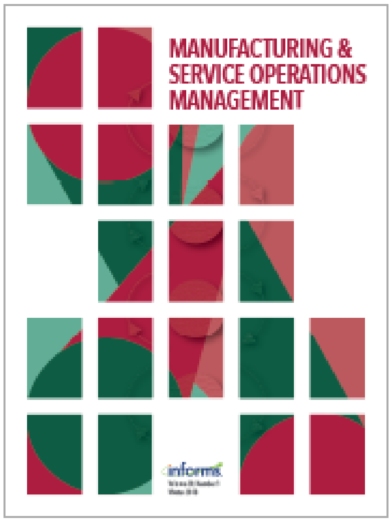

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OM FORUM

Distributed Ledgers and Operations: What Operations Management Researchers Should Know About Blockchain Technology

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Abstract. ***Problem definition***: Blockchain is a form of distributed ledger technology. While it has grown in prominence, its full potential and possible downsides are not fully understood yet, especially with respect to operations management (OM). ***Academic/practical relevance***: This article fills this gap. ***Methodology***: After briefly reviewing the technical foundations, we explore multiple business and policy aspects. ***Results***: We identify five key strengths, the corresponding five main weaknesses, and three research themes of applying blockchain technology to OM. The key strengths are (1) visibility, (2) aggregation, (3) validation, (4) automation, and (5) resiliency. The corresponding weaknesses are (1) lack of privacy, (2) lack of standardization, (3) garbage in, garbage out, (4) black box effect, and (5) inefficiency. The three research themes are (1) information, (2) automation, and (3) tokenization. ***Managerial implications***: We illustrate these research themes with multiple promising research problems, ranging from classical inventory management, to new areas of ethical OM, and to questions of industrial organization.

Supplemental Material: The online appendix is available at https://doi.org/10.1287/msom.2018.0752.

Keywords: visibility • information aggregation • validation • resiliency • smart contracts • digital assets

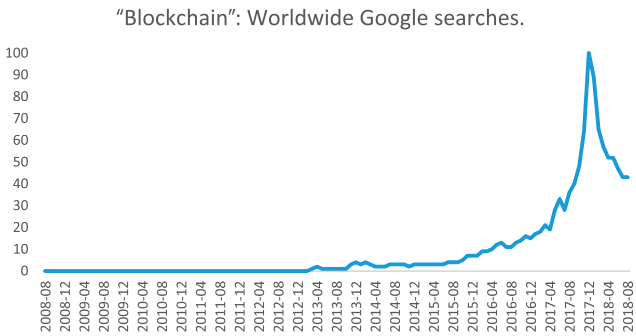
1. Introduction

As a consumer, would you pay more for cannabis (legal in Canada and some U.S. states) if there was a reliable way to verify where the plant was grown and what its chain of custody was before the sale? As a vendor, would you pay to simplify the paperwork of reporting the source of your cannabis to state regulators? As a regulator, what would you do with more reliable information? This is not an entirely hypothetical question, as IBM proposed to the government of British Columbia to use blockchain technology to accomplish exactly that—to verify the provenance of legal cannabis, "from seed to sale," to multiple stakeholders (Dyble 2017).

If the cannabis example strikes you as being far fetched, what if we replaced cannabis with antimalaria medicine? Wall (2016) reports that more than 120,000 people per year die in Africa alone just from counterfeit malaria drugs. Worldwide, the percentage of counterfeit drugs can be as high as 10% (Berkrot 2012), affecting millions of people every year. If blockchain technology has promise in tracking the provenance of cannabis, why not medicines? What about food? The Grocery Manufacturers Association estimates that 10% of food sold worldwide is adulterated—a $49 billion per year cost (Grocery Manufacturers Association 2016). As we are writing this, blockchain technology is being developed to track the provenance and the chain of custody of fish[1] and of coffee (Naydenova 2017). A consortium of companies, led by Walmart, will work with IBM to identify where global food supply chains can benefit from blockchain technology (IBM 2017). In response to the wave of product adulteration cases, Walmart has piloted the use of blockchain to track pork in China (Nash 2016). Since 2015, Everledger has recorded the provenance and the chain of custody of over two million diamonds on a blockchain.[2] Maersk and IBM created a joint venture for creating a more efficient and secure platform for global trade (Moise 2018). Veridium Laboratories and IBM are working on a blockchain solution to improve the operations of carbon-credit markets (Hankin 2018). Naturally, these possibilities have generated a widespread interest. According to Google Trends, the popular interest in blockchain spiked at the end of 2017 (Figure 1).

Nevertheless, blockchain (and the other forms distributed ledgers even more so) remains an emerging technology. New partnerships, joint ventures, and projects are constantly announced, but thus far, there are very few examples of successful blockchain applications on a large scale. In fact, Browne (2017)

Figure 1. (Color online) Number of Searchers for "Blockchain" Worldwide, According to Google Trends



presents a sobering statistic: 26,000 new blockchain projects were started in 2016, and only 8% of those were still active in 2017. There are signs of a bubble forming in the financial markets and the broader economy. For example, Long Island Iced Tea announced that it is moving from being in the beverage business to blockchain mining and changed its name to Long Island Blockchain (CB Insights 2018). Over two days following the announcement, the stock price went up 344%. Similarly, the stock price of Delta Technology Holdings (a chemical manufacturer in China) went up 200% on announcement that it will be involved in blockchain. In both cases, the stock price has since reverted to the preannouncement level. These stories are reminiscent of the internet development and dot-com boom. What started as an eclectic collection of esoteric concepts that simmered for decades became a mainstream technology over just a few years. This rapid emergence led to excesses and many dead ends, in part because investors and managers had a hard time conceptualizing the strengths and weaknesses of this new paradigm. The internet bubble busted in 2000. By now, the internet represents an important but somewhat mundane part of our economy. Internet development has generated countless research articles. Distributed ledger technology may follow a similar path.

In this article, we take the perspective of operations management (OM) researchers and attempt to lay out a research agenda for the OM field, from thinking about the effect of blockchain technology on classical OM problems (such as the bullwhip effect, its causes, and mitigation strategies) to novel business models, such as digitizing claims on supply chain assets and creating virtual markets. Aside from revisiting traditional OM problems, we also discuss less mainstream issues that stem from economics of contracts. We believe that OM expertise can be instrumental in understanding which applications of blockchain technology are valuable and why, and in taking the technology through its current "bubbly" stage to the plateau of productivity. Because of the likely hype associated with the technology now, we intentionally neither attempt to enumerate current applications nor review or evaluate claims made by blockchain evangelists.

Instead, we provide a high-level technology description and distill a sea of technology features to only the few essential ones (Section 2). We point out how these essential technology features provide five strengths of blockchain technology over the alternatives, in certain circumstances. For every strength, however, blockchain technology comes with a weakness. These strengths and weaknesses are summarized in Table 1 and are discussed in detail in Section 3. The OM research agenda is laid out in Section 4 and is summarized in Table 2. We find three themes in this research agenda: (1) information, (2) automation, and (3) tokenization. In addition to the OM-focused work, the new technology requires advances in economic theory in general. We believe that OM researchers can make a contribution there as well, but we present it in a separate section, Section 5 (Table 2). We conclude in Section 6. The online appendix, Section A, describes the Bitcoin blockchain. Section B of the online appendix provides additional ideas for the research agenda (see Table 2; in addition, see Babich and Hilary 2019). Section C of the online appendix presents a list of blockchain examples used in this article.

Looking beyond the current hype, we hope to provide a benchmark against which future researchers can measure the advances in blockchain technology. Perhaps five years from now, future researchers can analyze why the development of the technology (as it applies to OM) deviated from the predictions made in this article, explain why some applications succeeded, and marvel at the ideas and inventions that we have failed to imagine.

