Transportation Research Part E 142 (2020) 102067

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Blockchain technology in supply chain operations: Applications, challenges and research opportunities

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ARTICLE INFO

Keywords:
Blockchain
Supply chain
Logistics
Integration
Applications
Literature review

ABSTRACT

Blockchain is a technology with unique combination of features such as decentralized structure, distributed notes and storage mechanism, consensus algorithm, smart contracting, and asymmetric encryption to ensure network security, transparency and visibility. Blockchain has immense potential to transform supply chain (SC) functions, from SC provenance, business process reengineering to security enhancement. More and more studies exploring the use of blockchain in SCs have appeared in recent years. In this paper, we consider a total of 178 articles and examine all the relevant research done in the field associated with the use of blockchain integration in SC operations. We highlight the corresponding opportunities, possible societal impacts, current state-of-the-art technologies along with major trends and challenges. We examine several industrial sectors such as shipping, manufacturing, automotive, aviation, finance, technology, energy, healthcare, agriculture and food, e-commerce, and education among others that can be successfully revamped with blockchain based technologies through enhanced visibility and business process management. A future research agenda is established which lays the solid foundation for further studies on this important emerging research area.

1. Introduction

1.1. Blockchain and its implications on supply chain operations

Blockchain is an innovative, decentralized, and distributive "state-of-the-art" technology, which maintains confidentiality, integrity, and availability of all the transactions and data. It is a shared, open and distributed ledger that can help store/record data and transactions backed by a cryptographic value (Choi, 2020a) across a peer-to-peer network (Chang et al., 2019a; Choi et al., 2019). Blockchain is a digital shared ledger which is distributed over the network. Once the records are added they cannot be edited without changing the previous records (with the consent of all/majority of involved parties), which makes it very safe to business operations. It has endless applications in various fields like designing smart contracts to track frauds in finance or securely share medical records between healthcare professionals. Fig. 1 shows how blockchain improves the transaction journey (O'Leary, 2017; Bogucharskov et al., 2018). Blockchain enables a distributed consensus mechanism that allows its participating entities to be informed of every event and transaction by creating an irrefutable record in the public ledger.[1] It has disrupted many industries like banking, SC, operations, real

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[1] This refers to the public blockchain. For private blockchains, companies can choose to selectively show what records that they would like to share.

https://doi.org/10.1016/j.tre.2020.102067
Received 11 May 2020; Received in revised form 21 July 2020; Accepted 18 August 2020
Available online 29 September 2020
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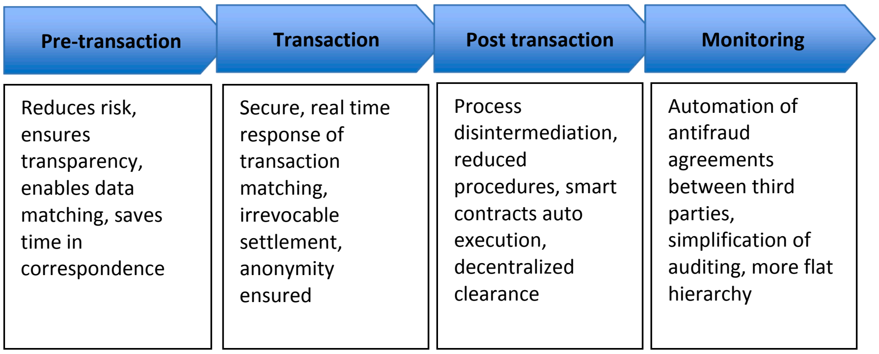

Fig. 1. The blockchain supported transaction journey.

estate, insurance, healthcare, electronic health records, copyright, music, and renewable energy and is continuing to grow its foothold and impact in these sectors due to its decentralized, verified and immutable nature. There are many examples of successful transformations of SCs with blockchain technology but there is still a barrier in terms of usability, security, privacy (Peck, 2017; Firica, 2017) and cost (Choi, 2020c). Along with transforming SCs of various sectors, it also helps improving the functionality and security of current digital platforms (Cai et al., 2020) including Internet of Things (IoTs) and other Industry 4.0 related technologies. Every industry has varied needs with respect to their privacy and security control. To adhere to varied needs, blockchain can have 3 structures – public (non-permissioned), private (permissioned) and consortium (hybrid). Public blockchain is accessible to all the users on the network and implemented via peer to peer network. Private blockchain provides role-based access to data and uses cloud networks for improving flexibility. Blockchain can also support social media analytics (Choi et al., 2020c). Consortium blockchain possesses the functions of both public and private blockchains and provides a balance between both (Qiao et al., 2018).

Blockchain has an immense potential to transform every step of SC, from raw materials procurement to distribution to the consumers (Goyat et al., 2019; Babich and Hilary, 2019). It also enables SC reengineering by establishing a blockchain-based BPR (Business Process Reengineering) framework (Chang et al., 2019a). Every transaction made can be restructured using blockchain technology and the journey can be made faster and more secure.

The structure of the blockchain is organized in a way such that it ensures security and transparency of SCs. We outline the related mechanism of a typical blockchain system as follows. Each block in the blockchain has a hash number (256 bit), which is created with consensus by a scientific algorithm. The blocks are linked to each other with reference to previous block's hash which creates a secure and independent chain. Before adding blocks to the blockchain, they need to be validated, which can be in the form of proof of work which is known as "blockchain mining". After validation, block becomes a part of the network's auditable and immutable blockchain. There is also a built-in defense mechanism. To be specific, any corruption which is detected by the blockchain as malicious (including attempts to alter block changes the hash functions of all the blocks) will be captured and "defended". The corrupted block in the infected node will also be corrected.

1.2. Scope of this study

Our work aims at incorporating all the literature that has been published as articles, articles in press, review papers and short survey pertaining to the applications, integration and implementation of blockchain technology in SCs and logistics. It strives to capture the meaningful data from the plethora of literature available using a systematic literature searching methodology. It uncovers the current trends of blockchain in SC operations and paves way for future research. As a remark, the scope of this work is restricted to SCs. The trend of research in this area has been accelerating since 2017 and has continued at an enormous pace. Through this paper, we try to provide insights by addressing the following research questions:

How can blockchain enhance SC performance?
What are the sectors most impacted by blockchain technology?
Which SC functionalities are most impacted and in which way?
What are the different applications of blockchain in SCs of various sectors?
What are the challenges and future scope of research for blockchain implementation in SC?

1.3. Organization

This work has the following structure: Section 1 gives a short introduction about blockchain and its functionality and applications in transforming SCs. Section 2 entails in detail the research methodology adopted in this work. Section 3 gives a detailed explanation of the functionalities of blockchains which enable it to be the future disruptive technology in this arena. Section 4 walks us through some of the functional areas of SC which can be improved using blockchain as per the current research. Further, Section 5 gives an idea about different sectors where blockchain has been implemented and has the potential to improve. The managerial implications,

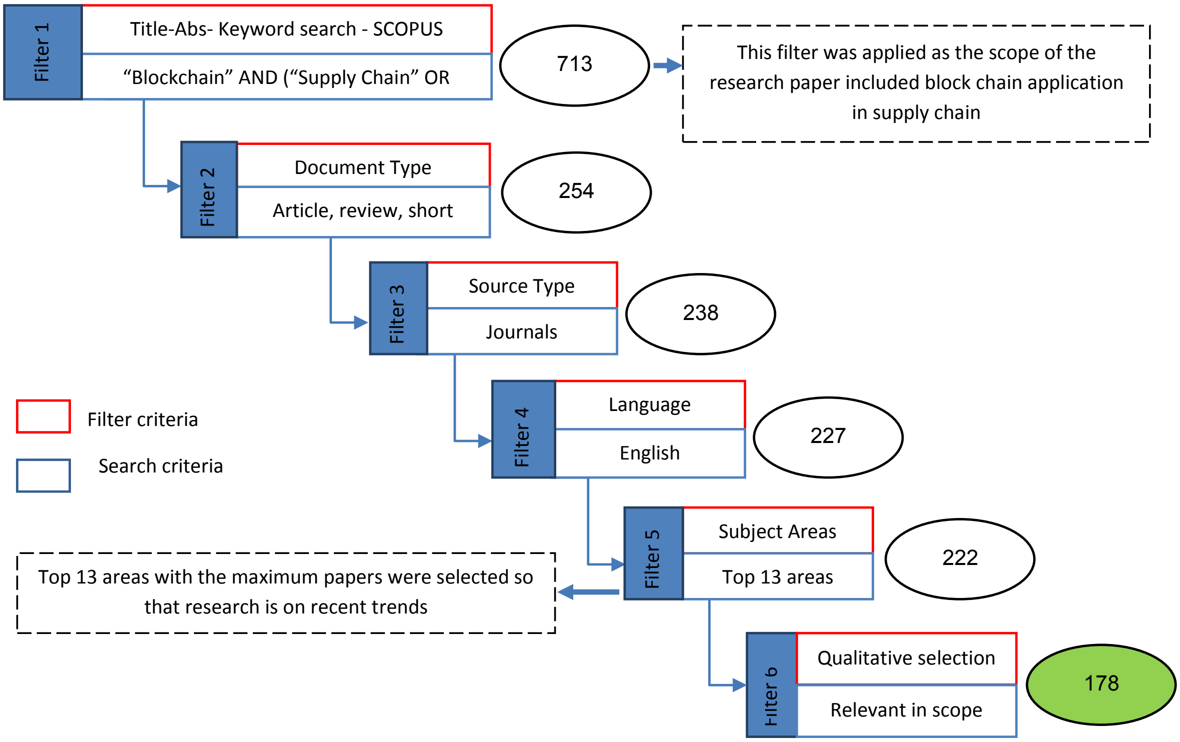

Fig. 2. Search methodology.

societal impacts and challenges of blockchain implementation in supply chain management (SCM) and logistics services are presented in Section 6. Section 7 summarizes the work with future research followed by the conclusion in Section 8.

2. Review methodology

With the attempt to examine the related literature on blockchain's applications in SCs, we have undertaken a systematic literature review of all the relevant papers and following review methodology has been adopted.

2.1. Searching methodology for literature

The searching is conducted on the "Scopus platform". Fig. 2 shows the search methodology with the way of finding related articles. Note that we exclude some types of articles such as editorials as they are not deemed as original research or survey.

2.2. Descriptive statistics

2.2.1. Subject wise classification

Our study considers top 13 subject areas, which include a total of 178 papers. The chart in Fig. 3 clearly shows that Computer Science, Engineering, Business Management and Accounting, and Social Sciences are the major areas in which related research has been published. Material Science, Decision Sciences, Medicine, Finance and Environmental Sciences have also seen an upward trend in publishing research on blockchain technology in SCs.

2.2.2. Year wise analysis

The major research in blockchain for SCs started from 2017 onwards. We can see a substantial increase in the number of papers from 2017 to 2018. Also, in 2019, there has been an exponential increase with more than 165 papers published, which indicates an explosive growth trend in this area for research (Fig. 4). If we look at the studies more closely, we will also find many studies focusing on specific industries. This hence shows that blockchain is being studied at a much-accelerated pace across various industries, partially because of its increased industrial applications in practice.

2.2.3. Country wise analysis

The trend (Fig. 5) here shows that USA and China have the maximum number of published research for blockchain. But India is also moving forward and contributing to the research in a substantial way. The interest of the top economies of the world shows that

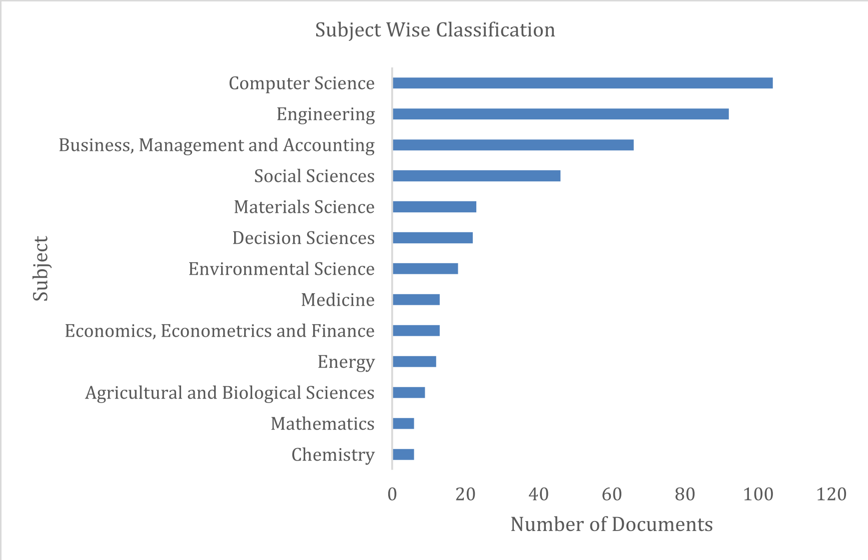

Fig. 3. Subject wise classification.

blockchain has a potential to transform the economies and improve the SC in various domains. South Korea and European nations like the UK, Italy and Germany are also majorly contributing in this area of research.

