockchain technology or through pricing. Their results advocate for government subsidy because it benefits both customers and society and could be a better approach than government enforcement efforts. Shen et al. (2021) examine how permissioned blockchain technology (PBT) combats copycats in the supply chain, and how it benefits brand name companies. Although PBT implementation helps novice customers identify product authenticity and the real quality of products, they show that, if and only if the number of novice customers is large enough, then selling through a PBT retailer can effectively combat copycats.

3.5 | Internet of Things (IoT)

POM is yet to publish any studies specifically on IoT-related issues.

To summarize, our review of the *POM* papers that study issues and impacts related to Industry 4.0 technologies suggests that most focus on operations-related issues in firms that aim to optimize productivity, profitability, cost efficiency, and customer service. We are aware of only two *POM* papers discussing the impacts of advanced technologies on broader societal issues. Corbett (2018) points out that the large-scale use of big data will have some undesirable consequences, including social and ethical issues. Tang (2021) uses case examples to describe how innovative operations, enabled by advanced technologies such as mobile phones, online platforms, solar technology, blockchain, AI, and the IoT, can empower women to alleviate poverty, reduce hunger by improving health, increase access to clean water and sanitation, and increase access to education and decent work.

3.6 | Industry 4.0 and ADROIT Framework

We propose that the potential value of Industry 4.0 technologies in creating competitive advantage can be explained via the ADROIT framework with six components: ***A***dding revenues; ***D***ifferentiating or increasing willingness-to-pay (WTP); ***R***educing costs; ***O***ptimizing risks; ***I***nnovating by generating and deploying knowledge and other resources and capabilities; and ***T***ransforming business models and processes (Mithas, 2016). We briefly explicate each component of the ADROIT framework.

First, Industry 4.0 technologies help organizations add revenues. For example, advanced analytics give managers data-driven insights and facilitate informed decisions about planning product and customer strategies. The flexibility provided by Industry 4.0 technologies (e.g., sensors) improves asset utilization, which offers opportunities for increased revenue. Second, Industry 4.0 technologies help organizations differentiate their product or service offerings. For example, AM enables the mass customization of goods by reducing product development and manufacturing time and cost. The automation and self-optimization of process improvements facilitate responsiveness to customers, increasing the differentiation and WTP of customers.

Third, Industry 4.0 technologies help firms reduce costs. For example, IoT provides information and improves the efficiency of manufacturing processes. IoT facilitates real-time monitoring and quality control, reducing waste and rework. AM enables quick prototyping, lowering the cost of engineering. Robots perform tasks with precision, increasing productivity. Fourth, Industry 4.0 technologies help firms optimize risks. For instance, IoT enables machines to communicate with each other and share real-time data from multiple sources. Blockchain enables data transparency and enhances information sharing in the supply chain. Increased data and information sharing in manufacturing processes and across the supply chain reduces uncertainties and associated risks. Fifth, Industry 4.0 technologies help firms innovate. For example, firms can create "smart factories" that provide the knowledge of production processes and track production in real time using wireless sensors and IoT. Finally, Industry 4.0 technologies help firms transform their business processes. For example, AM enables flexibility and responsiveness by facilitating the adjustment of production processes for multiple types of products and changing conditions (Frank et al. 2019). Sensors, blockchain, AM, data analytics, and robots facilitate the creation of cyber-physical systems. These systems integrate networking and physical processes, making it easier to monitor and control physical processes.

Table 1 shows how the Industry 4.0 papers published in POM map to components of the ADROIT Framework, with the blank cells suggesting opportunities for further research.[2]

TABLE 1 The ADROIT framework applied to Industry 4.0 studies in *Production and Operations Management*

	Additive manufacturing (AM)	Drones, autonomous vehicles, robots	Artificial intelligence (AI), big data, machine learning	Blockchain	Internet of Things (IoT), smart sensors
Add revenues	X		X		
Differentiate	X		X		
Reduce costs	X	X	X		
Optimize risk			X	X	
Innovate				X	
Transform		X	X		

Abbreviation: ADROIT, *A*dding revenues; AV, autonomous vehicles; ML, machine learning; *D*ifferentiating or increasing willingness-to-pay (WTP); *R*educing costs; *O*ptimizing risks; *I*nnovating by generating and deploying knowledge and other resources and capabilities; and *T*ransforming business models and processes

4 | WHERE TO GO FROM HERE: NEW FRONTIERS OF RESEARCH OPPORTUNITIES IN OM

Industry 4.0 technologies open new frontiers of research along several dimensions for OM researchers, both in terms of several research domains and methodologies. Table 2 provides a summary of future research directions.