2. Blockchain Technology in 2018

Blockchain is not a single technology. Rather, it is a family of technologies used to develop and maintain distributed ledgers (i.e., databases that are massively replicated on all the "nodes" or machines in the system). In contrast, traditional databases are centralized, meaning that there is only one master copy of the database at any given moment. There are other forms of distributed ledger technology, such as directed acyclic graphs or hashgraphs, but the blockchain is currently the most developed one. Popular blockchain platforms and protocols (from hundreds of choices) include Ethereum, Hyperledger

Table 1. Blockchain Strengths and Weaknesses, Relative to the Alternatives, in Certain Cases

Blockchain strengths	Blockchain weaknesses
1. Visibility	Lack of privacy
2. Aggregation	Lack of standardization
3. Validation	Garbage in, garbage out
4. Automation	Black-box effect
5. Resiliency	Inefficiency

Table 2. Research Agenda

Section	Topic
4	Research agenda for blockchain technology in OM
4.1	Production, procurement, and inventory: the bullwhip effect
4.2	Data aggregation
4.3	Contract automation
4.4	Supply chain risk management
4.5	Blockchain in ethical, sustainable, and responsible operations
4.6	Collateralizing supply chain assets
4.7	Blockchain queueing and optimization
5	Economics of blockchain in supply chains
5.1	Economics of information, contracts, and governance
5.2	Industrial organization of blockchain
Online appendix	Additional ideas for research agenda of blockchain technology in OM
B.1	Crisis management
B.2	Tokenization and capacity management
B.3	Blockchain in supply chain finance

Fabric, and Ripple. Although the specifics vary with each implementation, one key advantage of distributed ledgers is that the system is robust to the failure of single nodes, even when there is imperfect information about whether a component failed (this feature is known as Byzantine fault tolerance). However, it is typically more inefficient than the traditional database technology, and scalability is a serious issue.

A blockchain is organized as a chain of data blocks, linked to each other. In standard applications, data in the blocks contain a hash (cryptographic "fingerprint") of all previous blocks. This feature makes it harder to tamper with prior records. However, it is worth noting that there are very few properties that are common to all blockchains. For example, even data immutability (i.e., the fact that records cannot be altered retroactively) is a feature that is present in many versions of blockchains, but contrary to common beliefs, is not present in all. It is also important to note that blockchain technology is about storing data, not about acquiring data (e.g., through sensors, such as radio-frequency identification [RFID]). To a large extent, it is also not about data exploitation (e.g., through artificial intelligence [AI]). However, we discuss below new protocols that are intrinsically linked to blockchains and facilitate data processing (e.g., smart contracts, tokens). In the remainder of this section, we review the common elements that are important for OM applications and point out some of the ways these elements have been implemented. In addition, in the online appendix, we discuss the details of the original blockchain application: Bitcoin. This section discusses bare-bones concepts only. The interested reader can find a more complete description of the technology in Hilary (2018). Toward the end of this section, we discuss an important concern about blockchain: technological uncertainty. This shortfall may impede wide-scale technology adoption. Last, we compare blockchain with alternative technologies.

2.1. Core Elements of Blockchain Technology

2.1.1. Data Governance, Permissions, and Consensus Mechanisms. Data governance is important in the context of blockchains. Some networks are permissionless (everyone can join these public networks). For example, cryptocurrencies (such as Bitcoin) typically rely on public networks. In contrast, private blockchain networks vet participants. These networks can be set up to allow a few firms to interact with each other. There are also models that lie between the completely permissionless networks and the completely permissioned private networks. For example, different agents can receive different levels of permissions to read or affect the consensus database.

One important consequence of decentralization is that the versions of the database can temporarily diverge from each other. Therefore, blockchains require a *consensus mechanism* to ensure that these different versions converge. Different blockchain technologies have different methods to achieve this. The nature of the network (e.g., public versus private) influences the choice of consensus mechanism. For public networks, a key issue is to ensure that no single actor is able to dominate them. For example, Bitcoin, a public network, uses proof-of-work (PoW) as a consensus method. PoW offers a robust way of ensuring data immutability (in the current environment), but it is inefficient in its usage of resources such as electricity, bandwidth, and CPU time.

In contrast, in private blockchain networks that vet participants, the risk of a single agent dominating the network is managed through network permissions. Therefore, technologies commonly used in these networks (such as Hyperledger Fabric) use protocols that preserve computational resources. For example, the mechanism can simply rely on votes to approve a new consensus. The challenge in this case is to find a technical solution that balances data verifiability, resource efficiency, and the optimal privacy level. In response to these specific needs, dozens of consensus protocols have already emerged, and new ones appears regularly.

As discussed above, the distributed ledger technology is Byzantine fault tolerant. This is due to the existence of multiple copies of the blockchain database, which are integrated through a consensus mechanism. These feature provides immutability (common in many applications) and higher resiliency. In Section 3, we expand on these strengths.

2.1.2. Smart Contracts. Another important point is that records in the blockchain databases can contain different types of objects, including executable software. This allows the automatic execution of smart contracts. A smart contract is a computer protocol designed to facilitate, verify, or enforce the negotiation or execution of a contract. For example, various trade finance platforms (such as Populous) allow for immediate and automatic payments when certain contractual conditions are met. In spite of their names, these contracts remain relatively simple at the moment and may not be legally binding.

In addition, many smart contracts need external validation that finds and verifies real-world occurrences, because a blockchain cannot easily access information outside of the network. This can be achieved by designated agents, called "oracles." For example, an oracle can obtain electronic data from an external website (e.g., a currency price or a temperature level in a country) and certify that conditions for smart contracts are met. The need for oracles is a problem because the interest in blockchain technology partly lies with removing the need for trusted intermediaries. One of the issues is that oracles are also subject to security challenges. There is little benefit in having an incorruptible ledger if the inputs are systematically corrupted. To directly interact with the real world, blockchain networks need sensors and actuators. The availability of these devices depends in part on the availability of RFID scanners or the development of the internet of things (IoT). Companies such as Oracalize aim to reduce this risk by providing cryptographic evidence of the sensor's readings and antitampering mechanisms rendering the device inoperable in the case of a breach. Platforms like Signatura offer digital signature solutions. A digital signature is a cryptographic tool that ensures that a document has not been tampered with during the transit between sender and signer. Ironically, most oracles are centralized and thus not Byzantine fault tolerant. Recently, ChainLink became perhaps the first decentralized oracle service that communicates with off-chain systems. If ChainLink is successfully developed, it will also make oracles Byzantine fault tolerant.

2.2. Tokens

Tokenization has emerged as a corollary of blockchain development. Tokenization is the process of converting rights to an asset into a digital token on a blockchain. Immutability and mechanisms to prevent double-spending are essential for creating tokens. Tokenization can facilitate the trading of illiquid assets and enable micropayments. For example, IBM and Veridium announced in 2018 their plan to tokenize carbon emission quotas. In turn, tokenization has facilitated the development of the initial coin offering (ICO). Chod and Lyandres (2018, p. 1) define the ICO as a new form of financing "whereby an entrepreneurial venture obtains funds from investors in exchange for crypto tokens that are the sole means of payment for the venture's future products or services." Hilary and Liu (2018) review the applications of distributed ledger technology in a financial context.

2.3. Technological Uncertainty

The first application of blockchain appeared in 2008, and the state of technology has remained fluid 10 years later. For example, one of the most popular technologies, Ethereum, has reached version 3 and experienced two "hard forks" as of February 2018 (Wikipedia 2018). A hard fork is a permanent divergence from the previous version of the blockchain that creates a bifurcation in the blockchain (one path follows the new blockchain, another continues along the old protocol). Naturally, like any emerging technology, the blockchain is facing multiple issues. The overwhelming majority of blockchain projects are currently failing. Multiple technologies are competing with each other; their interoperability has not yet been fully established. This lack of well-established integration can increase the complexity of the technological systems. Obsolescence can be an issue even for the successful projects. For example, current encryption protocols may not be robust to quantum computing. More generally, security issues are not fully understood. The blockchain is often presented as a robust alternative, as the code is typically open source and based on end-to-end encryption. However, even the most mature platforms have experienced significant bugs. In addition, much of the blockchain activity is happening in back-end applications that may not have the same level of security as the blockchain protocol itself (e.g., the Mt. Gox hack).

2.4. Comparisons with Alternative Technologies

As described above, a blockchain is a database with a specific structure. Historically, databases were centralized entities with one owner (naturally, there could be multiple individuals representing this owner) and potentially many users. This basic technology started in the 1960s and now is very mature. For some applications, this approach still makes sense, even if it requires significant upfront costs. For example, a stock exchange may want to centralize all transactions on one trading platform, or a company may want to use a central database for employee records.

However, in many other situations, there is a need for multiple actors with potentially diverging interests to share data. For example, two companies may need to share sales/purchasing records, but need to maintain separate records. The traditional solution has been to establish multiple databases that need to exchange data with each other. Electronic data interchange (EDI) solutions have been developed to facilitate these transactions. For databases that do not interact efficiently (and have no EDI), data exchange can involve significant and costly human intervention. For example, brokers dealing in illiquid securities often trade over the phone. The setup costs for these informal networks is low, but it is very costly to process high volumes of transactions through them or even to add more nodes.