3. Blockchain overview

Blockchain is an immutable, tamper-proof distributed ledger technology (DLT), which is utilized in a shared and synchronized environment where all the transactions are validated by users and are traceable. It enables a decentralized environment where all the members of the network can interact securely without the need for a trusted authority. Hence it eliminates the need for a central entity by validating and storing all transactions through distributed consensus. To implement blockchain with these functions, Fig. 6 shows the typical "work flow" of using blockchain for a transaction. Note that this work flow is rather standard (see Min, 2019; Fu and Zhu, 2019a).

Blockchain is formed through a series of connected blocks, where transactions history can be easily traced through previous blocks making the technology transparent and trustworthy. Each block contains its own unique ID and has the hash of the previous block, thus ensuring transaction security. All transactions are validated and recorded by the users in that network; they are also time stamped, arranged in a chronological order, connected to the previous block and are irreversible once added to the network. This entire structure of blockchain makes it a "trusted technology" (Queiroz et al., 2019). One of the most important functionalities which make blockchain trusted, secure and transparent is the so called "consensus mechanism". Records are embedded in blocks linked through hash values and the decision to add a new block to the system is taken through the consensus mechanism. For any alteration of an existing block, the adversary must compete with all the users to construct a longer branch which helps DLT to maintain protection of historical data with collaboration mechanism.

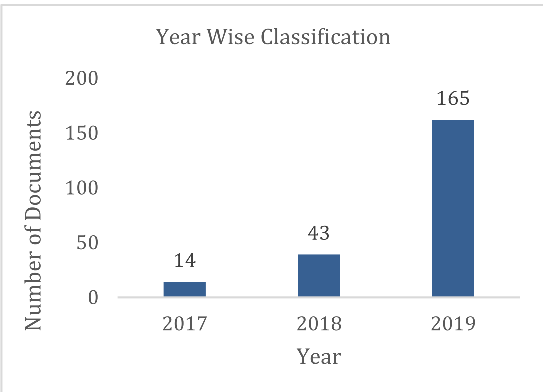

Fig. 4. Year wise classification.

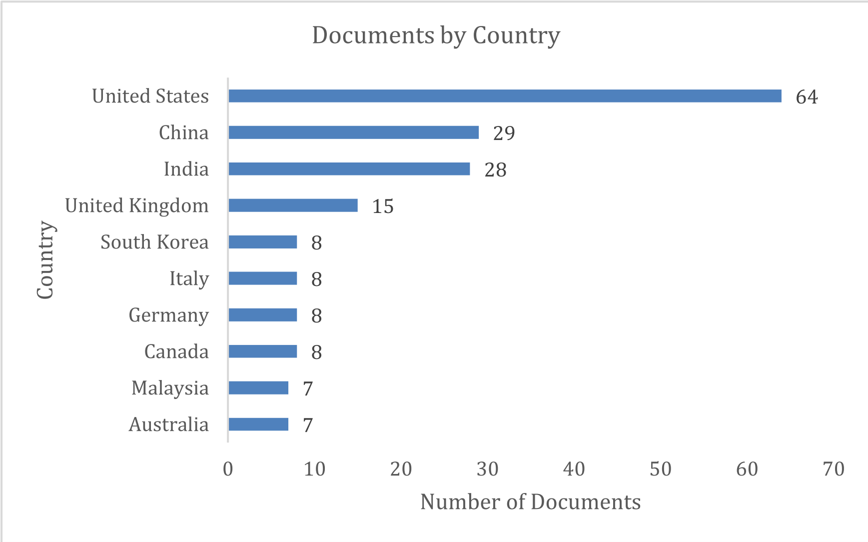

Fig. 5. Country wise classification.

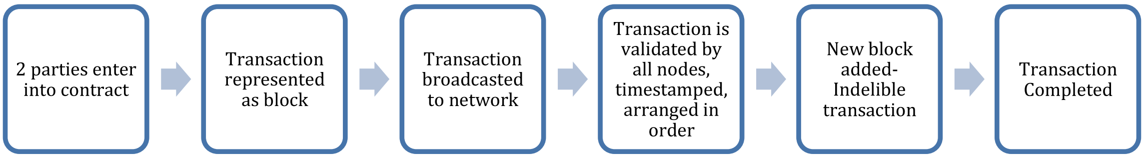

Fig. 6. Blockchain work flow.

3.1. Characteristics of blockchain

The characteristics of blockchain which make it unique and promising for future industrial applications are:

- Decentralized: The data on the system can be accessed, monitored, stored and updated on multiple systems.
- Transparent: Data is recorded and stored on the network, with consensus from the network and is visible and traceable throughout its lifetime.
- Immutable: Blockchain provides timestamps and controls to ascertain immutability
- Irreversible: For every transaction ever made, a certain and verifiable record is kept in each blockchain.
- Autonomy: Each node on the blockchain can access, transfer, store and update data by itself safely without third party intervention.
- Open source: Blockchain provides open source access to everyone in the network with sense of hierarchy.
- Anonymity: As data transfer occurs between nodes, the identity of the individual remains anonymous.
- Ownership and uniqueness: Every document exchanged on the blockchain stores its ownership records with a unique hash code
- Provenance: Every product has a digital record document in the blockchain which proves its authenticity and origin.
- Contract automation (i.e. smart contracting): It is a small computerized program to help execute contract. It replaces the need of a usual contract with providing better security and lower transaction costs. Smart contracts are usually coded to include conditions for rules, penalties and actions that will be applied for all the parties involved in the transaction. Smart contracting supports quick response (Li et al., 2019a) operations in supply chains.

3.2. Blockchain architecture

It consists of five modules that govern the respective operations and create protocols for blockchain applications (see, e.g., Min, 2019; Choi et al., 2020b).

- ***Data source module:*** It helps create the blockchain in the "distributed and shared databases". It ensures that the data retrieved by the users of the blockchain would be unaltered and uncorrupted. Note that data immutability, tamper-proofed storage with any form and shared data ledger through data "Application Programming Interface (API)" are the key aspects of blockchain.
- ***Transaction module:*** It monitors, manages, enables and supports the "journey of a transaction in blockchain". It helps to validate and facilitate addition to the blockchain. Though smart contracting transaction gates, data are transferred. Along with shared

visibility of transactions, the flow of information across the SC is constituted through the bockchain. Transactions are bundled and delivered to each node in the form of a block. Note that transactions once executed are almost impossible to delete or roll back in blockchains.

- ***Block creation module:*** Blocks can be regarded as data structures created by the miners. They contain information and details of transactions that are replicated to all nodes of the network. The block creation module enables the addition of new blocks to an existing SC by providing hash values and connections of the previous block. The sequences of transactions are saved in "chronological blocks" and blocks that store invalid transactions can be identified and tracked easily.
- ***Consensus module:*** Proof of work and proof of state algorithms are used to confirm and validate all the transactions to avoid corruption of data. Data consistency is maintained in the distributed network through the carefully designed "consensus algorithms". Distributed concensus helps in both verification of the validity of transactions and link creation among the blocks in the blockchain system.
- ***Connection and interface module***: It monitors the tracking of transactions and helps provide real time data on smart contracts. This module synchronizes all the information technology (IT) platforms, algorithms and software required for blockchain applications. Depending upon the use cases, multiple distributed ledger platforms could be made available in the market that offer consensus algorithms for the blockchain system, no matter whether the blockchain is public, private, permissioned or non-permissioned.

3.3. Major drawbacks of blockchain technology

Blockchain technology can provide a tool to support publicly viewable and secure transactions. However, due to the irreversible nature of transactions in blockchain, the receiver does not get any refunds unless a new transaction is issued. Also, the laws and regulations surrounding blockchain environment are not clear which can lead to confusion among consumers. Finally, blockchain is in fact not as cheap as some people believe. The non-trivial operations cost and implementation cost of blockchain systems should never be under-estimated.

3.4. Prior related review papers on blockchain in supply chains

Blockchain technology has also been reviewed by various prior studies (Hoek, 2019a; Saberi et al., 2019; Hald and Kinra, 2019). Most current review papers commonly include bibliometric review of many blockchain papers, including conferences. Some of them focus on examining blockchain adoptions for understanding applications and future research in SCM (Surjandy et al., 2019a; Gurtu and Johny, 2019; Saberi et al., 2019). Hastig and Sodhi (2019) examine blockchain applications for SC traceability, and some important successful implementation factors. Khosla et al. (2019) discuss the basic overview of blockchain in SCM and its usability in practices. Juma et al. (2019) present a survey on blockchain in trade SCs and its challenges in SC design while integrating blockchain. Wang et al. (2019a) highlight that blockchain majorly has a potential for enhanced data sharing, record management and role-based access. The authors focus on the related research in designing new structural frameworks, models, architecture, etc., but details about actual or prototype implementation are largely missing. In Shen and Pena-Mora (2018), the relevant application cases for smart and sustainable cities are discussed based on four pillars - social, economic, environmental and governmental. The authors also show that Ethereum and Hyperledger Fabric are the most commonly used platforms for blockchain applications. In Choi et al. (2019), the authors review the analytical literature using the mean–variance approach for responsive supply chain operations using air logistics. The authors highlight the role played by blockchain.

Although the above prior review papers have been published, our paper is different from them in various aspects. First, we cover a comprehensive overview of blockchain's application in SCs, with an exhaustive review of journal articles. Second, we idenitfy many key takeaways and propose the subsequent challenges and opportunities. To be specific, we conduct a thorough review on blockchain technology's applications in various industrial SC operations that include healthcare, energy, food and agriculture, finance, government services, education, manufacturing and environment among others. The corresponding societal impacts are also highlighted.

4. Blockchain technology for supply chain functions

SCM is an enormous sector and is the main skeleton of every industry (Hughes et al., 2019). However, traditional SC systems are not versatile and transparent enough to accommodate the growing needs and demands of the future leading to huge overheads in terms of error handling, costs, administration and fraud management.

4.1. Benefits of using blockchain in supply chains

In the Industry 4.0 era (Fernández-Caramés et al., 2019), blockchain is proposed as a way to organize records in a distributed manner through consensus mechanism (Gao et al., 2018; Benčić et al., 2019). It has the potential to transform SCM through its features of transparency, authenticity, trust and security, reduction of cost, disintermediation, efficient operations and reduced waste (Philipp et al., 2019; Gurtu and Johny, 2019). Furthermore, all the transactions supported by blockchain are more efficient, secure, economic and transparent (Queiroz et al., 2019). It is hence commonly believed that the distributed nature helps blockchain to mitigate risks in the SC (Arza et al., 2020; Zhang et al., 2020) associated with piracy, hacking, vulnerability, expensive compliance with government rules and contractual disputes (Min, 2019). Blockchain also helps to facilitate real time order settlement and

Table 1
Benefits of using blockchain in supply chains.

Benefits of blockchain in SCs	Details
Data management	- Enables calibration of data located across diverse SCs. - Improves security of data stored. - Real time capturing of all information is done
Improves transparency	- Helps track status of an item during a process - Automates data analysis activities - End to end transparency based on permission level via hierarchy
Improves response time	- Creates a dynamic and real time SC with better utilization of its resources
Smart contract management	- Customized and individual contracts can be defined for each function and can be coordinated with each other - Helps in process design for business operations - Improves visibility and eliminates the need of intermediary
Operational efficiency	- Improves end to end speed of SC process - Identifies bugs and issues in the beginning to make the process robust
Disintermediation	- Leads to an uninterrupted chain of transactions - Increases speed - Increases trust among stakeholders of process
Immutability	- Consensus mechanism for all modifications - Ensures security of all transactions
Intellectual property Management	- Intellectual Property protection and registration

automation of manufacturing tasks with the smart contracting implementation (Sheel and Nath, 2019). Blockchain also ensures the mitigation of ripple effect in SC minimizing the disruption caused through changing paradigms (Ivanov et al., 2019). Table 1 shows some of the benefits of blockchain implementation in SCs (Chang et al., 2019a; Wang et al., 2019a; Saberi et al., 2019; Surjandy et al., 2019a; Shamout, 2019; Narayanaswami et al., 2019).

Thus, blockchain deployment in SCs not just increases efficiency and decreases cost but also improves relationships among all the stakeholders. It also garners more trust and streamlines the related business processed (Queiroz et al., 2019). There have been examples of successful implementation of blockchain with SC for wood and shipping industry. In the wood SC, blockchain has been implemented to provide end-to-end traceability from the moment of cutting to transforming it into usable materials (Figorilli et al., 2018; Li et al., 2019a). In China, blockchain has reduced the load at its international trading ports by integrating and sharing information among all stakeholders (Tan et al., 2018). Blockchain integration transforms the structure of the SC by ensuring collaboration between all the actors involved through the utilization of digitalization and smart contracts (see Saberi et al., 2019 for more).