4.1 | Doing “normal science” in OM with emerging technologies

Industry 4.0 technologies provide opportunities to revisit topics in conventional OM research, such as total quality management, project management, and buyer–supplier relationships (Bardhan et al., 2007; Bendoly, 2014; Mishra et al., 2016; Mithas & Jones, 2007; Mithas et al., 2011; Singhal, 1994; Whitaker et al., 2007). Such investigations can help assess how findings concerning pre-Industry 4.0 technologies generalize to newer technologies and how newer technologies complement or substitute older technologies. For example, researchers can assess the extent to which Industry 4.0 technologies influence or enable operations and supply chain management capabilities and thereby influence other firm performance measures. Such investigations constitute incremental “normal” science and will help refine our understanding of the role of Industry 4.0 technologies in operations (Roth et al., 2016).

Mathematical models in OM (e.g., lot-sizing models, inventory models, aggregate planning models, and scheduling models) are built on underlying assumptions that reflect the technological reality of the time when the model was created. As manufacturing and information technologies evolve, these assumptions and model setups may need to be revised to make these models relevant in the era of Industry 4.0 technologies. For example, when blockchain technology is widely adopted, information availability and the way information is shared in the supply chain will be very different from the current reality (Babich & Hilary, 2020), prompting a reexamination of several research questions. How will the bullwhip effect change with the widespread adoption of blockchain? How will the relationship between different parties in the supply chain change? How will consumers (who have access to every bit of information about a product) change their shopping behavior? As a result, how should retailers' pricing strategies change? How can Industry 4.0 technologies be used to identify risks in the supply chain and mitigate harm automatically? Moreover, significant differences between AM and conventional manufacturing processes in economies of scale and scope (Baumers & Holweg, 2019) will require modifications in existing production planning and scheduling models as AM diffuses further and becomes more viable. AM technology can also impact how firms make production facility location decisions and downstream decisions in the supply chain, such as inventory ordering and logistics decisions.

4.2 | Will technologies enable new “dual” strategies and overcome conventional tradeoffs in OM?

Because of the limitations of traditional pre-Industry 4.0 technologies, conventional value activities often involve tradeoffs among customers, employees, and infrastructure management activities with different underlying economies of scope, speed, and scale (Hagel & Singer, 1999). As a result, the conventional “either-or” strategy concepts relied on the logic of “tradeoffs” to suggest the pursuit of either efficiency (i.e., lower costs) or differentiation. For example, prior work suggests that revenue expansion and cost reduction could be achieved simultaneously only in certain sectors such as manufacturing, but not for service sectors where high-quality human labor tends to be more expensive (Anderson et al., 1997). However, Industry 4.0 technologies can influence those tradeoffs. Prior research in OM has devoted significant attention to such tradeoffs and emphasized the potential role of newer technologies in overcoming tradeoffs or better understanding when these tradeoffs are likely to arise or become detectable (Bardhan et al., 2007; Cachon & Terwiesch, 2006; Rosenzweig & Easton, 2010).

Indeed, newer technologies make it possible for activities to be performed by different players and monitored or coordinated through market signals and prices due to a reduction in transaction costs (Chandler & Cortada, 2000). In