Aside from the initial cost to set up the database and marginal costs to process subsequent transactions, EDI systems are tied to specific processes, computer protocols, and, more generally, document formats. The cost of integrating these different elements can be significant and increases as the number of nodes in the network increases. They are often redundant, as multiple parties need to incur them. Value-added networks are informational clearing houses that are set up to facilitate EDI by centralizing and dispatching the data (through a hub-and-spoke system). They can mitigate some of these transaction costs, but require that they are trusted.

Although distributed ledger technology removes the need for some forms of trusted intermediaries and offers additional features (such as robust validation), a key benefit of distributed ledger technology is that it offers an alternative cost structure for databases. Very few things are not technologically feasible without a distributed ledger technology. However, some of these possibilities are not economically feasible, and for many, distributed ledger technology is more economical. Naturally, this is not the case in other situations. We offer a conceptual discussion of the strengths and weakness associated with technology features, as it applies in OM in Section 3. We discuss several potential applications of these cost structures in Sections 4 and 5 and in the online appendix, Section B. We also discuss their limitations and failure points.

Earlier in Section 2, we discussed the interactions between blockchain and other technologies, such as artificial intelligence and RFID. In the online appendix, Section B.3, we also discuss how blockchain technology can complement or disrupt current practices in trade finance, such as letters of credit and escrow accounts.

3. Strengths and Weaknesses of Blockchain with Respect to OM

In this section, we summarize the strengths and weaknesses of blockchain technology with respect to OM (Table 1). We rely on the discussion in Section 2 for the technology and the discussion in Section 4 for illustrations of these strengths and weaknesses through applications to OM.

The majority of the current applications are in supply chain management. Therefore, we use supply chains for motivation. Supply chains comprise firms, organizations, and individuals, independent and self-interested, but linked through physical, informational, and financial flows. Their activities enable products and services to be created and consumed. Distributed ledgers, containing credible and usually immutable information, facilitate interactions between these firms, organizations, and individuals and help to integrate the three flows in supply chains. More generally, when used for OM applications, blockchain technology exhibits five strengths: (1) visibility, (2) aggregation, (3) validation, (4) automation, and (5) resiliency.

Visibility means the ability of supply chain participants to follow items through the entire supply chain. For example, in the majority of supply chains, the ordering party may be able to monitor some aspects of operations at its tier 1 suppliers, but rarely at tier 2 or beyond. Blockchain technology has the potential to provide visibility into higher tiers. For example, as discussed in Section 4.2, Walmart was able to identify inefficiencies in their supply chain after blockchain deployment.

Aggregation means that information on the blockchain can come from a variety of sources: firms, customers, regulators, and smart sensors. Information also has a temporal dimension, as prior records of transactions are permanently captured in the subsequent transaction records. For example, as discussed in Section 4.2, the Everledger diamond blockchain contain videos, certificates, geolocations, etc.

Validation is the fact that once information is captured in a distributed ledger, it has been authenticated, and thus it is difficult to tamper with. The blockchain accomplishes

Table 3. Cost Comparison of Technologies

	Centralized database	Network without EDI	Network with EDI	Blockchain
Owners	One	Many	Many	None
Setup cost	4	1	3	2
Cost of adding a node	*	3	2	1
Cost of adding a transaction	1	4	2	3

Note. 1, lowest cost; 4, highest cost; *, context dependent.

this through its identity management features and conflict resolution protocols. The blockchain has the potential to provide a decentralized identity management with strong security features. Furthermore, the validation dimension of the blockchain presents an opportunity to create digital claims on assets in the supply chains and engage in the trading of these assets. Arguably, validation strength is particularly salient for applications in OM, because validation is difficult to achieve in bilateral interactions typical in supply chains, whereas other strengths (information aggregation, visibility, automation, and resiliency) can be implemented with alternative technologies (however, as noted in Section 2.4, this may not be cost-effective). Validation strength engenders trust among supply chain members in the quality of the information being shared, and this trust is a key to new business models. For example, as discussed in Section 1, cannabis, fish, and coffee blockchain applications rely on the validation strength of the technology.

Automation is the ability of the blockchain to execute certain transactions automatically in response to prespecified conditions (Section 2.1.2). For example, some blockchain protocols include pieces of code that can make payments at the component level when subcomponents have been fully integrated and delivered to the final customer. In another example, orders for replacement parts can be automatically placed throughout the entire supply chain when a machine is brought in for repairs.

Resiliency is the fact that the entire blockchain database is fault tolerant because it is replicated on every node. Fault tolerance (Section 2) is the property that enables a system to continue operating properly in the event of the failure of (or one or more faults within) some of its components. If a node is disabled, the entire system can continue to function. This allows for a better recovery after a natural disaster or a cyber incident, such as a distributed denial of service attack. However, if the fact that the database is massively replicated offers protection in the case of physical shock, the potential effects of computer malware are poorly understood at this point.

Naturally, like any innovation, blockchain technology suffers from weaknesses. We discuss five of them: (1) the lack of privacy (2) the lack of standardization, (3) the "garbage in, garbage out" (GIGO) problem, (4) the black-box effect, and (5) inefficiency. As Table 1 illustrates, these are flip sides of the five strengths of the technology. Some of these are general weaknesses of blockchain; others are salient for OM applications particularly.

Privacy. Blockchain networks (public networks in particular) are often designed to make erasing data difficult (although not impossible). This may make compliance with privacy regulations difficult. Ironically, a blockchain may create a situation in which both deleting data and conserving data are difficult (the latter because of technological obsolescence).

Lack of standardization. Blockchain is not a unique technology, but an umbrella describing a portfolio of protocols (Section 2). These protocols are not yet stable and, as they age, they become obsolete, and legacy issues are created. This will be a particularly acute problem for a technology developed to keep permanent records. This lack of standardization also fosters technological uncertainty.

GIGO problem. The key issue for applications of blockchain technology to OM is establishing a link between the physical state and information recorded in the distributed ledger. There are two ways in which discrepancies between the two can occur. First, incorrect information about the physical state can be introduced into the distributed ledger at the point of information origination (the "state-zero" problem). This can be done by mistake or by a rogue agent. The state-zero problem is less of an issue when the asset is natively digital (e.g., pollution rights, intellectual property). Second, the physical state can change without the information in the distributed ledger being updated. The fact that some transactions need to be certified by both the buyer and the seller reduces state-zero problem somewhat. Third-party verification is a possible solution to the state-zero problem as well. But this can be expensive, especially if there are many participants of the blockchain network whose states need to be certified. Another possible solution is a network of sensors that keep track of the physical state and update the distributed ledger. This can be done credibly, but investments in sensors can be expensive.

Black-box effect. Blockchains can remove the need to trust a counterparty in some circumstances, but it requires "metatrust" in the blockchain concept (i.e., trust in a protocol, a distributed system, not a specific company, individual, or government entity). For example, consumers need to trust the integrity of the process without understanding the technical underpinnings. Furthermore, even if one trusts the concept of distributed ledgers, one needs to trust the specific implementation as well. This requires trust in third parties, who may not be a part of the supply chain.

Inefficiency. Blockchains are often inefficient by design. For example, in the original case of Bitcoin, the PoW method requires a large amount of electricity to perform calculations and significant bandwidth to propagate the results. Although problems associated with the PoW methodology do not necessarily extend to private networks with alternative consensus rules, it is not obvious in many cases that a blockchain network is superior to a centralized database and a mobile app.

4. Research Agenda for Blockchain Technology in OM

Next, we discuss research ideas for applications of blockchain technology to OM. They illustrate the five strengths and five weaknesses presented above and are organized around three themes:

1. Information. *Advantages:* The blockchain provides a platform for connecting multiple decision makers with multiple sources of information and generates a richer informational landscape for OM applications. There are other ways of collecting and sharing information (proprietary networked systems, smart sensors, internet, mobile apps), and blockchain technology will not supersede these, but rather complement them. The main differences between blockchain and some of the existing technologies are the lower costs of adding new participants, data encryption, and record validation. The latter engenders trust in information shared, as we highlighted previously.

Disadvantages: Decision paralysis induced by information overload is likely to become more common. Information is more likely to be used for unintended purposes. False records will be more difficult to delete. Managing privacy and access rights may become difficult.