4.2. Blockchain for major SC functions

SC reengineering, security, resilience, provenance, process management and product management are some of the major functions that can be transformed with blockchain technology.

4.2.1. Supply chain provenance

Blockchain technology and IoTs help in granular provenance of physical goods, which are produced and transported in complex, inter-organizational, or internationally spanning SCs which are studied using traceability ontologies and constraints on Ethereum blockchain (Kim and Laskowski, 2018). SC provenance is delivered by providing certifiability, traceability, verifiability and tractability of product information, origin and authenticity assurance and integrity along the entire SC spanning across borders (Montecchi et al., 2019; Liu and Li, 2019; Tang and Veelenturf, 2019). It has been the core function of blockchain for diamond supply chains (see Choi, 2019 for the Everledger's case). In particular, "Hyperledger Sawtooth" project has been implemented using blockchain and IoT technologies (Pally and Reddy, 2019). SC provenance framework using blockchain which stores all the critical information, ensures role-based access to data and safeguards the data through secure encryption has been developed by Engelenburg et al. (2019).

4.2.2. Supply chain resilience

Blockchain technology enables SC resilience by reducing impacts of disruptions, applying preventive and proactive approach for risk management and providing multilayer protection for SC network (Liu et al., 2019). The structural design of blockchain helps capture both the organizational and network risks associated with any SC.

4.2.3. Supply chain reengineering

Blockchains enhance the transparency and visibility of SC, enable process automation, eliminate intermediaries and enable real time tracking through traceability, privacy and data management techniques which are all the cornerstones of SC reengineering. A properly reengineered SC can achieve synchronization of tracking information in all arenas of businesses. Moreover, usage of smart contracts can help reduce the time and cost required further assisting SC reengineering (Chang et al., 2019a; Dolgui et al., 2019; Liang et al., 2019).

4.2.4. Security enhancement

Blockchain enables authentication, confidentiality, privacy and access control, data and resource provenance, and integrity assurance in the services it provides (Mackey et al., 2019; Yi, 2019). It also enables the formation of risk control analytics framework to study the connection among business, information and engineering and to gather an analytics perspective on digitalization in SC (Ivanov et al., 2019). Even in a big production enterprise, blockchain can provide robust risk management due to its ability to scale up as per requirements (Fu and Zhu, 2019b). Blockchain is much more secure than traditional IoT systems or traditional security services due to its capabilities of enhanced cybersecurity and better performance (Kshetri, 2017a). The following systems are enhanced when integrated with blockchain technology, which can lead to a more secure SC:

a. **IoT security**: The traditional IoT system is a centralized network of digital integration. Blockchain ensures high security of IoT system by enabling a consensus mechanism for dynamic data storage, securing end-to-end transmission of data and providing product traceability and monitoring (Qiao et al., 2018). Rules and hierarchy-based consensus algorithms all help improve the security in IoT devices and facilitate the throughputs of transactions (Cho et al., 2017). Further, by its nature, blockchain is less prone to tampering and identity frauds as it provides a decentralized sharing platform for data verification and provides an immutable ledger structure (Kshetri, 2017b).
b. **Intrusion detection system**: Blockchain helps create the collaborative intrusion detection systems where the product codes can interact with each other and exchange data throughout their entire journey. There is a risk associated with the tampering and security of the codes which can be resolved by the use of blockchain technology because it helps to ensure the integrity and transparency of data storage (Meng et al., 2018).
c. **RFID security**: Blockchain improves the transparency, data protection, reliability and cost management for RFIDs using an ultra-light weight mutual authentication RFID protocol. This protocol is compatible with decentralized databases and enables seamless communication with RFID devices. RFID is mainly used for traceability of products and services in SC which can be improved drastically with its integration with blockchain (Sidorov et al., 2019). Walmart and IBM tracked consumer products with RFID systems using blockchain technology (Pally and Reddy, 2019).

4.2.5. Business process management

Blockchain enables efficient business process management through smart contracts by compiling the control flow and business logic of interorganizational business processes. Blockchain can also be used with smart contracts for hyperconnected logistics (Betti et al., 2019). These controls are enabled by triggers and they act as a bridge between the enterprise applications and blockchain. A pilot study of contract management for a grid operator has revealed that information gap between various stakeholders results in sub-optimal business performance. This creates strong arguments and a high level of distrust amongst the associated parties. A proper smart contract implementation for any request of modification or payments would automatically trigger a process flow based on appropriate approvals achieving speed, trust and improved business performance (Downey et al., 2018). Blockchain technology can also be effectively used for customer-order-process management (COM) and improve the efficiency, traceability and visibility of orders (Martinez et al., 2019). Asset management is also enabled by blockchain through its “proof of concept algorithm” which guarantees transparency, reliability and efficiency (Notheisen et al., 2017). Pilot prototypes like DAO (Decentralized Autonomous Organization) have been implemented to replace the traditional management system with automated governance but have to be halted due to security breach (Hütten, 2019). Blockchain technology adoption and implementation needs to be carried out in a stage by stage process to ensure optimal integration with business processes and reduce security concerns. Rahmanzadeh et al. (2019) propose the adoption of blockchain together with fuzzy sets for registering best possible ideas and tactical decision making of SC strategies.

4.2.6. Product management

Blockchain improves cycle time, productivity and quality, opens new business opportunities and enables product differentiation through its integration with SCs. Extensive research has been done on efficient product deletion and price management through blockchain technology. Some details are elaborated in the following.

a. **Product deletion**: Product deletion requires recognition, analysis and revitalization, evaluation and decision making and implementation of the decisions. All these functionalities are facilitated by blockchain by real time tracking, multilayer data management, better demand forecasting, risk reduction and automated decision making (Zhu and Kouhizadeh, 2019). A relationship exists between blockchain, circular economy and product deletion. The information stored in the blockchain can be used to analyse policies developed by companies on product deletion and circular economy (Kouhizadeh et al., 2019).
b. **Price tracking in product distribution:** The traditional price tracking system is developed in a non-transparent way and does not show end-to-end price variation across the SC. It only shows the final price of the item to the consumer directly during trasnactions. Blockchain can allow the consumers to know the exact pricing from raw materials to distributors to suppliers and disclose all the data to the public domain. This will result in dissemination of honest information by all the stakeholders thus ensuring price transparency. A pilot implementation has been done through smart contracts on Ethereum network where price transparency is guaranteed (Yoo and Won, 2018).

From the above discussions (Sections 4.2.1–4.2.6), we can see that improvement of these functionalities will resolve the major problems associated with traditional SCs and make it scalable for future use. Blockchain implementation and integration with SCs can

Table 2
Blockchain for major supply chain functions.

Functional aspects of SC	Details
Supply chain resilience	- Reduces the impacts of disruptions by applying "preventive and proactive" measures for risk management and providing multilayer protection for SC network - The structural design of blockchain helps capture both the organizational and network risks
Supply chain provenance	- Helps in granular provenance of physical products, which are produced and transported in complex, inter-organizational, or internationally spanning SCs - Provides certifiability, traceability, verifiability and tractability of the product information
Supply chain reengineering	- Enhances the transparency and visibility of SC and enables process automation - Eeliminates intermediaries and enables real time tracking through traceability, privacy and data management techniques
Security enhancement	- Enables authentication, confidentiality, privacy and access control of data, and integrity assurance in the services - Integrating with IoT and RFID, blockchain helps in enhancing security, consensus mechanism for dynamic data storage, transparency and data protection, reliability and cost management
Business process management	- Enables efficient business process management through smart contracting by compiling the control flow and business logic of interorganizational business processes - Effectively used for asset management and customer-order-process management which improves the efficiency, traceability and visibility of orders
Product management	- Improves cycle time, productivity and quality, and enables product differentiation through its integration with SCs. - Helps in product deletion and price tracking during the product distribution in the end to end SCs

further be improved via a 2-step block construction model using distributed technology where block reservation and data generation are separated into two steps (Gao et al., 2018). This mechanism will help to reduce latency, improve scalability, and mange inter-operability of "adding a new block". It also gives proper access controls for distributed ledgers. Instrumented, interconnected and intelligent SCs can be built using blockchain and IoTs. As a remark, consortiums like CBSR (Central Baltic Sea Region) are established by professionals across the world to apply blockchain to SCs (Gromovs and Lammi, 2017). Table 2 provides a brief summary on use of blockchian technology in major SC functions. Blockchain implementation in SC operations with key themes and objectives of each papers studied are presented in Table 8 in the Appendix.

5. Applications of blockchain technology in different sectors of industry and society

Blockchain technology has the capability of resolving bottlenecks, paving way for future research, addressing issues using shared, secured, distributed and permissioned transactional ledgers. These features have made it inevitable and a forefront runner of the research in various industrial sectors (Al-Jaroodi and Mohamed, 2019). Blockchain helps inter-chain management, improves project management, enhances inter-chain sustainability, relationship modelling, new product development and inter-chain coordination in different sectors globally (Pankowska, 2019; Cole et al., 2019). Blockchain also drives innovation in business modelling and value propositions, especially in start-ups and entrepreneurs. Provision of open source software, new set of applications and removal of third party all would help blockchain to boost innovation in industries (Hughes et al., 2019). Blockchain, if consciously applied to the SC problems, can generate huge benefits (Hoek, 2019b). We have found numerious applications and implementations of blockchain in SCs of different industries and sectors that would help enhance the welfare of the society. In the following, we present some of the key sectors with its industrial and societal impacts.

5.1. Financial services

With its origin in finance, blockchain technology has been extensively implemented in the financial sector owing to the growth of bitcoin and cryptocurrency. Blockchain has the potential to speed up and simplify cross border payments, revolutionize share trading, improve identity management and ease money management in the financial sector. Financial services and public administration can utilize the blockchain technology to create a new virtual currency for the society, although proper regulations and strict control would be the key for a successful implementation (Wamba et al., 2018). It can be used to support "sophisticated fractional calculus models" for SC finance systems (Chen and Wang, 2020). The emergence of cryptocurrency also influences the society and people's lives. In the future, transactions, both local and international, may be supported by all kinds of virtual cryptocurrency and that will create another totally different financial system from the current exchange rate based financial systems.

5.2. Blockchain enabled credit accounting and management systems

Cryptography enabled credit transactions enhance security, reduce time and cost of tracking, automate monetization of credits and make the execution, verification and recording of credit journey transparent and searchable. It is reported that the "Belt and Road Blockchain Consortium" has used blockchain as a fast and efficient way to transfer funds across borders of more than 56 countries for China's One Belt One Road initiative (Pournader et al., 2020). Another example is the AgriDigital platform which is a "closed blockchain application" that leads to faster and secure payment after delivery (Tönnissen and Teuteberg, 2019). Some other functions are discussed below:

- **Asset management and trade finance**: Blockchain enables tamper proof transactions of securities and assets, overrides the requirements of financial intermediaries like payment systems, stock exchanges and money transfer services and enables proficient asset management (O'Leary, 2017; Wang et al., 2019b). Trade finance instruments are another area where blockchain can be used for process automation and efficient processing of transactions. Research has been done on the interaction of trade finance participants using blockchain, with the aim of identifying roadblocks, adoption strategies and success factors for their integration (Bogucharskov et al., 2018). This is critical to asset management for people in all places.
- **Value added tax (VAT)**: Blockchain based indirect tax systems can be created, which would record tax collections at each and every step of transaction, in the value chain bringing more transparency and validity to the entire tax structure (Alkhodre et al., 2019). This helps avoid arguments and facilitates the calculations of VAT. This has an important societal impact.

5.3. Technology sector

The biggest threat in the technology sector is identity management and robust cybersecurity which can be resolved through integrating the technology platforms with blockchain. Cloud, Industry 4.0 and IoTs are being widely used across all the sectors but are prone to the security threats due to their centralized manner. Blockchain integration with cloud technologies would help improve the security and scalability of the cloud network. IoT platforms also have a centralized structure which leads to the threat of single point of failure. Blockchain supports decentralized IoT systems where both technologies complement each other and make a robust and intelligent technology (Hütten, 2019; Lin et al., 2019). Due to varied factors like globalisation, human error and regulatory inefficiencies, there is a need for an independent system that could support real-time data sharing with complete transparency. However, traditional ERP solutions are prone to single point failures, corruption and hacking and therefore blockchain can help in the design and development of a sustainable SCM using its decentralized and super-secure structure (Zelbst et al., 2019; Nayak and Dhaigude, 2019). Blockchain can also be used to derive causal relationships in an industrial system. With blockchain and "Industrial IoT" (IIoT), the entire process can be automated (Maiti et al., 2019).