TABLE 2 Research agenda for studying Industry 4.0 technologies

Broad theme/ topic	Illustrative research questions
Doing “normal science”/revising existing models	Which technologies (e.g., sense, analyze, collaborate, execute) better fit different stakeholders in influencing the outcomes they care about? How can we deploy configurations of technologies to optimize multiple outcomes in operations management (OM)? As manufacturing and information technologies evolve, how should current assumptions underlying many existing OM models be revised? With the widespread use of IoT and blockchain technologies, will the bullwhip effect still exist in the supply chain? How will customers change their shopping behavior? How should retailers’ pricing strategies change? With the wide adoption of AM, how should existing production planning and scheduling models be modified to reflect the new technological reality? How can Industry 4.0 technologies be used to identify risks in the supply chain and mitigate harm automatically?
Pursuing dual strategies/overcoming conventional tradeoffs	How can we craft and execute digital strategies to enable new types of dual strategies and overcome conventional tradeoffs in OM? With the help of AM, for what types of products can firms pursue both customization and cost efficiency? Using sophisticated AI and big data tools, is it possible to pursue a dual supply chain strategy that is both highly responsive to customer demand and highly cost-efficient? Under what conditions can drones be more cost-efficient than trucks? How can trucks and drones be used together to achieve faster delivery and lower cost?
Improving service productivity	How can firms utilize big data and analytics to redesign their business processes? How should underlying service processes be redesigned with advanced robotics and automation deployment in service systems? Is it possible to eliminate some process steps due to advanced technologies? How can robots and automation technologies be leveraged to assist human operators in achieving higher productivity in many labor-intensive service systems? How can Industry 4.0 technologies help firms manage demand at a more granular level to fulfill customers’ individualized needs?
Addressing emerging concerns such as sustainability, social responsibility, and human cost	How will the deployment of Industry 4.0 technologies influence employment, job security, compensation, satisfaction, burnout, turnover, and stress? How can Industry 4.0 technologies be configured and implemented in harmony with humans? How can these technologies be leveraged to address emerging concerns? How can we avoid compromising resilience by cutting any slack for efficiency’s sake? How can we avoid negative externalities created by outsourced production and service processes across country borders?
Addressing the dark side of Industry 4.0	How can the dark side of technologies be avoided via proactive legislation? How can we manage the risks and challenges posed by Industry 4.0 technologies? What are cultural and organizational changes that complement data-driven/analytics-led operations?

other words, newer technologies today allow firms to pursue more complex strategies, often powered by a portfolio of IT systems or configurations of IT systems, to create internal complexity that prevents replication by competitors while retaining external simplicity to attract customers (Mithas & Rust, 2021). Such configurations enable revenue growth and cost reduction simultaneously while retaining the agility to reconfigure the internal IT portfolio and make new competitive moves. Through their “digital ambidexterity,” which has significant importance in contemporary firms to gain competitive advantage, Industry 4.0 technologies may enable firms to adopt a dual-focus strategy (e.g., focus on both revenue enhancement and cost reduction) and thereby help firms reap greater rewards than those firms that adopt and pursue a singular focus. Industry 4.0 technologies can also help organizations offer personalized products to customers while using mass-production methods to make those products. For instance, sensors provide greater knowledge of the manufacturing process, supply chains, and distribution chains, thereby creating opportunities for innovation by facilitating changes in business processes, developing new products, and optimizing the supply chain.

Another tradeoff relates to environmental sustainability and profit (Saldanha et al., 2023). Industry 4.0 technologies can enable both types of strategies. For example, advanced manufacturing facilitates environmentally sustainable manufacturing while also speeding up production. Likewise, AI and sensors in production processes can monitor energy usage and drive both the sustainability and efficiency of processes (Mithas & Rust, 2016; Saldanha et al., 2023).

Related to tradeoffs, we propose three specific research topics as follows. First, although AM has the potential to make customized products with mass production efficiency (Mahamood & Akinlabi, 2016), it is unlikely that AM can realize such a potential for every product. Hence, it would be interesting to identify the types of products for which firms can pursue both customization and cost efficiency with the help of AM. Second, as discussed in Section 3.3, big data and machine-learning tools are successfully applied to improve demand forecasts and make better predictions (Chang et al., 2021; Lau et al., 2018; Zhu et al., 2021). With the help of such tools, firms may be able to better match supply with demand. A widely adopted supply chain strategy proposed by Fisher (1997) prescribes that firms should focus on customer service by being responsive when selling innovative products with high demand uncertainty and focus on cost efficiency when selling functional products that usually have low demand uncertainty. Using sophisticated AI and big data tools, it would be interesting to study whether firms can pursue a dual strategy in their supply chain under which they are both highly responsive to customer demand and highly cost-efficient.