2. Automation. *Advantages:* The blockchain allows faster transactions by reducing the time required to obtain confirmations from multiple participants, by providing reliable and verified information, and by allowing automation of some of the transaction logic through smart contracts. Smart contracts (Section 2.1.2) can automate OM transactions, increase their velocity, and facilitate complete contracts. For example, smart contracts can open areas of business-to-things (B2T), things-to-customer, and things-to-things (T2T) interactions, and new sources of large up-to-date and high-quality data sets.

Disadvantages: If rules coded in smart contracts are put in place ahead of a system's deployment and are not dynamically updated, the system may become too rigid for the needs of dynamic environments. But if a smart contract logic is modified dynamically (e.g., by AI), there is a risk of AI making wrong or unethical decisions. Yet this outcome can lead to immutable changes to the logistics, information, and financial networks that support human consumption, production, and existence. It also increases the problems stemming from the "black-box" nature of technology. Automation progress can be impeded if humans need to validate conditions (Section 2.1.2).

3. Tokenization (digital assets). *Advantages:* Blockchains can create verifiable digital claims ("tokens") corresponding to production, inventory, and financial assets and facilitate the sharing, trading, and exchanging of these assets among multiple participants (Section 2.2). This makes the coordination of extended supply and distribution chains easier (virtual vertical integration) and the coordination of actions of firms at the same level possible (virtual horizontal coordination). The precise attribution of rights to various features of assets makes the management, exchange, and trading of these assets easier. Contracting, business-to-business (B2B), and business-to-customer (B2C) interactions can be more formal, thereby reducing legal and transaction costs. Essentially, creating precisely defined claims paves the wave to markets (either along the supply chain or across the supply chain tiers).

Disadvantages: The danger of overspecifying contracting relationships is that the roles of trust and implicit contracts are diminished. Both trust and implicit contracts are essential in the uncertain environments where the role of "unknown unknowns" is significant.

Next, armed with the framework of five strength, five weaknesses, and three themes, we looking into example of research ideas. Some of these ideas are based on classical OM problems, like the bullwhip effect; others have not been studied yet. Some ideas stem from current blockchain applications. For others, we imagine novel business models. For each of the ideas, we explicitly discuss how blockchain technology can help and why it may fail, and point out promising research directions for OM researchers. Some of the causes for success and failure can be more general than just the blockchain technology, but they are salient in the context of the distributed ledger technologies.

4.1. Production, Procurement, and Inventory: The Bullwhip Effect

We begin with the bullwhip effect because most OM researchers are familiar with it.[3] The bullwhip effect, in which the variance of orders to the suppliers is greater than the variance of sales of the buyer and distortion propagates upstream (see Lee et al. 1997), is one of the classical topics in OM. The consequences of the bullwhip effect include excess inventory across supply chains, poor customer service, and inefficient capacity utilization. Lee et al. (1997) point out four possible causes of the bullwhip effect: demand signal processing, rationing games, order batching, and price variations. The authors recommend sharing sell-through data and inventory information across supply chains to improve coordination and mitigate the bullwhip effect.

How can these suggestions be implemented in a supply chain? Although retailers can share their sales data with suppliers, the credibility of these signals can be low because retailers have an incentive to inflate forecasts, in an attempt to induce suppliers to add capacity and stock higher inventory. Similarly, information about the inventory or capacity of the suppliers can be unreliable. The supplier benefits by creating an impression that resources are limited because this makes the retailers order more, in an attempt to secure greater share of the supply.

How Can Blockchain Help? Whether it is information about demand or supply, there is a problem with the visibility and validation of information, and a blockchain application is useful because of its visibility and validation features (Section 3). Trustworthy information about sales can reduce the bullwhip effect (Chen et al. 2000). Importantly, blockchain technology makes it easier to collect information across multiple firms (in particular, multiple tiers of supply chains). This information aggregation (see Section 3) can be done selectively, where only the information that is needed for improving system efficiency is shared, and other information (including identities of firms or customers) is not.

Furthermore, blockchain technology can create a virtual market for supplier capacity in which retailers can exchange claims to it. Properly designed, this can produce efficient outcomes in which resources are allocated to retailers that have the greatest value for them. These exchanges can occur in external markets (like those for the ICOs and the subsequent secondary trading) or in internal markets (in our example), but the fact that the markets are external or internal does not change the nature of the process. Blockchain technology can help to organize trading in assets that are not part of standardized exchanges, bypassing traditional intermediaries. This is an application of tokenization (Section 3).

Challenges and Why Blockchain May Fail. Overordering could be desirable for the supplier, even though it is wasteful from the system's perspective. Therefore, unless the supplier is properly compensated, the supplier might choose not to participate in a blockchain system, depriving the rest of the supply chain of information about this supplier's state. Furthermore, the production capacity depends on the supplier–buyer pair, and it is not perfectly substitutable among buyers, requiring adjustments to be made by the supplier. The supplier may also have other considerations, such as expanding strategic relationships with certain retailers. Therefore, the supplier may wish to hinder the free trading of claims to its production capacity. We further discuss economic issues related to incentives in Section 5.

What Is the Research Potential? OM researchers can apply insights from the literature to quantify the value of the blockchain technology in managing the adverse consequences of the bullwhip effect. In particular, OM can inform the firms about the trade-offs between efficiency gains and competitive-advantage losses from sharing information. OM researchers can identify what information needs to be collected and stored on the distributed ledger. For example, extending work on transshipments (e.g., Anupindi et al. 2001) to supplier capacity sharing and understanding the supplier's costs, benefits, and incentives is also interesting.

4.2. Data Aggregation

Information flows in supply chains have been a major research topic in OM (Ha and Tang 2017). Information visibility, aggregation, and validation (see Section 3) are the main ideas for the following discussion. There are three directions for information flows: downstream (from suppliers and manufacturers to consumers), upstream (from consumers to manufacturers and suppliers), and multidirectional (up and down a supply chain, as well as to and from entities that are not directly involved in a supply chain for a particular product).

In Section 4.1, we have discussed information about sales flowing upstream to suppliers and information about the supplier inventory flowing downstream to retailers. We add to these examples here. Blockchain technology can help to provide more detailed data to consumers than is currently available. At present, consumer-choice models use few factors that describe products (one dimension, i.e., "quality," is ideal for analytical results), but in reality, each product comes with a multidimensional and complex history. Consider the simple act of buying mangos. Currently, consumers buy mangos in supermarkets using simple information, such as their appearance, aroma, organic label, and price. Imagine if consumers could learn where each container of mangos originated from, what fertilizers and pesticides were used, what weather conditions occurred during the growing season, what labor practices occurred, how long the container spent on the ship or in the port, etc. Blockchain technology promises to provide this information and companies, such as Walmart, would like to take advantage of it. Walmart ran a pilot project of tracking mangos from Mexico to Walmart shelves. The pilot involved 16 farms, two packing houses, three brokers, two import warehouses, and one processing facility. Over a 30-day period, Walmart captured 23 different lot codes and tens of thousands of sliced mangoes, according to a story by the New Food Economy (McKenzie 2018). If blockchain technology delivers, the consumer choice will become drastically more complex.

Blockchain technology is great at aggregating information from multiple sources and information of different natures. Recall the example of the diamond ledger from Section 1. For a diamond,[4] a ledger contains a record of a country of origin; a picture of the diamond after it was mined; a picture of a Kimberley Process Certification Scheme certificate;[5] professional information on individuals involved in diamond planning, cutting, and polishing; videos of the diamond as it goes through the various steps of the production process; a picture of the finished product; and finally a link to a Gemological Institute of America report.[6] Information aggregation is particularly relevant in the context of big data. The aggregated information can be used synergistically, improving system performance and reallocating benefits among participants. This may prove particularly useful in the absence of formal markets. For example, consider a situation in which electricity generators possess private information about equipment maintenance schedules, consumers possess private information about their energy needs, and regulators have information about the geographic distribution of pollution levels and effects. Consumers might be willing to adjust their demand, but regulators and generators may not know about that flexibility. Electricity producers might be willing to shift generation to a different fuel or a different plant, depending on the current pollution conditions, and depending on the consumers' willingness to adjust their demand. Regulators might consider relaxing their requirements if the consumer needs are critical. But, it can be difficult to combine all three (or more) streams of information. There are markets that bring together consumers and generators, and there are markets where pollution credits are traded (although not for all forms of pollutants). However, there is no market where all three parties are present together. Conceivably, blockchain technology can fill this gap.