5.4. Manufacturing sector

Blockchain helps to incorporate the shift to shared and distributed systems in manufacturing ecosystems using a cross enterprise framework which supports a higher level of knowledge sharing. Blockchain integration helps companies to build flexible and scalable businesses at a lower cost in a more secure, effective and well-controlled way. It also increases a firm's profit and its competitive ability by providing real time transparency and cost savings (Ko et al., 2018). Moreover, it helps to incorporate agile manufacturing practices and enable product customisation, smart automation and improvement in employee empowerment (Gunasekaran et al., 2019). Examples of blockchain integration in the manufacturing sector can be seen where a company resolves issues of fake products in additive manufacturing by linking a chemical signature or tokens in the underlying database systems (Kennedy et al., 2017; Westerkamp et al., 2019). It can also be used for diamond authentication (Choi, 2019). The inventory data collected through UAVs can be verified using blockchain which would further bring transparency and data trustworthiness.

5.5. Shipping industry

Blockchain can be incorporated in the cargo shipping sector to create a verifiable and distributed shipping system to integrate and interconnect all the business activities (finance, banking, IoT, SC, manufacturing, insurance) in the view of a shipment. Blockchain ensures reduction of transaction, enforcement costs and disintermediation in maritime SCs (Philipp et al., 2019; Jugović et al., 2019; Grzelakowski, 2019). Integrated and connected merchant ships can ensure minimum delays in real time transactions, transparency of transactions from remote areas, extra vigilance for data confidentiality, transaction validation and fraud management (Komathy, 2018). Blockchain can also reform the maritime industry by organizing projects, people, information, payment and communication in safer, smarter and more efficient ways. It also helps to reduce the risk of corruption and develops safer documentation and control systems (Gausdal et al., 2018). Blockchain based solution with IoT enabled smart containers, smart contracts can be used to manage shipments, automate payments, track violations and make the whole SC efficient (Azzi et al., 2019; Christodoulou et al., 2018). It is reported that Maersk and IBM have collaborated and implemented blockchain based SC for their container shipping business by digitizing and tracking all the containers. T-Mining, a start-up in Antwerp has created a blockchain based solution for secure and efficient shipping container release operations and streamline the flow of documents through smart contracting (Chang et al., 2019b). Recently, Samsung has been able to reduce its shipping costs by one-fifth by implementing blockchain across its SC network (Astill et al., 2019).

5.6. Automotive sector

The current market requirements faced by the automotive industry include integrated, personalized and on demand services through a connected, shared and autonomous environment. The solution for these demands lies in the proper use of blockchain technology by creating a distributed framework model and ensuring SCM, unparalleled security, evidence integrity and secure storage, mobility solution for resource sharing, automated maintenance services, ability to audit records, transparency, execution speed and cost reduction. The entire lifecycle of the automotive industry can be incorporated in the blockchain framework model with a miner node selection algorithm (Sharma et al., 2018).

5.7. Energy sector

Blockchain has the potential to transform the energy sector by enabling transparent, secure and efficient electrical energy transactions. Blockchain also helps to establish transactional energy systems where distributed agents can trade and communicate directly with each other in a flat trading and decentralized system. It enables a decentralized and distributed accounting mode to fit the current requirements of participant's distributed needs in the energy market by dividing the trading process into 2 stages: the call auction stage and the continues auction stage. The use of blockchain peer to peer network for energy systems will not only conserve energy but also save money and allow multiple energy resources to be democratically connected so that users will have access to low cost, high quality energy at all times and places (Park et al., 2018). This brings a huge impact to the society as energy is a critical part of all walks of life. Blockchain can help ensure energy is well-utilized, well-supplied and the allocation is efficient and transparent. This directly enhances social welfare.

5.8. Healthcare sector

Today the healthcare sector is facing some major roadblocks and challenges: fragmented SCs, inefficient data management, insecured data sharing, data privacy challenge, drug counterfeiting, etc. Current data management systems in healthcare, unfortunately, tend to lead to slower treatments, poorer health management and public-backlash. These can potentially be solved by enhancing the data management capabilities using blockchain technology. Blockchain can be used to improve patient outcomes, lower costs, enhance compliance and ensure security, transparency and better use of healthcare data (Mattke et al., 2019). The product provenance information can be well-kept in blockchain supported data base and could be provided to all related parties. In fact, blockchain can be applied across many functions in healthcare namely, neuroscience, EHR medical, genomics medicine, biomedicine, clinical trials, vaccine supply and traceability (along with IoT can help in better tracking) in the pharma industry (Jayaraman et al., 2019; Padmavathi and Rajagopalan, 2019). It enables data collection, storage and recommendation, improves medicine and vaccine traceability, supports brain augmentation and simulation and assists transparent data sharing in a clinical trial management process and managing drug recalls (Mackey et al., 2019; Kirkner, 2018; Radanović and Likić, 2018; Yong et al., 2019; Gurtu and Johny, 2019). As an example, drug counterfeiting is a major problem all over the world. Nowadays, pharma-co-surveillance blockchain systems have been proposed to transform the entire distribution chain in the pharma industry. Hyperledger fabric based on blockchain can be used to enhance the SC and drug records (Jamil et al., 2019). Similarly, blockchain can be utilized in creating a vaccine traceable blockchain and transparency that would build trust between institutions and patients (Yong et al., 2019; Jamil et al., 2019). A healthcare blockchain system, which can be a proper combination of private and public chains, helps to ensure the data will be distributed across all nodes but visibility is limited to people with encrypted keys (Sylim et al., 2018). Note that Tseng et al. (2018) report a Gcoin blockchain system, where G means global Governance which addresses mainly double spending and counterfeiting problems associated with pharma SC. It is a purely consensus-based system of nodes with no central authority for approval. Blockchain implementation has also been examined with a focus on data integrity, access and management of health records in the biomedical domain (Drosatos and Kaldoudi, 2019). Also, blockchain aims at solving the worldwide trade of counterfeit medicines by ensuring secure and easy data storage and sharing (Mackey and Nayyar, 2017). Today, blood management systems may be prone to corruption and adulteration due to poor monitoring. Private cloud based blockchain systems have the potential to be fast and reliable and ensure visibility of the entire blood SC and minimize frauds (Kim and Kim, 2018). Blockchain based smart contracts can help to instill the related intellectual property rights for exclusively selling drugs and completing transactions to the rightful owner. It can also be used for monitoring cold SCs for temperature sensitive drugs (Clark and Burstall, 2018).

5.9. Agriculture and food sector

The agricultural SC developed today is extremely complex with a large number of stakeholders involved and hence needs to be digitized and improved with blockchain. The current traceability system in place has the risks of data tampering. Blockchain implemented on a double chain structure helps increase openness and security of transactions, privacy of enterprise information and can achieve proper resource allocation among all stakeholders in the agriculture sector. It also enhances the overall efficiency of the system, eases business expansion, increases throughput and credibility of the related platforms (Leng et al., 2018; Hasan et al., 2019). Blockchain and IoT based solutions are being used to deal with the trust issues that customers are having in the organic product SCs (Khare and Mittal, 2019). Along with efficiency and product tracking, it also helps to maintain a fair relationship between the small farmers and big buyers and democratize the supply process (Scuderi et al., 2019; Mondal et al., 2019; Kshetri, 2019). Food suffers from adulteration and tampering on a large scale. Using blockchain can solve this problem by facilitating the end-to-end traceability (Behnke and Janssen, 2019). An enterprise level smart contract helps to resolve the sensitive information disclosure, data tampering, transfer of trust and need of trusted intermediary issue with the help of proven authenticity and identity (Salah et al., 2019). Furthermore, to reduce the problem of data explosion, a collaborative approach of "on chain and off chain" management of data is utilized so that a single node is not overloaded with data. Blockchain DLT technique can be used to securely link all the actors of the entire food SC from the source to the consumers which can help eliminate food adulteration, ensure high resolution of food safety issues, improve management of quality issues and reduce the social chaos caused by uncoordinated issues thereby increasing the sustainability (Pearson et al., 2019; Galvez et al., 2018; Bumblauskas et al., 2019; Kittipanya-ngam and Tan, 2020; Kshetri, 2017b; Kamble et al., 2019a). A credit evaluation system has also been developed based on blockchain technology, which aims at strengthening the supervision and management, by the stakeholders in the food SC (Mao et al., 2018). An example of blockchain integration with food SC can be seen in coffee production. Blockchain integration with coffee SCs can enable automatic transfer of payments, support recording data of each production stage of coffee and management of all data records throughout the SC (Thiruchelvam et al., 2018). A successful application case is on the startup, AgUnity that is safeguarding farmers using blockchain (Helo and Hao, 2019). Another example is Prochain, a new transparent and traceable SC system which has been conceptualized to help cover all the aspects of SC. It can enhance both transparency and traceability in food products in the Malaysian market (Chan et al., 2019). As food safety is critical to all walks of life, blockchain can directly improve social welfare.

5.10. Aviation sector

Aviation industry can incorporate digitization and securitization by integrating RFID technology with their SC which will assist in tracking ports and implement process improvement. RFID technology integrated with blockchain and IoT further increases the security and ensures transparent and immutable data management of RFIDs. An example of this integration can be seen in Airbus who is among the earliest adopters to integrate their SCs with RFID. There is an enormous scope for integration of blockchain technology with the current aviation SC (Santonino et al., 2018). Current implementation of blockchain includes the use of Airport Collaborative Decision Making (A-CDM) in a blockchain based platform that reduces inefficiency, mistakes and uncoordinated operations by encouraging cooperation between different players in aviation industry and the air traffic controllers (ATCs) (Vaio and Varriale, 2019). Blockchain can also be used for risk analyses associated with SC in air logistics (Choi et al., 2019). Note that blockchain's deployment in aviation industry can improve air logistics and transportation. This directly improves the social welfare.

5.11. Construction sector

In the construction industry, blockchain can be used in categories like smart cities and shared economy, smart homes, construction management, smart energy, smart government, smart transport, etc. using conceptual frameworks (Isikdag, 2019). The construction sector needs to be prepared for the implementation of blockchain technology and organizational restructuring (for example, the real estate rental services) for future success (Choi et al., 2020a). Xiong et al. (2019) have studied the use of blockchain technology in construction SCs for faster information management and payment security.

5.12. E-commerce sector

Blockchain technology will help to transform the e-commerce sector by solving the problems associated with payment systems, risk management, SCM and data security. Furthermore, blockchain also improves the process of e-procurement by making it simpler and safer. Blockchain reduces the barriers of e-procurement implementation through enhanced security, uniformity, data management, and transparency (Isikdag, 2019). In the literature, Li et al. (2019b) propose the use of blockchain for e-commerce logistics services. Choi et al. (2020a) develop a blockchain system supported pricing strategy in an on-demand service platform for consumers.

5.13. Education sector

The education sector faces problems of reputation management, productivity, peer review processes and predatory publishing which may be resolved by blockchain decentralized data distribution, data immutability and elimination of third party intervention (Novotny et al., 2018). Blockchain helps establish trust of the published materials, individual researchers, institutions and sources of information and data and hence is of utmost importance in the education sector. This is an important application of blockchain and helps to create high societal impacts.

5.14. Entertainment and tourism sector

In the integrated casinos and entertainment sectors, the major challenges are to leverage traffics, demand and storage allocation which can resolve through the decentralized system of blockchain. Integration with blockchain reduces the overall cost of infrastructure for information and communication, enables tamper resistant transactions with consensus mechanism, reduces systematic risks and enhances efficiency (Liao and Wang, 2018). Blockchain also helps in digital right management by giving back the ownership, control and distribution rights to artists themselves. The media industry can also benefit with the development of blockchain as it can improve the content lifecycle visibility, credibility and effectiveness while making sure customer privacy is preserved (Plant, 2017). In tourism, blockchain can improve the current trend of virtual reality-based tourism and provide an enhanced experience to the firms. Note that many of the Fortune 500 companies are a part of the Enterprise Ethereum Alliance for unified developments in this field (Mofokeng and Matima, 2018). In Choi et al. (2020b), the use of blockchain supported social media platforms is examined. The authors include a careful review of the related area as well as discuss the highlight how blockchain-supported social media platforms have been implemented in real world. All these applications enhance consumer surplus and also improve social welfare.

5.15. Online advertising

The major problem with the current online advertising model is the interference and untrustworthiness of the intermediaries. All these problems would lead to suspicions of frauds, right to privacy issues, ad misplacement and diminishing ad budgets. Hence, blockchain integration and implementation with online advertising can help in many ways. For instance, the specific needs like transparency, reduction in ad fraud and privacy are fulfilled. But cost benefit analysis and technical compatibility need to be checked before integrating blockchain systems with advertising to ensure it is cost-effective (Parssinen et al., 2018).

5.16. Spacecraft sector

Blockchain can be applied in spacecraft SCs to reduce transaction costs, guarantee security and address the issue of information asymmetry among the SC participants thereby improving overall profit (Zheng et al., 2019). This is an important application which has high impacts.