Third, a growing number of firms, including Amazon, UPS, DHL, and Walmart, are promoting and researching last-mile delivery by drones as a possible alternative or complement to traditional delivery by trucks or vans. Compared to trucks and vans, drones can achieve faster delivery with less impact on the environment. However, trucks are generally more cost-efficient than drones because trucks have a much larger capacity and can visit many more customers in a trip than drones. Many studies in the operations research and transportation literature consider vehicle routing problems for drones or trucks and drones used together (Boysen et al., 2018; Macrina et al., 2020). By contrast, few studies investigate strategic issues such as the following: Under what conditions (e.g., service area, customer distribution, order characteristics, etc.) can drones be more cost-efficient than trucks? How can trucks and drones be used together to achieve faster delivery as well as lower cost? Another critical issue is whether Industry 4.0 technologies can promote flexibility (or agility) in supply chains. As Industry 4.0 technologies enable planning to be a continuous process and dynamically react to changing requirements and constraints, it would be promising to study how firms can use the real-time features of Industry 4.0 technologies to flexibly respond to changes in demand or supply and minimize the planning cycles.

4.3 | Will emerging technologies help improve service productivity?

Industry 4.0 technologies can improve service productivity by enhancing the customer experience. For instance, automated tracking and sensors facilitate problem resolution, improve product availability, and broaden customers' choices. Connected sensors and IoT reduce the time between data capture and decision-making, thereby enabling supply chains to react to real-time changes and reduce waste (Ben-Daya et al., 2020). Industry 4.0 technologies such as IoT facilitate quick action in the case of product recalls. IoT also enables the remote management of supply chain operations such as services and maintenance, better coordination with partners, and faster tracking and tracing. Such improvements ultimately help organizations improve their service productivity.

We propose a specific topic for future research. Business process redesign (BPR), or re-engineering, is one of the most powerful tools to improve productivity and transform an organization, especially in the healthcare industry (D'Andreamatteo et al., 2015; Harders et al., 2006). BPR and the associated lean and six sigma toolkits can be deployed without the help of advanced technologies, as such tools have been used by numerous organizations and extensively studied in academia since the 1990s. A natural question to ask is: How can Industry 4.0 technologies be used to help improve and redesign service processes? There are existing studies in the literature that examine the value of IoT, blockchain, and related technologies in business process management (Al-Rakhami & Al-Mashari, 2020; Shoukry et al., 2021). However, these studies mainly focus on integrating technologies and business processes, which is important in its own right. Little research attention has been paid to questions such as: (i) How can firms utilize big data and analytics to redesign their business processes by detecting and eliminating wasteful process steps? (ii) With the deployment of advanced robotics and automation in many service systems, including healthcare, how should the underlying service processes be redesigned? Is it possible to eliminate some process steps due to advanced technologies? (iii) How can robots and automation technologies be leveraged to assist human operators to achieve higher productivity in many labor-intensive service systems such as those in the healthcare and hospitality industries? and (iv) How can Industry 4.0 technologies help firms manage demand at a more granular level to fulfill customers' individualized needs in service systems?

4.4 | Emerging technologies and emerging concerns

While Industry 4.0 technologies have the potential to transform manufacturing and service organizations in terms of traditional metrics such as revenue, cost, quality, and efficiency, such technologies can also enable organizations to improve outcomes along several emerging dimensions. There is a need to investigate how a new generation of technologies will impact emerging concerns. Consider sustainability as an example. Sustainability is an essential outcome for organizations given the global challenges of climate change (Khuntia et al., 2018; Melville, 2010; Saldanha et al., 2023; Sodhi, 2015; Van Riel et al., 2021). Emerging technologies can play an essential role in promoting and achieving social responsibility and environmental sustainability with quality and profits (Sodhi, 2015). For example, connected sensors can self-regulate energy usage based on real-time use and demand. Big data technologies facilitate real-time data processing, business process optimization, and firms' ability to be more energy-efficient and reduce carbon emissions.