How Can Blockchain Help? Blockchain technology provides a platform for combining information from multiple sources (firms in a supply chain, regulators, and consumers) and over time without the single centralized authority to control the process. This information is validated (Sections 2.1.1 and 3). Smart contracts (Section 2.1.2) can automate actions based on the aggregate information, reduce lead times, and create markets where nonstandardized resources are traded (Section 3). In a B2C context, this makes the history of the product available for consumers' purchase decisions. In a B2B context, a blockchain creates a verified ledger of past transactions, which can be used by the buyers in the supplier selection process or by the suppliers to signal their quality to the buyers. In B2T and T2T transactions, a blockchain can integrate data from multiple smart sensors, share it with decision makers, and even automatically execute contracts. For example, the mango pilot discussed above revealed that it took three days for the mangoes to get from the customs broker to a processor, and that if Walmart could cut down on that time, this would extend the shelf life of that product by a day or more, so that the consumer would get fresher food and, consequently, there would be less food waste (McKenzie 2018).

Challenges and Why Blockchain May Fail More data are not always better, because data may hide essential information. Consumers can be overwhelmed with additional data and make either bad choices or no choice at all. Furthermore, not all consumers want to know "how the sausage is made" (literally, in some of the provenance applications, such as the provenance of pork products; e.g., Nash 2016). More detailed information can lead to the fragmentation of the supplier market, reducing supplier competition. The GIGO weakness discussed in Section 3 is a serious concern. Decision makers need to trust that all data recorded by multiple firms on a distributed ledger correspond to physical reality. The benefit of data aggregation depends on the willingness of various parties to either participate in data sharing or to provide data truthfully.

What Is the Research Potential? There are many interesting research questions. For instance, how would consumers process multidimensional information? What information should be collected, recorded, and shared? How can product assortment be optimized when each product is "unique," once the history is taken into account? How should we write contracts that are based on both aggregate market information and individual buyer and seller information? How should we design systems to provide incentives for participants of supply chains to share information and to do so truthfully? Does having more information exacerbate the GIGO problem, because there are greater chances that incorrect information is present, or does it reduce the GIGO problem, because of informational redundancy (information from some participants can be used to validate information provided by other participants)? Blockchain can formalize implicit relationships. In economics and OM there are numerous studies of incomplete and relational contracts (Hart and Moore 1988, Baker et al. 2002, Taylor and Plambeck 2007). Findings in the prior literature (e.g., Hilary and Huang 2015) suggest that when interactions become more contractual and formal, the cooperation, goodwill, and effort of the participants can decrease. As blockchain technology practice develops, researchers will need to develop the theory that captures the implicit versus explicit contracting effects on effort in supply chains and on managing contracts that are more complex and dynamic. Last, how should we aggregate individual needs and resources and repackage them to what market participants prefer to use (effectively collateralizing them)? What effect does this have on the social welfare (the ability to shift consumption from lower utility to higher-utility customers)?

4.3. Contract Automation

There are at least two potential benefits of automation through blockchain. The first is the increased coordination through the supply chain. Imagine that a company operates a machine (e.g., a robot on an assembly line) and that a sensor detects that a part in this machine is about to fail. Ordering a replacement part ahead of the failure event will minimize the downtime. Currently, some printer models automatically place an order for a replacement ink cartridge; some "smart" refrigerators can order milk and other groceries. But the current technology is limited to communications between the smart appliance and the supplier of the part. It would be far more beneficial if, in addition to alerting the immediate supplier of the part, the entire supply chain received a signal to start the replenishment process. Furthermore, if the downtime of the machine is unavoidable, customers who receive products manufactured on this machine should be informed about the potential disruption to their supply. How should we make these communications credible? How should we reach beyond the immediate suppliers and customers? How can we do so automatically? Whereas machine maintenance and part replacement are classical problems in OM (a surveys of this area is Barlow and Proschan 1996), the integration between machine maintenance and supply chain management is a less researched topic, especially in the context of automation.

The second benefit of automation is the possibility for different parties to credibly commit to future actions by making procurement contracts ex post enforceable. Currently, buyers may have a credibility problem when conveying their intentions to place large orders. Unless buyers sign binding contracts (sometimes even if buyers signed binding contracts), they can renege on the promises as new information becomes available. This clearly hurts the suppliers and makes the initial communication from the buyers not fully credible. Smart contracts (Section 2.1.2) can make commitment irreversible—when conditions are met, the orders will be automatically executed.

How Can Blockchain Help? Blockchain technology with smart contracts (Section 2.1.2) allows the automatic activation of the entire supply chain. Systemwide production, shipping, and inventory decisions can be automated and synchronized. Information about orders and payments is verifiable (Section 3). Automated contracts provide buyers with the commitment power.

Why May Blockchain Fail? The complexity of automatic system optimization is tremendous. Because of this complexity and because algorithms are placing orders, there is a risk that these algorithms will make wrong decisions and humans will not realize this until it is too late and damage has occurred. The black-box weakness of the blockchain technology (Section 3) is a significant concern in the context of automation.

What Is the Research Potential? What should the optimal policies look like in the presence of smart contracts, where orders are placed with the entire upstream supply chains? What benefits do they have compared with the current, less information-intensive policies? How should we take advantage of the ability to commit to future minutely specified actions in procurement contracting?

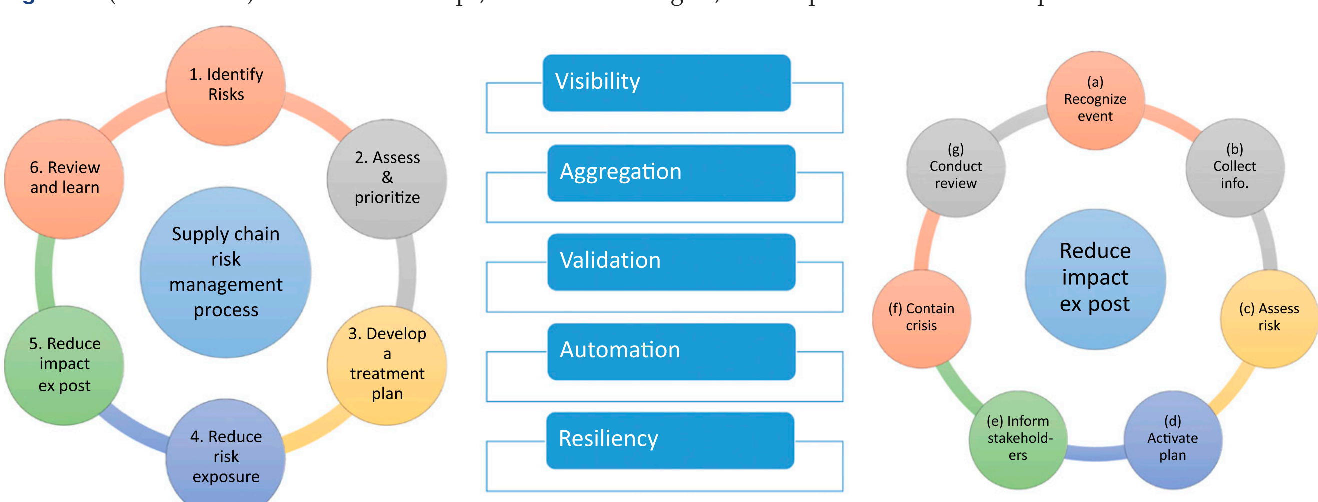
4.4. Supply Chain Risk Management

Supply chain risk management (SCRM) is important in practice. SCRM has been extensively researched in the academic literature (see Aydin et al. 2012, Tomlin and Wang 2012). Academics and industry practitioners have developed a good understanding of the SCRM process and what the best practices are. In this subsection, we shall discuss blockchain applications using the SCRM process and best practices as the lens.

The steps of the SCRM process[7] are to (1) identify risks, (2) prioritize them, (3) develop a treatment plan, (4) reduce risk exposure ex ante, (5) reduce risk impact ex post, and (6) review the performance and learn. To expand this further, Step 5, involves (a) recognizing that a risk event has occurred, (b) collecting information, (c) assessing risk, (d) activating the plan, (e) informing stakeholders, (f) taking steps to contain the crisis, and (g) conducting a postincident review. Figure 2 illustrates the process.