5.17. Governments

Blockchain can be of assistance to governments for protecting democratic principles. Management of registries, digitization of land right, secure and lawful execution of voting are some ways in which blockchain can help transform government activities (Hughes et al., 2019). It can also be used to expedite, justify, and enforce contracts. Government can utilize blockchain to facilitate cross organizational partnerships for the development of rural ecosystems. With this revolutionary technology, public as well as rural SMEs can increase the efficiency of their operations by removing unnecessary middlemen (Prause and Boevsky, 2019; Wong et al., 2019). This potentially has a huge impact on the society and citizens may be well-benefitted.

5.18. Postal services

Postal service clients face huge losses due to stamp fraud such as counterfeit and unaccounted postage stamps, which can be solved using blockchain. A digital assets-based crypto taken stamp can be introduced, which operates like a physical stamp during circulation, but its issuing, sale/resale and cancellation are all integrated with the blockchain network. This helps to keep reliable records of all purchases and uses (Yanovich et al., 2018). This application of blockchain can facilitate postal services and can improve consumer surplus as well as social welfare.

5.19. Sustainability management

Blockchain is very useful for establishing sustainable operations in supply chains. It can potentially improve the environment and enhance sustainability substantially. It helps create sustainable and green SCs through the following activities:

- **Vendor selection and supplier development:** Blockchain helps to track the historical sustainability performances of suppliers, execute supplier development and remove intermediaries. Blockchain can be used to track the environmental impacts created from the upstream suppliers' ingredients (Hoek, 2019c). This not only benefits the firms in vendor selection, but also reduces emissions and enhances environment.
- **Mobile service operations:** Under COVID-19, many local service operations are disrupted. Choi (2020b) has examined how service operations can be conducted on a truck in the "bring-service-to-your-home" mode of operations. The use of blockchain is also highlighted to foster trust and enhance transparency of the operations.
- **Materials management and inbound logistics:** Blockchain helps to trace sustainability values in materials and product history. Blockchain can also enable monitoring of environmental impacts of transportation. Cui et al. (2019) and Xu et al. (2019) have studied blockchain-based electronics parts SCs to enhance the traceability with security and sustainable logistics during the respective transportation.
- **Production and internal operations:** Blockchain helps to manage required certifications, transform the shop floor into eco-friendly and evaluate sustainability performance and continuous improvement of all the operations. A blockchain based approach can be developed for reducing both emissions and operational costs within a multi-echelon SC under a carbon taxation policy for an optimal SC (Manupati et al., 2019).
- **Outbound logistics and marketing:** Blockchain enables verification of sustainability performance of transportation in outbound logistics and improves green marketing through smart and traceable packaging. For example, the use of blockchain can help implement the "physical internets" for sustainable logistics (Meyer et al., 2019).
- **Reverse logistics:** Blockchain helps to support tracing the location of the materials and authenticates all actors involved in recycling process (Kouhizadeh and Sarkis, 2018; Kouhizadeh et al., 2019; Xu et al., 2019). This is critical and enhances closed loop supply chain management.

Table 3 shows a summary of the major applications of blockcahin in different SC operations across different industrial sectors. Table 4 provides some important blockchain applications and deployment in real world pactices (Sandner, 2017; Mire, 2018; Hammerich, 2018; Perboli et al., 2018; Hirsh et al., 2018; Xiong et al., 2020). The reviewed research papers on various blockchain enabled industries with key objectives of each paper are presented in Table 9 in the Appendix.

Table 3
Applications of blockchain in supply chain operations across different major sectors.

	Scalability	Privacy	Interoperability	Auditing	Product Provenance	Latency	Visibility	Disintermediation
Finance	Y	Y	Y	Y	Y	Y		Y
Healthcare	Y			Y				Y
Manufacturing	Y			Y	Y		Y	
IoT	Y	Y		Y		Y	Y	
Social Service		Y	Y	Y			Y	
Shipping		Y	Y	Y	Y		Y	Y
Agriculture & Food	Y		Y	Y	Y		Y	Y
Education		Y	Y	Y				Y
E-commerce	Y		Y	Y	Y		Y	Y

6. Managerial implications, social impacts and challenges

Blockchain technology has enormous potential in various sectors which has led to worldwide research on its adoption, implementation, technology and architecture in different sectors. Section 5 examines the implementation of blockchain in sectors such as energy, healthcare, agriculture and food, finance, education, technology, government services, manufacturing, shipping, e-commerce, automotive sectors and the like to improve their efficiency and scalability. We examine and discuss some related managerial implications, social impacts and challenges in this section.

6.1. Managerial implications

In day-to-day business operations, the use of blockchain can fetch numerous benefits to SC mangers. From secured and tampered-proof storage of data to improve response time, transparency in transactions, clear visibility across the nodes, and trust among SC members. The disintermediation mode of blockchain operations can bring the SC operations, SC reengineering and business process management to new heights and create competitive advantages.

The SC coordination among SC partners are being studied and researched over the decades. Integrating with IoT, the use of blockchain technology with appropriate consensus mechanism in various SC echelons would enable big data management, improved connectivity, intellectual property rights and efficient SC contacting.

6.1.1. Supply chain transformation

Blockchain technologies are gaining momentum in the field of SC with end-to-end visibility and traceability, decentralization, enhanced data security, decision making, knowledge sharing, end-to-end integration, and management being the primary focus areas (Surjandy et al., 2019a; Gurtu and Johny, 2019; Feng et al., 2019).

Research is being done on configuration of blockchain backed SC systems like Origin Chain (Wang et al., 2019a). Origin Chain has already developed a traceability system which is secure, transparent and has flexibility to accommodate regulatory changes in compliance. It separates the raw information and hash data, keeping the raw sensitive data off-chain and hash data on-chain (Lu and Xu, 2017; Shamout, 2019). Big companies like Toyota have incurred huge losses in the past due to lack of traceability of paint points in the SC journey. Efforts are being taken by giants like Accenture, Alibaba, JD.com, and Walmart to implement blockchain in SC, B2B e-commerce and other industries to fight frauds, facilitate traceability, and easier transactions with a focus on high value products (Kshetri and Loukoianova, 2019). Thus, the key is to transform the supply chain which is scalable and dynamic with respect to changes in the market.

6.1.2. Related theories

Blockchain implies transformational benefits to managers and their organizations. Blockchain implementation if done rightly can help organizations achieve strategic advantage over the competitors (Wamba et al., 2018). Elimination of third-party involvement results in much shorter transaction times and lower costs; there is an enhanced visibility across the entire SC and improved connectivity amongst all stakeholders due to seamless integration of physical and digital worlds (Min, 2019). Analytics done on the data contained in the blockchain can provide huge value to the company. The analytics engine can provide dashboards, predictive models and compliance checking. Artificial intelligence can be further applied on the data (Dillenberger et al., 2019). But a detailed assessment of implementation of blockchain in the businesses needs to be done to give it a concrete roadmap ahead. This will not only help the managers understand the needs, expectations and requirements of consumers, but also the feasibility and organizational readiness for its adoption (Sander et al., 2018). It needs to be done in a step wise manner and the "GUEST (GO, UNIFORM, EVALUATE, SOLVE, and TEST)" methodology has been proposed to improve the returns from integrating blockchain with SC (Perboli et al., 2018). Also, there is a need to use a combination of publc and private blockchain as the firms need to limit access to their sensitive information to auditor or regulator (O'Leary, 2017). It is also important that access to blockchain technology should be kept low cost, simple, and easy to implement and deploy which will require global standards for encryption of data and access of DLT architectures (Pearson et al., 2019). Creation of a decision support framework would aid managers looking to implement blockchain in SC (Hoek, 2019b). Various structural and managerial changes are required which relate to the following theories:

Table 4
Real world applications of blockchian technology in different sectors.

Sectors	Companies/Organizations	Real applications of blockchain
Energy sector	· LO3 Energy	· Smart grids and local trading of solar energy
	· Korea Electric Power Corporation	· Blockchain-based P2P (peer-to-peer) energy transaction platforms
	· Innogy	· Automated billing of electric vehicle charging stations
	· Wien Energy	· Trading of energy between utilities
Financial services	· Abra, BitPesa, Circle, Mycelium	· Remittances and payment systems
	· Corda	· Hyperledger fabric for financial transactions and insurances
	· Credit Union Alliance	· Fractional calculus model for bank credit system
	· Piper Jaffray	· Securing provider identities and credentialing
	· Professional Credentials Exchange	· Securing identification
	· NASDAQ, Australian Securities Exchange	· Record keeping and clearing
	· Swarmcoin	· Direct transfer of equity into ventures
	· Predictious, Fairlay	· Markets prediction
	· Kingdom of Saudi Arabia	· Value added tax structure
Healthcare sector	· Estonian e-Health	· Storage of a million health records
	· MediLedger Project	· Blockchain ecosystem application for pharmaceuticals SC
	· Center Point Clinical Services	· Clinical trial sponsors, patients, principal and site admin
	· Philippine Food and Drug Administration	· Pharmaco surveillance blockchain system
	· MedVault, Fatcom, BitHealth, Gem Health Network, Healthcare Data Gateways, MedRec	· Improving medical record management
	· Edinburgh Napier University, National Health Service	· Tracking of medical devices and monitoring of patient care pathway
Technology sector	· Everledger	· Registration and transaction history
	· IBM, R3, OpenXcell, Deloitte, Accenture	· Blockchain platform and business process management
	· ABN-AMRO, Intel, JP Morgan, Red Hat, VMware, Wells Fargo	· Hyperledger framework and data management, smart contracts
Manufacturing sector	· Skuchain	· Smart contracts is applied with increased transparency of SC data
	· Genesis of Things, Moog Aircraft Group	· 3D printing and manufacturing
	· Hijro	· Decentralized networks
	· Xage	· Security layer for IoTs
	· Filament	· Increasing IoT connectivity
	· SyncFab	· Supporting parts manufacturing
	· Factom Iris	· IoT device identification
	· IBM-Watsom IoT, IOTA	· Protection of IoT data
Shipping industry	· Syncron	· SC visibility
	· IBM & Maersk Partnership	· Improvement of provenance and transparency
	· Provenance	· Transparency in product information in the entire SC
	· Fair Trade	· Third party product information
	· Soil Association	· Transparency in product certification
Automotive industry	· Ford	· Ethical sourcing
	· Volkswagen	· Preventing “odometer fraud”
	· Hyundai	· SC financing ecosystem using hyperledger fabric
	· MOBI initiative	· Blockchain adoption
Agriculture and food sector	· Etherisc	· Decentralized crop insurance
	· Walmart, Alibaba, JD.com	· Food safety and traceability
	· AgriChain, Ripe	· SC traceability
	· AgriDigital	· Optimizing transaction costs
	· AgriLedger	· Establishing trust and accountability
	· Ripe	· Improving visibility for food SC
	· OriginTrail	· Blockchain driven provenance solutions
	· AgriDigital	· Commodity management platform for grain industry
	· Ambrosus	· Blockchain powered IoT for SC solutions
	· Lokaal	· Crypto funding for small and local farmers
	· UPS	· Logistics challenges
	· WorldCover, Arbol	· Ethereum blockchain-based smart contract
	· Tsinghua University	· Hyperledger blockchain system to food SC
	· Walmart, Nestle, Dole, Golden Food & IBM	· SC traceability in food supplier’s misconduct

(*continued on next page*)

Table 4 (*continued*)

Sectors	Companies/Organizations	Real applications of blockchain
Aviation industry	· Singapore Airlines · Norwegian Airways · Cathay Pacific · Webjet · Air New Zealand · The Italian airport infrastructure	· Digital wallet app · Cryptocurrency exchange · Unlocking "more miles" · Managing booking disputes and reconciliations · Reduction of transactional costs for customers · Airport Collaborative Decision Making (A-CDM)
Governments	· Estonia, Denmark, Australia, Singapore · State of Illinois · Russian Post Indicia	· Keyless Signature Infrastructure (KSI) · Provider identities and credentialing · Helping digital assets based crypto stamp in postal service
Education sector	· RecordsKeeper, LearningMachine, Blockcerts · Academic publishing · Lipscomb University · LiveEdu, ODEM · Open Source University	· Use of blockchain in securing records and certificates · Permissioned blockchains with hyperledger fabric · Securing provider identities and credentialing · Decentralized marketplace for educational resources · Distributed database system
E-commerce	· Amazon · Alibaba · Sweetbridge · Zeex · AORA · OpenBazaar · Expedia, Overstock	· Database, SC traceability and AWS · Blockchain platform for logistics process · B2B e-commerce powered by blockchain solutions · Crypto based instant online payment system · Cross border e-transactions through crypto currency · Creating a decentralized market place · Transactions through cryptocurrecy
Entertainment sector and tourism	· BitSong, PeerTracks · SingularDTV · Winding Tree	· Securing digital rights and fair payments · End-to-end blockchain based transactions and loyalty · Travel solutions to customers
Fashion and accessories	· Everledger (diamond SC) · Levi's (apparel SC) · TrustChain	· Product provenance information · Ethical sourcing · Product provenance information
Construction industry	· HerenBouw, Amsterdam · Briq, California	· Blockchain based project management system · Ledger based project documentation

a. **Principal Agent Theory (PAT)**: It is believed that a major challenge in maintaining a SC is to select the right agents and building a relationship of trust. Specific blockchain characteristics like increased transparency, immutability and persistence of information enable a better relationship between the principal and agents. Thus, PAT can be applied to derive more insights on blockchain implementation in SCs.
b. **Transaction Cost Analysis (TCA)**: The efficiency (e.g., production and transaction costs) of different types of governance systems is closely related to the selection of the most efficient types of inter and intra organizational structures. Blockchain changes organizational boundaries, and affects the contractual agreements between companies due to its inherent nature of security. This feature helps blockchain to minimize transactions costs by reducing the costs for searching information, negotiation, decision-making, control, adjustment in the process of a transaction (Roeck et al., 2019). In the literature, a mathematical model based on M/M/1 queue model has also been developed to assess the processing time required for transactions (Srivastava, 2019).
c. **Resource Based View (RBV)**: A company can attain a competitive advantage with possession of scarce resources and is able to protect them, assuring absence of substitutes. Blockchain enables reallocation of important resources and creates new areas of competitive advantages. Thus, RBV becomes an important theory for blockchain related studies.
d. **Network Theory (NT)**: Exchange processes and adaption processes help a company to establish stable yet changing relationships with a firm which are a mandate to gain access of external resources. Company needs to establish a cooperative and trust-based environment to endure in the long run. Blockchain changes the nature and quality of business relationships due to increased transparency in information and trust. This will create another "network" and business environment. Hopefully, if trust is well-established via blockchain, it will create another revolutionalized scenario.