Although newer technologies help create efficiencies that benefit suppliers of capital or owners of production resources, they also impose high costs in human terms. For example, some reports cite Amazon's use of Kiva to automate warehousing operations in association with creating quotas and worker injuries (BBC, 2020). There are also concerns about substituting knowledge work by AI and related technologies, creating prospects of unemployment and underemployment, and threatening even high-skill occupations (Jain et al., 2021; Mithas & Whitaker, 2007). Similar concerns have been raised about global supply chains enabled by prior generations of technologies that enabled significant outsourcing and offshoring of production elsewhere. These supply chains rely on cheap labor working under challenging conditions or at extremely low wages in other countries, sometimes in unsafe environments. There is increasing realization that the optimization of production systems or global supply chains without considering human externalities provides only a partial and misleading view of the impacts of technologies. Global optimization may not only create significant local suffering but can also create brittle supply chains that compromise resilience (The Economist, 2020).

There are also concerns about the externalities created by technologies in an economic system that overemphasizes shareholder capitalism over employee or customer capitalism (Martin, 2010; Van Riel et al., 2021; Zingales, 2020). Some calls for research reflect these concerns on how innovative operations enabled by technologies (mobile phones/online platforms, solar technology, blockchain/AI, and the IoT) can empower women to alleviate poverty, reduce hunger by improving health, increase access to clean water and sanitation, and increase access to education and decent work (Tang, 2021). More broadly, how can firms make the new technologies work with humans in harmony without incurring human costs? We join Corbett (2018) and Tang (2021) in their call for research to study emerging issues and bring the "man" back into the "man–machine" picture that concerns the broader domains of OM.

4.5 | Dark side of Industry 4.0 and some caveats: The role of governance and complements

Although Industry 4.0 technologies can transform operations and manufacturing processes, they also pose challenges that highlight potential pitfalls. For example, IoT can result in privacy concerns, compromise the security of data and Internet Protocol addresses, and increase the chance that hackers may exploit vulnerabilities in these devices. AM is prone to production inconsistencies and human error; it also poses risks to intellectual property protection due to the digital nature of inventories (Nelson, 2020). Additional challenges and limitations posed by Industry 4.0 technologies include a greater demand for 24/7 services, an increased need for human resource capabilities, and the need for restricted access to knowledge (Ivanov et al., 2021). Further, the interface of Industry 4.0 technologies with the existing information and communications technology (ICT) infrastructure, scalability, and increased need for data processing capabilities are other challenges. As organizations seek to leverage Industry 4.0 technologies in OM, managing the risks and challenges posed by these technologies will be crucial.

To the extent that general-purpose technologies (e.g., steam engine, electricity, the transistor, and laser) need complements in the form of organizational innovations such as better-skilled workers, teamwork, redesigned processes, and new decision rights governance, different capabilities of "Industry 4.0" technologies should be mapped to such complements (McAfee, 2006). For example, some technologies may require complements such as better-skilled workers, teamwork, redesigned processes, and new decision rights but may allow users to implement and modify them over time in a bottom-up approach. By contrast, other technologies may impose complements and define tasks, sequences, standardization, and monitoring with a top-down approach. Any successful deployment of technology needs careful attention to the governance of decision rights, role and configuration of the IT department, allocation and justification of dollars, and delivery of projects (whether in-house or outsourced/offshored) in a way that is synchronized with the company's strategy (Mithas & McFarlan, 2017). Because governance ultimately dictates how strategy is deployed and executed, managers should use governance levers as a platform to integrate organizational strategies and initiatives, just as an operating system allows a variety of applications to be built by leveraging a common platform.

4.6 | Methodological issues

Our review of Industry 4.0 papers in *POM* in Section 3 suggests that modeling and analytical methods were the most frequently used, accounting for about 38% of the papers. Conceptual and literature review papers, which discuss how new technologies can be applied in the OM field and provide directions for future research, were the second most frequent type, representing about 31% of the papers.[3] Note that some specific topics such as IoT were covered only by conceptual papers; one reason for this may be that IoT is a general-purpose technology or a collection of technologies. Also, big data was the focus of seven conceptual papers but was empirically tested by only three studies. Empirical papers related to Industry 4.0 represent 28% of our sample and cover four technologies: machine learning, big data, AI, and UAVs. Technologies such as 3D printing, blockchain, IoT, and advanced robots are yet to be empirically examined in *POM* studies. Finally, only one paper in our sample employed a qualitative method to review the bibliography on blockchains.