4.4.1. Steps 1–4 of the SCRM Process. The conventional wisdom in SCRM practice and theory is that risks

Figure 2. (Color online) SCRM Process Steps, Blockchain Strengths, and Steps to Reduce Risk Impact Ex Post



often arise where no one is paying attention (Waters 2011). This often means higher-tier suppliers, as numerous cases of product adulteration by subcontractors illustrate. In 2007, Menu Foods issued a recall of its pet foods because of adulteration with melamine. The culprit of adulteration was a Chinese subcontractor of a supplier of Menu Foods, ChemNutra Inc. (see the discussion in Yang et al. 2009). It is important to note that Menu Foods was unaware that ChemNutra had outsourced to a subcontractor. Another example (Hoyt et al. 2008) is that of the Mattel toy recall in 2007 because of several defects, including the use of lead paint. Lee Der (a supplier of Mattel) ordered paint from Dongxing, which was not on a list of approved paint suppliers at Mattel. Dongxing purchased a batch of paint from the internet. The paint came with a certificate that it was lead-free, but this certificate was falsified. Similar to Menu Foods, Mattel did not have visibility into the higher supply chain tiers. There are similar examples for heparin, Aston Martin cars, and NATO airplanes and helicopters—higher tier subcontractors, whose identity is not known to original equipment manufacturers (OEMs), introduce adulterated or counterfeit materials into supply chains (Haft 2015).

How Can Blockchain Help? Connecting the entire supply chain, from raw materials producers to retailers, to a blockchain platform can help companies to increase visibility into the structure of their extended supply chains, identify factory locations, discover potential bottlenecks, and unveil excessive geographic concentrations of production resources (Section 3). In fact, many current applications of blockchain technology are intended to establish product provenance. These include (as we discussed earlier) tracking the movements of products through supply chains for fish,[8] pork (Nash 2016), mangos (McKenzie 2018), diamonds,[9] and coffee (Naydenova 2017). This is instrumental in identifying risks, estimating the probabilities of adverse events, and forecasting their consequences (Steps 1 and 2 of the SCRM process). For example, to assess the impact of a disruption, it is helpful to aggregate information across the supply chain on backup capacities and raw material inventories. Thus forewarned, companies can prepare mitigation plans and take steps to forestall supply disruptions and reduce their impact (Step 3 of the SCRM process).

Tang and Babich (2014) argue that the lack of visibility is one of the key factors that contributed to the surge in adulteration cases of products made in China in the late 2000s. Thus, if blockchain technology can increase visibility into supply chains, it will reduce some types of supply risk (Step 4 of the SCRM process). For example, if Menu Foods could trace where products were coming from, it could detect the use of an unauthorized subcontractor. For instance, the identities of authorized contractors can be stored on a ledger, and if a company not on this list shows up in the chain of custody for a product batch, smart contracts can alert the OEM of the deviation.

Challenges and Why Blockchain May Fail. Suppliers may resist the effort by OEMs to map out the extended supply chains and discourage their own suppliers from joining the blockchain system. For example, Toyota's car production was affected for months following the 2011 Japanese earthquake. According to Greimel (2012), even after the disaster, only half of 500 of Toyota's tier 1 suppliers shared their supply chain information with Toyota, and the other half refused. Greimel quotes Shinichi Sasaki, Toyota's global procurement chief, as saying "Half of that is black-boxed to us."

Another potential negative for blockchains is that by increasing the visibility and eliminating some types of supply risks, blockchains may encourage unethical suppliers to engage in other forms of risk taking. For example, the reason unethical suppliers in China used melamine for the adulteration of food products[10] is that melamine increases the nitrogen count, which helps to fool the tests that look for evidence of the dilution of products with water, and there were no tests directly looking for the presence of melamine. One can argue that product inspections reduced the risk of mild product adulteration with water, but increased the risk of serious product adulteration with melamine. It is conceivable that blockchains may have similar adverse effects.

Another observation regarding possible blockchain failures is that merely knowing the chain of custody might be not be sufficient to eliminate adulteration. The Kobe Steel case illustrates that. Business media reported in 2017 that Kobe's employees falsified specifications for the company's aluminum and steel products. More than 500 of Kobe's customers were affected, including Boeing, Toyota, Honda, Nissan, and Ford. The use of blockchain technology would not have prevented this type of falsification. It is conceivable that adding smart sensors and smart contracts to keep track of the composition of inputs and outputs from a factory might make cheating (e.g., for Kobe employees) more difficult, but this is not obvious, and it requires additional investments.

What Is the Research Potential? In the academic literature, Yang et al. (2009, 2012) and Yang and Babich (2014) are examples of papers that explore the role of information about supply disruptions in managing supply chain risk. But the majority of researchers working on models with asymmetric information in the context of SCRM consider single-tier systems. There is literature on multiechelon systems with random yields (see Sobel and Babich 2012 and references therein), but this stream does not discuss the role of information. Advances in blockchain technology may change this. We hypothesize that when higher-tier suppliers' identities are known to a larger retailer (like Walmart), these suppliers will be less likely to cut corners on quality and risk their aspirations for future business with this retailer. Related to this, tier 1 suppliers will be less likely to subcontract to unauthorized firms. Although the frequency of supply risk events would decline, we suspect that the potential impact of the events that do occur would be larger. Information about the overlap of the extended supply chains affects strategic interactions among firms (Wadecki et al. 2012). However, there is still relatively little academic research on this subject, in part because firms have not had full visibility into their extended supply chains. Blockchain technology increases such strategic interactions and demands further investigation.

4.4.2. Steps 5 and 6 of the SCRM Process. Let us consider how blockchain might be helpful in mitigating the impact of the disruption ex post of the risk event (Step 5). One of the wisdoms in SCRM and crisis management is that it is essential to quickly recognize that an adverse event has happened, deploy the response team, and inform the stakeholders.

How Can Blockchain Help? Monitoring the chain of custody for a product may trigger warnings when nonauthorized sources are used. After a warning, potentially defective products can be inspected and diverted away from downstream production stages and customers. This capability would have been valuable in the Menu Foods' case. Knowing the chain of custody can also help companies to triangulate the source of the problem (to a particular supplier, factory, or workstation, depending on the resolution power of the blockchain identity information). Blockchain can also help to identify all customers affected by defects and those who are unaffected. The notifications can be done automatically, using a smart contract feature (Section 2.1.2).

Smart contracts and validation features of blockchains can activate crisis-response teams across the entire supply chain. Production schedules can be changed, payments exchanged, and additional workers deployed, all in response to automatic and credible signals. To a large extent, supply risks mitigation plans can be put on smart contracts, freeing response teams to deal with nonstandard, unanticipated aspects of the disasters. In the Kobe Steel and Mitsubishi cases (McLain 2017), the companies did not notify customers for months, while knowing that something was wrong with the products. They could not determine the extent of the problem and did not wish to cause confusion. Meanwhile, defective materials were used in trains, cars, ships, and the space shuttle.

One might wonder why they did not err on the side of caution and notify all customers. Unfortunately, this would also have resulted in extensive economic damages to the customers, who would have had to idle their production lines unnecessarily while the investigation was ongoing. Consider a food safety application. While a food manufacturer investigates which batches of lettuce or mangos or meat are contaminated, perishable products spoil and must be thrown away even if they were not affected to begin with. To address the last SCRM process step (Step 6), blockchains can aggregate information across the supply chain. This information is necessary to review mitigation plans' effectiveness during the postdisruption debriefings and reviews.

Why May Blockchain Fail? The reasons are similar to the ones discussed in Section 4.4.1.

What Is the Research Potential? An interesting research question involves how to balance under- and overreaction to supply chain risk events, especially for those that are related to safety, how and when to inform customers optimally, and how much benefit reducing investigation time would bring to firms, customers, and society.

4.5. Blockchain in Ethical, Sustainable, and Responsible (ESR) Operations

ESR operations deal with important issues, such as labor conditions, child or involuntary labor, the funding of wars, the avoidance of famines, and the responsible usage of natural resources (land, water, and energy), as they relate to operations decisions. Prominent examples in this area include, on the negative side, the Nike child labor scandal, the Rana Plaza factory collapse in Bangladesh, and blood diamonds in Africa. Examples on the positive side are Toyota's efforts to reduce water usage, microfinance programs, and fair-trade programs.