6.2. Social impacts

6.2.1. Smart contracts for societal impacts

Smart contract, which are automated computer programs that are triggered to transfer digital assets upon meeting certain trigger conditions, is the core technology used in the application of blockchain in the humanitarian aid field (Al-Saqaf and Seidler, 2017; Galen et al., 2019). Corruption is a major problem in many third world countries, with multiple middle-men such as NGOs, local governments, etc. Smart contracts can help eliminate corruption by providing faster and less costly transactions with high transparency. Illegal, unreported and unregulated (IUU) fishing is another area that may benefit from the use of blockchain technology. For example, fishing of Pacific Tuna is increasingly being done by illegal fisheries with the use of slave labours. Blockchain technology can help fight these illegal activities for retailers through better traceability of the origins of the fish and make sure only legally sourced tuna fish products are sold (WWF-New Zealand, 2019). Taking the IUU example further, blockchain technology can help enforce labour and environmental standards in companies across the world through crowdsourced accountability. Companies like the American apparel company Levi Strauss & Co. have started to develop a blockchain-based system designed to augment outside auditors of factory health and safety with self-reporting by workers (Chavez-Dreyfuss, 2019). These are all beneficial to the society with high ipacts.

6.2.2. Cryptocurrency

Another societal impact of blockchain technology in SC operations is to (i) motivate customers to recycle through reward programs such as cryptocurrency tokens (use cases: social plastic project and RecycleToCoin app); (ii) support commitment to incorporate blockchain technology that can be added to values, vision and mission of the companies for increased and better participation; (iii) change policies which can create an ecosystem for companies to incorporate such technologies for better outcome in business operations (Saberi et al., 2019).

6.2.3. Smart cities and sustainable development

Blockchain for smart cities and its sustainable development is another area which could enhance the governance and citizen engagement, education, culture, science and innovation, health and safety, economy, transportation, energy, water and waste management, built environment, natural environment, and information and communications technology (ICT) (Shen and Pena-Mora, 2018). These are critical to the society and shape the future of human culture and lives.

6.2.4. Sustainability and circular economy

SC sustainability and circular economy are two important timely research domains that have started implementing blockchain technology for the green and societal impacts. The blockchain supports the link among the parties in the entire food SC from the source to the consumers. It helps to eliminate the problems such as food adulteration, ensure high resolution of food safety issues, improve management with respect to quality issues and reduce the social chaos caused by uncoordinated situations. Use of blockchain as a tool for industry 4.0 can help to improve the "product return management in reverse SCs" and waste reduction by effective tracing of materials that eventually drive the operational efficiency and promote cleaner production considering reuse, refurbishing and remanufacturing to achieve sustainable reverse logistics and circular economy goals. For example, the data driven decision making in e-commerce reverse logistics is the next big challenges for e-commerce industry for effective and efficient "product return management" (Dutta et al., 2020) and blockchain implementation in last mile delivery can play a crucial role through the triple bottom line support, namely, value recovery, reuse and recycling. Implementation of blockchain along with big data in agriculture and food SCs can help in the reduction of food wastage and recycling in the circular economy including food safety, since all the parties have real-time information regarding all the products available in the market (Kamble et al., 2019a; Kittipanya-Ngam and Tan, 2020). Also, it would potentially aid in keeping a check on soil nutrients, irrigation management, quality management among others (Kshetri, 2019).

Blockchian can also enable monitoring of on-road vehicles and city transportation and help in reduction of carbon emissions and improve environmental impacts. The quality of life in general can be improved by applications of blockchain technology for enabling sustainability by reduction in exhaust gas emissions, favoring proper and environmentally-friendly urban development and limiting food wastes (Astarita et al., 2020). Blockchain for sustainable and green SCs is one of the most critical topics in recent times (Shen and Pena-Mora, 2018). It indicates that the SC provenance, value of circular goods, and environmental sustainability can be enhanced by blockchain technology (Kouhizadeh et al., 2019). Table 5 provides several societal impacts of blockchian enabled SC operations and logistics services including some other sectors relevant to the society.

6.3. Challenges

Applications using blockchain are increasing at a fast rate, but interoperability is a problem, leading to standardization issues (Casino et al., 2019; O'Leary, 2019). Blockchain integration with SC increases visibility across the entire value chain, reduces paperwork and human errors, ensures transparency amongst all parties, enhances security of data, complements IoTs, helps identify counterfeit products, and enables efficient traceability and management (Tijan et al., 2019; Pournader et al., 2020). However, whether blockchain systems should be standardized and be compatible with one another deserves deeper explorations.

6.3.1. Organizational challenges

While benefits are manifold, several inter-organizational, intra-organizational, technical and external barriers hamper full-scale adoption. The various factors that influence adoption are organizational readiness, technical expertise, digital infrastructure, scalability issues, financial resources, legal and regulatory compliance, organizational resistance, performance expectancy (Min, 2019), standardization, security of models (Lacity, 2018), and country of business (Queiroz et al., 2019). Local and national laws often become a roadblock for blockchain innovations and hence there is an increasing need for involving government agencies for rules and regulation compliance while developing new blockchain based solutions (Chang et al., 2019b). Also, consumer awareness and empowerment plays a major role in the adoption of a new technology as consumers as well as employees will have to change the way of purchasing/operations (Sylim et al., 2018). Among these, organizational readiness and regulation are the least explored areas and need to be changed drastically in order for blockchain to have a broader reach and coverage (Hughes et al., 2019).

Observe that the legal aspects of business and regulatory framework are inevitable. The implementation of smart contracting systems in logistics by taking into account of all these issues must be researched further in the future (Philipp et al., 2019). Hence, this should be kept in mind while designing the blockchain platforms for effective performance of smarting contracting. The reluctance of

Table 5
Blockchain applications in different sectors and their societal impacts.

Sectors	Societal impacts
Financial services	- The emergence of cryptocurrency based secured and tampered proof transactions (e.g., bitcoins) will influence the society and people's lives with multifold benefits to their credit accounting and financial services - Helps in enhanced asset management, trade finance and smooth VAT services
Technology sector	- Enhance robust cybersecurity and improve the scalability of cloud networks - Covert the tradition ERP systems into a super secure structure and development of sustainable SC
Manufacturing sector	- Helps in transforming the manufacturing ecosystems through a shared and distributed systems - Enhance the real time transparency, agile manufacturing, enable product customisation, smart automation and improvement in employee empowerment
Shipping industry	- Creates a verifiable and distributed shipping system to integrate and interconnect all the business activities - Reforms the maritime industry by organizing projects, people, information, payment and communication in safer, smarter and more efficient ways - Ensures minimum delays in real time transactions, transparency of transactions from remote areas, extra vigilance for data confidentiality, transaction validation and fraud management - Blockchain based solution with IoT enabled smart containers, smart contracts can be used to manage shipments, automate payments, track violations and make the whole SC efficient
Automotive industry	- Benefits include integrated, personalized and on-demand services through a connected, shared and autonomous environment - Enhances automated maintenance services, ability to audit records, transparency, execution speed and cost reduction
Energy sector	- There is a good potential to transform the energy sector by enablingmore transparent, secure and efficient electrical energy transactions - Helps ensure energy is well-utilized, well-supplied and the allocation is efficient and transparent - Users will have access to low cost, high quality energy at all times and places
Healthcare sector	- Helps to improve better usage of healthcare data, patient outcomes, lower costs, enhance compliance and ensure security - Support many healthcare operations such as neuroscience, EHR medical, genomics medicine, biomedicine, clinical trials, vaccine supply and traceability - Helps monitor for SCs of drugs, blood, etc. for temperature sensitive drags
Agriculture and food sector	- Increases the transparency and security of transactions, privacy of enterprise information and achieve proper resource allocation among all stakeholders in the agriculture sector - Helps in establishing a strong end-to-end link between the sources or farmers and big buyers. - Democratizes the supply process that eliminate food adulteration, ensure food safety and quality, and enhance the social sustainability - Helps to establish a redit evaluation system supported by blockchain technology to strengthen the supervision and management in the food SC
Aviation sector	- Blockchain integrating with RFID and IoT can transform the aviation industry with better tracking of ports, more efficient scheduling of air logistics and transportation. - Blockchain also helps mitigate risks and high end security which eventually benefits the human life and the society
E-commerce sector	- Helps in transforming the e-commerce sector by enhancing the payment systems, e-procurement, SC risk management, last mile logistics and data security
Education sector	- Helps through decentralized data distribution, data immutability and disintermediation that enhance the institute's reputation, trust, productivity and review process that creates high societal impacts among the peers
Entertainment and tourism sector	- Reduces the overall cost of infrastructure for ICT, enables tamper resistant transactions, reduces systematic risks for tourism industry - Enhances the efficiency for virtual reality-based tourism - Helps in securing the ownership and digital rights, distribution rights and secure transaction in entertainment sector which directly support the social welfare

organizations to share the information on a global platform is still a major obstacle. Issues like lack of common standard across different organizations act as a hindrance in scaling up and would lead to interoperability issues (Sharma et al., 2018). The government and industry both need to work together for the development of a common standard to solve the issue.

6.3.2. Technical challenges

Although blockchian is known to be tamper-proofed data storage infrastructure and one of the highly secured transaction platforms, the block size in the blockchain can be a limiting factor in terms of performance and efficient utilization of the platform (Li et al., 2019c). Some of the technical challenges that are ofen faced while operating blockchain enabled SC operations are listed below (Krishnan et al., 2020; Casino et al., 2019; O'Leary, 2019).

Scalability: Some of the major scalability issues in blockchain implementation are chain limitations with ever increasing number of transactions, big block sizes, long response time and high fees. When the number of users is increasing day by day, the challenges in blockchain scalability are also increasing.

Privacy: Though the data security, storage and management are some of the key features of data management in blockchains, data privacy and confidentiality are still sources of problems. This is especially true for the public blockchain when data and many privacy related details are stored as a public ledger.

Interoperability: Exchanges of information for different block transactions or making use of information by different blockchain systems are an important interoperable architecture in blockchains and. When the number of blockchain applications is growing at a faster rate, interoperability issue is also getting more serious

Product provenance: Product history, origin and traceability in blockchain are termed as product provenance, which is a critical part of blockchain. How to properly and accurately present the product provenance information is critically important.

Latency: The transaction rate or each bitcoin block processing time along with security check takes several minutes which shows that blockchain architectures would face serious latency challenges.

Auditing, visibility and disintermediation are some other important features of blockchain technology that require a carefull monitoring for error free verification and auditability, easy tracking and no mediation of third party which can lead to uninterrupted and trusted transactions.

6.3.3. Operational challenges

When it comes to SC operations and logistics management, old challenges like damaging of raw materials and products, erroneous data entry, order mismanagement, etc. are still present. The effective implementation and smooth functioning of blockchain in SC systems would require the proper involvement and participation of varies parties including global logistics partners, operational efficiency, maintenance costs, big data management, and IT support. Apart from these, government regulations on cyptocurrency, data warehousing, scalability and high speed internet connectivity with enormous computing power are real challenges. Blockchain requires every transaction to be processed and validated through each node; and in developing and under developed nations, poor infrastructure and the above mentioned constraints can defeat the purpose of blockchain implementation goals (Min, 2019). Moreover, adaptability, standardization, expandability, and synergy between different technologies are other challenges and need to be researched upon (Sharma et al., 2018; Wang et al., 2019b).