Even though research in OM in general and that concerning pre-Industry 4.0 technologies has become increasingly more empirical over time (Terwiesch, 2019; Terwiesch et al., 2020), we join calls for empirical studies on Industry 4.0

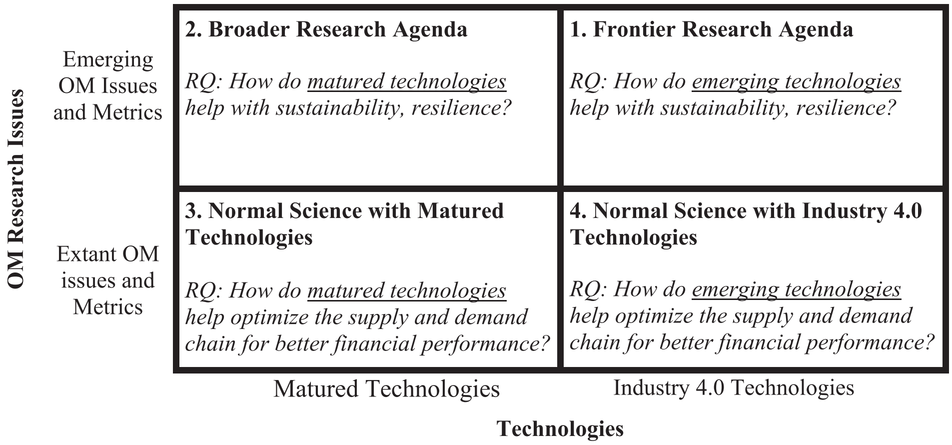

FIGURE 3 Mapping technologies with key operations management (OM) concerns

emerging technologies, with careful attention to causality and endogeneity issues (Gupta et al., 2006; Ho et al., 2017; Ketokivi & McIntosh, 2017; Roth & Rosenzweig, 2020). However, the emphasis on causality does not need to be too narrow or overemphasize a particular way of looking at causality as implicit in counterfactual or potential outcome approaches (Mithas et al., 2022a; Mithas et al., 2022b). Researchers in OM should also consider other ways of assessing causality such as qualitative comparative approaches that use a different notion of causality (based on necessary and sufficient conditions) and a set-theoretic configurational logic leveraging Boolean algebra (Mahoney et al., 2013; Park & Mithas, 2020). In other words, OM should not only embrace "combinative research value, created through complementary applications of empirics and analytics" (Roth & Rosenzweig, 2020, p. 188) but should also remain open to multiple stances toward causality in social sciences for a better understanding of the interactions among men and machines that concern the domains of OM (Barringer et al., 2013).

Figure 3 shows a mapping of the future research opportunities in terms of the nature of technologies and types of issues. We call for studies in Quadrants 1 and 4 that focus specifically on Industry 4.0 technologies and Quadrant 2 due to the relatively low level of research activity in that quadrant so far.

5 | CONCLUSION

New technologies bring new opportunities and challenges; Industry 4.0 will not be an exception to that rule. Some of the hype and speculation about Industry 4.0 technologies reminds us of Herbert Simon's predictions about AI back in 1960 (Simon, 1960). Although we are prone to overestimate the impact of technologies in the short run and underestimate their impact in the long run, new technologies provide exciting opportunities for OM researchers. These opportunities can expand the domains and boundaries of such research regarding the likely impacts of Industry 4.0 not only on business processes but also in shaping the human identity and rethinking "man's conception of his own identity as a species…a new way of describing his place in the universe" (Simon, 1960, p. 55). By parsing the key Industry 4.0 technologies, providing a theory of disruptive debottlenecking and frameworks, such as SACE and ADROIT, for characterizing and understanding their value, and proposing a research agenda for Industry 4.0 technologies, this article sheds light on this critical set of technologies and their role in OM.

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ENDNOTES

[1] See Appendix B in the Supporting Information for details. Appendix C in the Supporting Information provides a brief review of papers related to Industry 4.0 technologies in other top OM and information systems journals as well.

[2] See Tables C3 and C4 in Appendix C of the Supporting Information for further details.

[3] See Appendix D in the Supporting Information for details.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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