How Can Blockchain Help? The promise of blockchain technology is that knowing the provenance of goods can help to ascertain that production was performed in factories, which have been certified as capable of ethical or environmentally responsible operations. Although this requires the involvement of regulatory bodies (nongovernmental organizations, governments, industry self-regulators) to conduct the inspection and provide certifications, once certifications are in the blockchain system, they are immutable and publicly visible, if ledgers are public, as in the case of the diamond ledger.[11] Certificates can be issued for a particular action (e.g., planting a certain number of trees, reducing emissions). If set up properly, the blockchain will ensure that these certificates cannot be copied, double counted, or illegally sold. This simplifies accounting processes and allows creating of markets where these immutable ESR claims are traded. For example, Veridium Laboratories is working on implementing carbon offsets trading using blockchain tokens (Hankin 2018; Section 2.2).

Blockchain technology can help not only with tracing how products are manufactured, but also how they are disposed of at the end of their useful lives, by tracking the product flow through reverse logistics systems. The advantage of blockchain is in providing the shared, low-cost platform for multiple, unrelated companies, for example, manufacturers, recyclers, landfill operators, logistics providers, and regulators. Blockchain can aggregate information about a product's journey from collection to recycling and to landfills and validate this information.

Why May Blockchain Fail? As with many applications of blockchain technology to the physical world, the weak point is where information is created and entered into the ledger, that is, the state-zero and GIGO problems. Although the certificate indicating that trees were planted is incorruptible, can we trust the person who vouched for this fact? Do we know that trees have not been cut since the record was entered onto the ledger? If suppliers are certified to follow ethical practices, this certificate is verifiable, but can we observe what practices are actually being followed?

What Is the Research Potential? The tension between verified capabilities and verified actions has been explored in the OM literature with regard to product adulteration (Babich and Tang 2012), but in general, an important research question involves providing a taxonomy of applications in which trust in the capabilities is sufficient to also have trust in the execution.

4.6. Collateralizing Supply Chain Assets

OM researchers have studied the problem of achieving (frictionless) centralized outcomes in decentralized systems. Solutions include various coordinating contracts (Cachon 2003), internal markets (Kouvelis and Lariviere 2000), and mechanism design (Sharma et al. 2008). The challenge with contracts is that they are typically bilateral, whereas supply chain resources and demands are distributed across multiple firms, consumers, and regulators. The challenge with markets is that they work best with standardized, commoditized, substitutable items, whereas a majority of corporate and supply chain resources are customized.

To overcome the bilateral relations constraint, it would be helpful to issue claims (backed by resources) with the property that anyone holding the claim, even if they are not in the contractual relationship with the issuer, will receive what the claim promises.

To overcome the standardization constraint, it is necessary to aggregate information from multiple demand and supply sources for various resources and automatically match the demand with the supply in an efficient way, accounting for the substitutability losses.

How Can Blockchain Help? The validation dimension of the blockchain will help to create digital claims that can be circulated outside of the normal contracting relationships. The aggregation and automation dimensions of the blockchain help to create a market for trading customized assets (Sections 2.2 and 3).

For example, blockchain technology allows the trading of claims on assets in different divisions in corporations. This creates a substitute for internal corporate markets. Suppose various divisions of a corporation need raw materials, such as aluminum, or parts, such as fasteners. The procurement division can purchase those from the outside and then issue digital claims on them that can be traded among various product lines in a corporation, capturing relative needs for the product of each one. Moreover, a corporation can create digital tokens to be used not just internally, but also externally with the suppliers. If some division needs to purchase components from the outside supplier, the division can give the supplier blockchain tokens, as headquarters has validated the existence of assets behind the tokens. Effectively, each company will be able to create its own internal currency and collateralize it with assets, so that the outside world can accept them in lieu of cash payments. Suppliers can use the same tokens to pay their suppliers, etc. Liquidity (i.e., availability of cash) constraints in supply chains will thus be reduced.

How May Blockchain Fail? External verification of the value of corporate assets is needed before they can be used as collateral (this is less of an issue for internal markets). In addition, as the recent financial crisis demonstrated, collateralized assets and risks make it more difficult for the market participants to assess risk exposure. This is true when collateralization is used for relatively standardized securities, like mortgages, and where collateralization is performed by humans. If an algorithm performs the collateralization and if risks that are aggregated are not standard, the possibility of being exposed to the "model risk" is very high.

What Is the Research Potential? How should tokenization be implemented? What assets can be traded this way? How can informational discrepancies be overcome when creating such markets?

4.7. Blockchain Queueing and Optimization

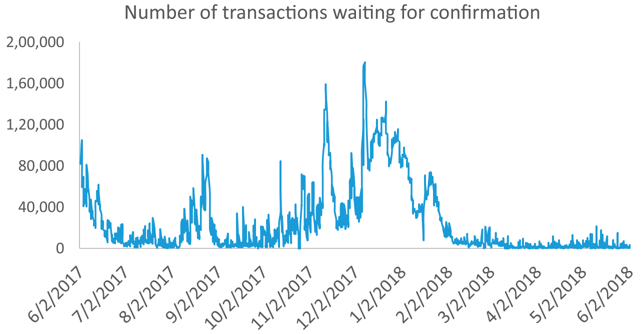
As we discussed in the technology section (Section 2), optimizing blockchain platforms will be difficult and important. For example, the trade-offs and interplay among multiple factors, such as processing speed, memory scalability, information processing costs, data pool liquidity, and privacy level, need to be understood and taken into account to achieve efficient operations of distributed ledgers.

Consider, for instance, the Bitcoin blockchain (for details on Bitcoin technology, see Nakamoto 2008). The time it takes to complete a transfer from one Bitcoin wallet to another one can be analyzed using queueing theory. On average, it takes 10 minutes to "mine" a block, that is, solve a cryptographic puzzle that allows a miner to record transactions. The actual mining time is random. The apparent inefficiency in the mining process actually plays an important role in providing the immutability of records of past transactions (Section 2). The size of each block is hard coded to be 1 MB (currently). There is a trade-off in choosing the block size. Larger blocks allow more transactions to be recorded. However, larger blocks may increase system latency, when being distributed among nodes of the blockchain network. What goes into blocks is important as well. Pointers to outside data are highly space efficient, but expose the system to the possibility that data to which those pointers point will be modified without the network's knowledge.

The transactions are waiting in a queue to be recorded. Depending on the demand for recording transactions, the size of this queue can be quite long (Figure 3). Miners might put transactions at the head of the queue for additional fees. Therefore, the queueing protocol and miner incentives are important for the analysis. The Bitcoin blockchain and Etherium blockchain are used for recording all kinds of transactions by many companies. For example, the number of pending transaction on the Etherium network increased sixfold in the weeks following the launch of CryptoKitties because the total demand for CryptoKitties transactions spiked at about 10%–15% of the total network traffic (BBC News 2017).

Blockchain structures are becoming more complex and nonlinear. Multilayer structures, such as the side chains we discuss in the Section 2 (e.g., Lighting), are likely to become common. To some extent, this optimization is a computer science problem (for recent examples, see Dorri et al. 2017, García-Bañuelos et al. 2017). However, OM researchers also have a role to play in modeling, analyzing, and optimizing blockchain network performance.

Figure 3. (Color online) Unconfirmed Transactions Queue Dynamics



Source. https://www.blockchain.com/charts/mempool-count

What is the Research Potential? Understanding the dynamics of demand, the supply (capacity constraints on block size and the stochastic nature of mining), and their interplay with queue waiting time are essential for the analysis of applications. OM researchers have the right tools to apply to this task.

5. Economics of Blockchain in Supply Chains

With the development of blockchain technology, the economics of the firm will be affected. For example, Coasian transaction costs (Coase 1937) may be reduced. Blockchain technology may also affect the Grossman–Hart–Moore model (Grossman and Hart 1986, Hart and Moore 1988) by enabling or forcing a greater degree of contract completeness. This may have implications for labor economics and management. If independent contractors become more prevalent, for example, telework may become more common. Compensation contracts may have to be altered. These developments may also have implications for OM researchers. For example, an increase in the number of contractors working on remote networks may affect the supply chain's robustness. On the finance side, ICOs have the potential to change the way firms are funded (for two recent examples of how this can affect R&D financing, see Catalini and Gans 2018, Chod and Lyandres 2018). We elaborate more on these themes in the next two subsections by discussing two specific topics in greater detail.