Table 6 discusses some of the challenges for blockchain implementation in SCs (Wang et al., 2019a; Kumar et al., 2020; Hartley and Sawaya, 2019; Allen et al., 2019). Note that in the literature, a unified theory of acceptance and use of technology model has been established to study the adoption factors (see Queiroz et al., 2019).

7. Discussions and future research agenda

Blockchain adoption needs to be studied more extensively and should be explored in more countries, industries and businesses to further identify the most important factors responsible for its successful implementation (Queiroz et al., 2019). A solid reference for adoption framework (identifying, discovering and analysing relevant processes) and organization redesigning process (new business and governance models) should be developed to take advantage of the opportunities posed by blockchain. We have identified and listed topics for future studies in various major SC arenas below:

Table 6
Blockchain adoption challenges in supply chain systems.

Challenges	Explanation
Organizational requirement and readiness	• Lack of understanding of benefits and technicalities involved. • Limited knowledge of the complex technology • Still an emerging technology and hence not many successful implementation references are available • A perception that most problems can be solved using traditional information and database systems and there is no need for blockchain.
Data collection and management	• Assuring integrity of input data is a difficult task • Convincing all stakeholders to share information is a challenge • Organization of such huge amounts of data and making an efficient use of it is a problem
Interoperability of systems	• Multiple efforts are being taken in silos and various blockchain systems are being developed. Standardization of all these and ensuring a smooth interoperability is a must • Otherwise it will make things very complicated and difficult instead of making it simpler.
Cost, security, privacy and legal concerns	• Organization wide technology change and adoption is a costly and time consuming • Privacy and security of models and data needs to be ensured as the technology is still very immature and vulnerable • Regulatory uncertainty can cause a lot of unwanted complications • Potential for organization wide hit if the system fails • Blockchain should be applied selectively after weighing in the economics of implementation in terms of both cost and risk
Transition and integration of people, processes and technology	• It is a huge change in all aspects of an existing business. • Large numbers of stakeholders are involved and changing age old mind-sets, culture and work methodologies are a big issue. • There can be conflicting objectives for different stakeholders. • Intermediators involved at various levels might be eliminated which can create rifts. • Uncertainty and lack of awareness hampers acceptance. • A perception that block chain implementation might lead to loss of jobs

7.1. Blockchain adoption and implementation

There are limitless possibilities for blockchain implementation; however technology is still in its emerging stage. Proper analysis and quantification of the impact of different variables like firm size, industry sector, IT staff, infrastructure and organizational resistance for real world cases are required for its adoption and implementation. Moreover, impact analysis via simulation setup can be done for blockchain implementation to scale it up on a larger platform. Critical success factors accounting for the success of blockchain adoption and implementation should be explored in good details. Further analysis on how the combination of blockchain technology and IoT would affect the SC performance should be conducted (Rejeb et al., 2019). Another need is the exploration on whether a common standard across different blockchain platforms should be developed to link them at the global level (Kumar et al., 2020). The respective pros and cons should also be examined.

Empirical studies and case based studies are encouraged to both researchers and practitioners. For example, start-ups in areas like e-commerce, technology, fin-tech services, online hyperlocal services and retail chains can invest on research and development for the implementation challenges and benefits of blockchain in their SC and logistics services.

7.2. Supply chain reengineering

A sincere effort and attention to standardize blockchain implementation in SC is required so that it can be scaled to a global level and can overcome the regulatory barriers. Implementing product deletion, price tracking, and business process management on SCs in different sectors in real life deserves further studies. Values of SC reengineering using blockchain should be examined in depth.

One of the biggest benefits of blockchain is that it integrates all the SC members into a single secure network. However, blockchain, once implemented in SCs, all the related data will be shared and visible among all the SC partners. This may hence adversely impact the confidentially and relationships among the suppliers and buyers, third party logistics providers and associated SC partners (Pournader et al., 2020). Industry experts, researchers and SC managers must explore this issue.

7.3. Supply chain resilience

Disruptions and SC vulnerability due to the events like natural disasters, strikes, virus outbreak (Choi, 2020b) and operational risks are common and managing the severe impact and consequences of such events on SC networks are always a challenge. Blockchain along with IoT or croudsourcing based social media platforms can help in improving the agility and SC resilience (Choi et al., 2019). For example, effective integration and deployment of blockchain with IoT and RFID can enhance the information management systems and SC security, consensus mechanisms for dynamic data storage, transparency, data protection and reliability. After the COVID-19 pandemic, organizations should rethink and redesign their SC risk management and resilience strategies with more foucs on digital platforms supported by technologies like blockchain, IoT and could computing. The use of robotics under blockchain-based system's control would also be important to reduce disruptions related to virus outbreaks.

7.4. Supply chain coordination

SC coordination is a well studied research area and several extensions are reported in the literature (Cachon, 2003; Li and Zhang, 2008). Blockchian for SC coordination can create a one-step solution for many such problems. For example, with the implementation of goods and service tax (GST) in India, the interstate VAT concept has been abolished. This gives interesting opportunities to FMCG companies to streamline their warehouse management from statewise warehousing to consolidated warehousing concept, and blockchain can play a role. Designing an integrated network for downstream SCs considering different transport modes, route optimization, and inventory policies with different product categories along with proper selection of consolidated warehouses can save huge cost for them. This requires SC coordination among echelons, timely information sharing among the SC partners, transparency and traceability of products movements, and data storage and security. Effective implementation of blockchain can help a lot and have multiple implications of research both for the industry and academics.

For global sourcing, coordination and strategic partnerships under international trades, use of blockchain in SC can be explored. The ownership transfer, cross country trades, information sharing and international transactions without using intermediateries, etc., can be easily managed using smart contracts of distributed ledger technology (Saberi et al., 2019; Pournader et al., 2020).

7.5. Security enhancement

Blockchain aims to be secure and traditionally, it does achieve a high level of security. However, for the future development and wider deploymentof blockchain, ensuring security, especially for cryptocurrency, is crucial. Moreover, the blockchain architecture needs to be integrated with IoTs and cloud computing to achieve its high performance. Being secure to ensure a minimum operational risk is hence essential for the respective blockchain based system (Min, 2019). The case based approach in areas like heathcare SC, Cab services, last mile in e-commerce, and other service sectors can be explored where customer authentication, data confidentiality and privacy, and integrity assurance must be restored with heigest priority. All these issues can be investigated in future research.

7.6. Business process management

Future research should explore how blockchain enables digital trust, demand supply management, confidentiality in customer order process, and interorganizational business process through smart contracts and distributed ledger technology. Inadequate infrastructure and prominent barriers for the adoption of blockchain are still major concerns for various industries. Issues like lack of understanding of blockchain implementation, data storage centers and maintenance costs, scalability issues, data ownership issues, lack of top management and organizational support, trained technical staff, trust among SC partners, and legal challenges are some of the key barriers. Supply chain operations managers should understand and do in-depth research on the cause-effect relationships, influences and dependencies among these barriers while implementing blockchain in their business settings.

SC finance is another theme which is emerging in recent days. How the financial instruments are involved, finance various SC partners within the network, and support the movement of capital behind the physical SC are all criticallu important. Possible research can hence be conducted on how digital currency and smart contracts can help instant payments, tampered proof transactions, transparency and reduce transaction costs, and improve business process management (Bogucharskov et al., 2018; O'Leary, 2019).

Some interesting research topics include: Once bolckchain is enabled in SCs, whether the SC echelons such as distributors, wholesellers, agents and intermediators would still add values or not? Whether it is still important to have supports from banks for financial transactions or not? Are accounting and auditing at individual echelons and parties of the networks still required or not? With such decentralized systems, how will different companies build the identity or maintain their reputation among the peers? Will bolckchain help eliminate corruption issues in many SCs? How will bolckchain along with IoT enhance humanitarian SC in emergency relief operations? How will blockchain address the legal matters, conventional laws and jurisdiction, privacy, data sharing regulations, and intellectual property rights in a decentralized network? (Wang et al., 2019b; Queiroz et al., 2019). All these deserve deeper research in the future.

7.7. Social sector and supply chain sustainability

Blockchain can create high impacts to society. This is a critical area to be examined. In particular, sustainability improvement using blockchains needs to be studied more at different organizational levels: strategic, tactical and operational levels to understand the most relevant factors affecting the adoption of blockchain technology in sustainable and ethical SCs.

For a sustainable SC, culture among the partnering firms is very important. Every organization differs in terms of SC analysis and tracking of transactions. Blockchain and IoT applicability must be understood in the industry context with a special focus on the respective norm and culture, before jumping on to implementation. For example, for blockchain applications in agro-SCs, there are barriers for adoption in domains such as ownership and quality of data, privacy concerns, platform and technology challenges and overall integration of sustainability goals (Kamble et al., 2019b). These issues must be explored further in details for case to case basis across various countries.

Fostering sustainable reverse logistics and closed loop SC for reuse, refurbish and recycling is an ever increasing research theme, especially for cleaner production and circular economy (Das and Dutta, 2016; Dutta et al., 2016). Use of blockchain and IoT for effective implementation of “product return management” would enhance the reverse logistics practices including social awareness and legislation guidelines. Green manufacturing has been addressed to be the future as it helps the company as well as the environment in the long run. Small and medium enterprises are recommended to implement blockchain technology by forming a logistics cluster and sharing autonomous transportation and warehousing for achieving long term sustainable advantage (Gružauskas et al., 2018). “Physical Internet”, a new concept which can help the SC to solve data trust issues, would provide a larger customer base, and help move towards a more digitized infrastructure. All these woukd benefit the company in the long run (Meyer et al., 2019). Managers can benefit from this when moving towards complete automation.

Therefore, combining blockchian with complementary technologies, such as big data, cloud computing and machine learning, can further augment the effectiveness of blockchain’s applications in SCs and their impact on overall social, environmental, and economical sustainability.

7.8. Sector based research

In previous sections, we can see that blockchain has high potential and impacts on various industrial sectors. Many potential future research areas can be identified. Please refer to Table 7 for more details. Note that some of these future studies are proposed in the reviewed studies, and some are based on our examinations of the real world practices.

Table 7
Potential research in different industrial sectors.

Sectors	Details
Finance	Blockchain technology is not scalable enough to handle the amount of transactions taking place in the finance industry on a daily basis. Also, determining power and access allowance to different entities and actors based on their size and contribution is a major problem that needs to be resolved to garner the benefits of blockchain. Lack of industry wide standardization of also is a hindrance in the adoption of the blockchain based DLT solutions.
Manufacturing	Blockchain can be implemented to improve machine communication and asset sharing so that all the operations can be integrated into a decentralized environment. Further, research should also be made to identify the use cases of blockchain in 3-D printing, product digitalization and distributed manufacturing.Another future scope in the manufacruting sector is to utilize the collaborative efforts from producers, users, and other stakeholders alike for better management of product life cycle (Kiritsis et al., 2014).
Shipping and maritime	Due to lack of complete and integrated information, blockchain adoption remains a challenge in shipping industry. Information flow needs to be improved and a unique blockchain model needs to be designed which will help integrate all the disoriented stakeholders together.
Energy	While current efforts are focused on peer-to-peer energy trading, blockchain technology has the potential to accurately track the energy production and usage assisting in real time monitoring of energy performance and enhancing supply- demand efficiency.
Healthcare	Blockchain must overcome the barriers of organizational preparedness and data ownership to be able to benefit the healthcare sector. The uncertainty surrounding rules and regulations need to be catered. Also, blockchain needs enormous storage capacity which needs to be affordable and manageable to implement.
Food and agriculture	Blockchain can significantly benefit the farmers and other underprivileged sections of the society by reducing the intermediators involved and improve transparency in the process. Blockchain based digitization and traceability can be used in both plants as well as animal food chains. However, the challenges for such an implementation are varied as per different industry needs, skill set of workforce and technical capabilities. But blockchain holds great potential in saving time, increasing customer trust and reducing costs and risks in the food SC (Longo et al., 2019a). Hence, focus is needed to give the blockchain research and implementations in social aspect and direction. A solution can be developed for automated payments and proof of delivery where the parties are paid in cryptocurrencies automatically upon physical delivery of crops (Salah et al., 2019).
Aviation	The future scope of blockchain may include the utilization of the mean variance theory to be applied for the management of flight schedules with varying lead times (Choi et al., 2019). Airport Collaborative Decision-Making disruption management system can be developed to standardize and streamline every decision involved in operation of airport for better efficiency and coordination (Vaio and Varriale, 2019).
E-commerce	Implement RFIDs enabled with blockchain and do a cost benefit analysis through a pilot project in the e-commerce sector. Research needs to be done to understand the implementation and adoption challenges for blockchain in e-commerce so that it can eliminate the issues related to product counterfeiting and tampering of data by intruders
Education	Blockchain can be utilized to eliminate the problem of fake degrees and fake background verifications by integrating all the data together on a single immutable platform which will be much easier and faster to access.
Entertainment and meida	Operations can be made more transparent and secure via smart contracts so as to ensure hierarchy and authority-based access control.
Fashion	Blockchain can be implemented to enhance the poor data quality problem for demand forecasting in the fashion industry of emerging markets.