5.1. Economics of Information, Contracts, and Governance

Blockchain technology has the potential to change the economic or even legal structure of supply chains. Traditionally, supply chains were organized along two mutually exclusive models. The first model is integrated within an entity (e.g., a company), and it relies on a central planner (e.g., the headquarters) to optimize supply chain structure through fiat. The second one is a decentralized model in which different entities form a chain of contracts and flows. Blockchain networks offer an intermediate step that facilitates supply chain optimization without a full integration. This is achieved by creating an institution (i.e., a network) that exists in its own right.

This raises two questions. The first is what level of integration leads to a solution closer to the first-best one. For example, scholars can investigate whether blockchain technology provides advantages over the existing systems, such as a centralized database housed within a company or a regulatory body, and what these advantages are. The argument in favor of blockchain technology is that in most real-life supply chain applications, several parties are involved in the manufacturing and selling of products. The more parties involved, the greater the costs of sharing information among them credibly. The cost depends (in part) on the incentives to misrepresent information. The field of information economics describes the importance of information costs. However, the issue that requires exploration is the connection between the size of the supply network and these costs. This approach requires researchers to go beyond the standard principal–agent framework.

The second question is how to govern institutions associated with blockchain technology networks. At the macro level, structures have to be developed to ensure that the technology is working seamlessly across applications. The internet went through a similar process and the Internet Corporation for Assigned Names and Numbers was created as a consequence. Aside from understanding the factors that allow a technology to flourish, this issue is relevant for OM scholars because a breakdown of the ecosystem around blockchain technology can create risks for supply chains. At the micro level, once blockchain networks become institutions, they need a form of governance for their efficient implementation (Levinson and Marzouki 2015). For example, they need structures to make decisions, rules to implement them, and procedures to verify their enforcements. The economic analysis of institutions become relevant for supply chain scholars. For example, the following questions become important: How do we allocate voting rights in consensus-forming decisions? Should they be aligned with cash flow rights? If not, how do we address this separation between the two? Should a network have legal rights and obligations as such, or should only the members be granted these right and responsibilities? These governance issues have been explored by scholars in accounting, economics, law, and other social sciences. However, the development of blockchain technology opens an entirely new venue for OM researchers.

5.2. Industrial Organization of Blockchain

One way to approach this area is to distinguish among *horizontalities*, *verticalities*, and *diagonalities*. We define a *horizontality* as an organizational structure in which all parties are operating at the same level, for example, a spot market. Markets differ in their depth (trade volume and the number of traders). If there are many traders and the volume of trades is large, such as in the case of wheat and corn, there exist centralized exchanges (e.g., CME Group) where clearing occurs and standardized contracts are written and traded. If highly liquid exchanges already exist, blockchain technology is unlikely to offer much additional benefit. Although centralized exchanges are expensive to set up initially, their per-transaction costs are typically lower than those of blockchains. Then, there are markets that are extremely decentralized and unstructured. Their low depth and liquidity makes it uneconomical to set up centralized trading platforms. For such goods and services, blockchain technology offers a way of creating digital claims and processing the exchange of those claims for payments by requiring a lower setup cost than the one of a centralized system. For example, whereas there are derivative contracts (futures and options) on long-grain rough rice, traded on CME, there are no contracts for African rice, whose potential trade volume is smaller. Blockchain technology can help to create and operate this market, improving the efficiency for those using, growing, and trading this type of rice.

We define a *verticality* as the organizational structure in which processes are sequentially ordered and often integrated through a collection of contracts. Supply chains are often *verticalities* in which suppliers are arranged in tiers (this structure is described in the classical multiechelon serial supply chain systems). As discussed above, blockchain technology is likely to improve different dimensions associated with *verticalities*. For example, the ability to better observe the state of the supply chain mitigates the need for inventory. In addition, assets located in different tiers of a supply chain can be collateralized more easily, and claims on them can be traded within the supply chain. Overall, these different features may reduce the bullwhip effect.

Blockchain technology is also likely to affect *diagonalities*, a complex hybrid system in which *horizontalities* (e.g., spot markets) and *verticalities* (e.g., supply chains) are coming together. Imagine a consumer orders a toy from a supermarket. A delivery person (hired from a pool of independent contractors) picks up the item, orders a car, and delivers it. The door has a smart lock and opens if the right person with the right code shows up at the right time with the right product. The toy is recorded in a database, in case it needs to be serviced or recalled. This complex supply chain needs to integrate multiple parts: the traditional supply chain of the supermarket (possibly with intermodal transportations from overseas), different marketplaces to secure the delivery person and the car, the IoT to open the door, and a registry to keep track of the product after its sales. Smart contracts (Section 2.1.2) may facilitate these interactions, but the technical uncertainty (Section 3) may preclude full integration.

Amazon recently started to offer a product similar to the one described in the above paragraph, but with a different approach. The Seattle-based company has fully integrated the service (successfully or not, time will tell). In contrast, in the *diagonality* that we describe, one company would not be in control of everything; for example, Amazon would not own smart locks, items would not have to be purchased from Amazon, and the delivery person would not work for Amazon. The blockchain revolution will not have one company (e.g., Amazon) at the center of the process, but rather independent entities interacting in the decentralized fashion with the same (or better) effect. By allowing separate completion for specific parts of the bundle, it is possible for the delivery to become more effective. Conditions under which this statement is true are worth investigating.

In other situations, a traditional vertical supply chain can be integrated with shipping portals, trade financing markets, or with a registry of asset ownership after delivery. For example, it may be worth investigating how firms acquire and maintain market power when the concept of market power is extended beyond simple markets. Antitrust scholars have considered the effects of mergers on specific markets, in particular in the context of the acquisitions of suppliers or customers. The OM literature (Hu and Sobel 2005; Federgruen and Hu 2016, 2017) has also considered the effect of competition among entire supply chains. Blockchain technology has the potential to reframe these questions in environments with unprecedented complexity.

6. Conclusions

Blockchain technology is built around the concept of a distributed digital ledger. The technological implementation of this concept varies and is not yet stable. Bitcoin was the first application. However, by now, there are literally thousands of others (and the association of blockchain with cryptocurrencies may have some negative social connotations). Many of the recent developments are salient for the OM research community. In this article, we provided a research agenda for the OM field. There are many promising and exciting business models and new perspectives on the classical OM problems. At the same time, we caution against falling for the hype about blockchain. The technology is still emerging, and most projects will fail. For many situations, a centralized database is more efficient. The state-zero problem is a major issue. Sensors and trusted auditors can help, but they will not entirely solve the problem. Although in some applications collecting data through sensors is the main challenge, in others, validating stored data are more important.

Blockchain technology can improve supply chain operations by providing visibility, information aggregation, information validation, contract automation, and system resiliency. Blockchain technology can create more stable, transparent, secured, efficient, ethical, and robust supply chains. Blockchain technology can facilitate the integration of supply chains and finance. We observe the first real-life implementations, but many practical and theoretical questions remain unanswered.

Aside from offering new interesting ways to revisit the traditional OM questions, Blockchain technology offers the potential to introduce new perspectives. For example, with private blockchain networks, supply chains become more than an integrated collection of flows and contracts; they become institutions that need to be regulated and governed as such. Blockchain development also creates interesting issues from an industrial organization perspective.

Overall, blockchain is an emerging technology that has the potential to disrupt OM. Naturally, similar claims have been made before. In some cases, this initial enthusiasm was warranted (e.g., TCP/IP and the internet), but in other cases (ERP, RFID), the consequences of new technologies were more limited. One thing is clear, however: more research is required.

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Endnotes

[1] See https://sawtooth.hyperledger.org/examples/seafood.html.

[2] See https://www.everledger.io.

[3] Other technologies, such as RFID, were proposed as solutions to the bullwhip effect. We discuss our view on the relationship between the blockchain and other technologies, including RFID, in Sections 2 and 6.

[4] See https://diamonds.everledger.io/search/QSLIS013.

[5] The Kimberley Process Certification Scheme safeguards the shipment of "rough diamonds" and certifies them as conflict-free.

[6] See https://www.gia.edu/.

[7] These steps are adopted from the best practices documented by the Supply Chain Risk Leadership Council (http://www.scrlc.com/) and from Waters (2011).

[8] See https://sawtooth.hyperledger.org/examples/seafood.html.

[9] See https://www.everledger.io.

[10] See http://www.who.int/csr/media/faq/QAmelamine/en/.

[11] See https://diamonds.everledger.io/search/QSLIS013.

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