8. Conclusion

SCM has entered the big data era (Choi et al., 2018; Kuo and Kusiak, 2019), and blockchain technology has emerged as a disruptive technology. It is commonly believed that blockchain has a huge potential to transform the SCs, both global and local, by improving operational efficiency, data management, responsiveness, transparency and smart contract management. With blockchain bursting out on the scene, it can act as a source of competitive advantage for companies, governments and all kinds of organization in the society. Investments are being made by different companies and countries in exploring the new applications with blockchain to achieve a higher operational efficiency. The blockchain industry is also moving toward various areas, including the standardization issue and the way to integrate different blockchain systems together.

This article provides a thorough review of 178 research articles and covers several aspects of blockchain technology in SC and logistics management. It starts with a brief overview of blockchain architecture and its characteristics, as well as some of the important literature reviews on blockchain in SCs and the uniqueness of the current work. As mentioned earlier, the key benefits of blockchain in SCs, various applications of blockchain in different SC functions and operations, and societal impacts are some of the major aspects being covered in this review article, which are under-examined in the prior review papers.

This work also adds values by summarizing the recent developments in blockchain and examining its potential applications in various sectors like healthcare, finance, technology, energy, agriculture, trade, government services, e-commerce, shipping, aviation and automotive sectors. The work has identified and covered all the pertinent research studies published in this field and will significantly help both academics and practitioners to have a better understanding of the related studies. Nevertheless, the managerial implications and related big theories for future developments of blockchain enabled SCs have been discussed. The societal impacts and various challenges associated with blockchain have been examined. All these could act as valuable references for researchers and supply chain managers. An extensive future research agenda in various SC functions and operations, business process management and SC sustainability including potential research in different industrial sectors has been proposed.

Overall, this review article will help researchers and practitioners to better understand and identify SC areas and industry sectors in which blockchian technology could be used. The current trends, challenges, and potential scope for future research opportunities around the use of blockchain for supply chain operations are also discussed.

CRediT authorship contribution statement

Pankaj Dutta: Conceptualization, Writing - original draft, Methodology, Investigation, Visualization, Writing - review & editing, Supervision, Validation. **Tsan-Ming Choi:** Writing - original draft, Methodology, Writing - review & editing, Supervision. **Surabhi Somani:** Writing - original draft, Methodology. **Richa Butala:** Writing - original draft, Methodology.

Acknowledgement

The authors sincerely thank the guest editor and three reviewers for their critical comments which led to significant improvement of this paper. Tsan-Ming Choi's research is partially supported by The Hong Kong Polytechnic University (Project no.: P0009192).

Appendix A

(See Table 8 and Table 9).

Table 8
Summary of the papers studied: Blockchain technology for supply chain functions.

No.	Authors	Major scope/study purpose of the paper
Blockchain overview and adoption challenges in supply chains		
1	Al-Jaroodi and Mohamed (2019)	This paper highlights that the blockchain technology has the capability of resolving bottlenecks, paving way for future research, addressing issues using shared, secured, distributed and permissioned transactional ledgers which have made it inevitable and a forefront runner of the research in various industrial sectors.
2	Chang et al. (2019b)	In this paper, authors present the overview of blockchain in global SC and trade operations through industry reports and scietific articles with its challenges, opportunities and future scope of research. The focus of this paper is on the need of industry, government, and academia working together to harness the full potential of blockchain.
3	Crew (2018)	The paper talks about how blockchain can transform all the industrial and services sectors globally and how beneficial is it to switch to blockchain for firms.
4	Feng et al (2019)	It analyses the potential threat blockchain technology poses in the context of privacy and mechanisms to preserve anonymity along with transaction details.
5	Gurtu and Johny (2019)	The paper reviews the literature on blockchain technology, its trends, implications and the potential value that can be generated in the field of SCM.
6	Juma et al. (2019)	In this article, authors presents a survey document on various applications of blockchain in trade SC and its challenges in SC design while integrating blockchain.
7	Khosla et al. (2019)	In this paper, authors present a basic overview of blockchain technology in SCM and its ongoing popularity in SC applications.
8	Peck (2017)	Assesses the cost benefit analysis for implementation of blockchain technology, its comparison to current data management techniques and the feasibility analysis for it to scale up for future use.
9	Pournader et al (2020)	The authors propose a hypothetical structural model based on blockchain technology for traceability, transparency, trust, and trade.
10	O'Leary (2019)	The paper reviews the applications used for information capture and distribution and the concerns associated with the technology i.e. data independence and multiple semantic models for information distribution.
11	Queiroz et al (2019)	It analyses the application of blockchain in management of future SCs, possible integration and disruptions to be expected.
12	Saberi et al (2019)	The paper summaries the data gathered from respondents on blockchain implementation findings, what encourages and what discourages companies to adopt blockchain technology.
13	Shamout (2019)	This article reviews the papers documenting how blockchain supports SC and logistics industry.
14	Sidorov et al (2019)	It describes that blockchain technology is a decentralized option that ensures higher immutability, transparency, data protection, reliability and lower management costs for RFID as compared to a centralized database.
15	Srivastava (2019)	The efficiency (production and transaction costs) of different types of governance systems closely related to the selection of the most efficient types of inter and intra organizational structures is studied. A mathematical model based on M/M/1 queue model has also been developed to assess the processing time required for transactions.
16	Tijan et al (2019)	It explores the integration of blockchain in SC logistics and management with the use of decentralized storage systems for data.
17	Wang et al. (2019a)	It provides insights on the use of blockchain for SC and possible research directions. It was an early stage review and hence considered very limited number of articles.
18	Casino et al (2019)	It investigates the current position of use of blockchain in various potential fields like SC, data management, IoT, businesses, etc. It also identifies the shortcomings of implementing blockchain and the roadblocks.
19	Firica (2017)	Pros and cons are reviewed for blockchain adoption in different industries and service sectors.
20	Hoek (2019a)	This paper introduces a framework for conscious adoption of blockchain for the SC problems and emphasizes the need to understand that blockchain might not be right technology for all SC problems.
21	Kumar et al. (2020)	The paper offers a systematic way to weigh in the economics of block chain technology adoption in terms of cost and risk from the context of a food SC. It recom mends that the blockchain solutions should be used selectively and should not be applied in all the business problems.
22	Surjandy et al (2019a)	This article explores the 48 critical parameters for blockchain adoption in SCM.

(continued on next page)

Table 8 (*continued*)

No.	Authors	Major scope/study purpose of the paper
23	Zheng et al (2019)	The paper studies the risk decision making problem faced by a three-level spacecraft SC composed of a spacecraft builder, supplier, and logistics service integrator.
Supply chain reengineering		
24	Chang et al. (2019a)	It states that blockchains enhance the transparency and visibility and achieve synchronization of tracking information in all arenas of businesses. Moreover, process automation and elimination of intermediaries with the use of smart contracts further helps in process re-engineering.
25	Chen and Wang (2020)	The paper introduces fractional calculus to establish a three-dimensional SC game model and uses the non-linear dynamics theory to analyse it.
26	Dolgui et al (2019)	It studies the development and testing of a blockchain based dynamic model and computational algorithm using control for the smart contract design in the SC.
27	Epps et al (2019)	The paper explores standardizing blockchain implementation in SC so that it can be scaled to global level and can cross the regulatory barriers.
28	Gao et al (2018)	Blockchain is implemented in the SC for its distributed ledger technology which provides a way to organize records in a distributed manner through consensus mechanism.
29	Ivanov et al (2019)	SC risk analytics framework was formed to analyse the connection among business, information, engineering and gather an analytics perspective on digitalization in SC.
30	Khare and Mittal (2019)	The theme of this paper is on blockchain and IoT based solutions to enhance trust in organic product's SC.
31	Kim and Kim (2018)	This paper evaluates the utility of private, secure blockchains for securing and improving the cold blood management system.
32	Lu and Xu (2017)	Blockchain technology is used for tracing the product origins across complex SCs through development of origin chain which is secure, transparent along with flexibility to accommodate regulatory changes in compliance.
33	Perboli et al (2018)	Blockchain implementation into SC needs to be done in a step wise manner with first analysing the needs of all the stakeholders. GUEST (GO, UNIFORM, EVALUATE, SOLVE, and TEST) methodology is proposed to improve the returns from integrating blockchain with SC.
34	Tan et al (2018)	This paper studies how blockchain has reduced the load at China international trading port by integrating and sharing information and data with all the actors involved.
35	Treiblmaier (2018)	Blockchain implementation in SC leads to structural and managerial changes which is studied based on four theories: principal agent theory (PAT), transaction cost analysis (TCA), resource-based view (RBV) and network theory (NT).
36	Wang et al. (2019b)	This paper investigates the perceived benefits, potential sectors transformed and the challenges for implementation of blockchain in SCs.
37	Wu et al (2017)	In this paper, authors propose a framework for online tracking of information of items during their shipments.
38	Yoo and Won (2018)	It states that blockchain can enable the customer to know the exact pricing from raw materials to suppliers and disclose all the data to the public domain. This will result in dissemination of honest information by all the stakeholders thus ensuring price transparency.
Supply chain traceability		
39	Behnke and Janssen (2019)	The paper identifies the critical boundary conditions for sharing assurance information to boost traceability. It implies that only by modifying the SC system and fulfilling the boundary condition can lead to successful blockchain usage.
40	Choi (2019)	Diamond authentication using BTS platforms is analyzed in the paper. A digital thumb print of the diamond is generated with the help of blockchain which can then be used to get all the details associated with the diamond. The traditional stores are compared with the BTS platform for diamond sales by building analytical models and the results are analyzed.
41	Cui et al. (2019)	Here, authors examine an electronic products SC for its transportation of chips with integration of blochchain technology for security and traceability.
42	Fernández-Caramés et al (2019)	In this paper, inventory data collected through UAVs is verified using blockchain which brings transparency and data trustworthiness. The system's performance was tested in a real-life warehouse.
43	Figorilli et al (2018)	Blockchain is implemented to provide end to end traceability for wood SC from the moment of cutting to transforming it into usable material.
44	Hastig and Sodhi (2019)	In this paper, authors present a comprehensive study on blockchain for SC traceability, its success factors and overview of contemporary studies.
45	Kshetri and Loukoianova (2019)	It discusses about cases in automobile, food and other industries to highlight the crisis and huge losses incurred due to lack of visibility and traceability in SC, which can be solved using blockchain.
46	Liu and Li (2019)	It involves developing a block chain-based framework to solve the product and transactions traceability issue in SCM. It also discusses the effectiveness, security and implementation issues for the solution.
Security enhancement by blockchain		
47	Engelenburg et al. (2019)	The focus of this paper is to design a structure for data sharing between businesses and government based on certain protocols.
48	Fu and Zhu (2019a)	Here, authors use blockchain and big data technology for integellient logistics systems for operational efficiency and data security.
49	Fu and Zhu (2019b)	Authors propose that blockchain manages risk in SC through its application in the big production enterprise SC, where each of the business subject's problems is resolved and fraud detection is done more robustly.
50	Kim and Laskowski (2018)	Blockchain and IoT help in granular provenance of physical goods which are produced and transported in complex, inter-organizational or internationally spanning SCs. This is studied using traceability ontologies and constraints on Ethereum blockchain.
51	Kshetri (2017a)	The author proposes that blockchain strengthens cybersecurity and gives better performance in security, privacy protection and asset management than centralized IoT systems.
52	Liang et al (2019)	The paper examines a blockchain based new data management scheme to improve credibility and prevent performance risks in trade data processing.

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Table 8 (*continued*)

No.	Authors	Major scope/study purpose of the paper
53	Meng et al (2018)	This work proposes that blockchain helps create and collaborative intrusion detection systems where the product ids can interact with each other and exchange data. The protection and security feature of blockchain ensures integrity of data storage and transparency which will guarantee security of the IDs.
54	Min (2019)	It is proposed that blockchain technology can help capture both organizational and network risks associated with any SC due to their structural network of nodes.
55	Montecchi et al (2019)	This article focuses on how blockchain technologies deliver SC provenance by providing certifiability, traceability, verifiability and trackability of product information along the SC.
56	Toyoda et al (2017)	It develops a product ownership management system for anti-counterfeits in post SC.
Adoption and implementation of blockchain in supply chains		
57	Allen et al (2019)	It states that blockchain as a decentralized economic infrastructure can be applied for reducing the trade costs across complex global SCs. Block chain technology has potential to not only make the existing SCs more efficient but also open up new markets and trading patterns.
58	Azzi et al (2019)	The paper describes the integration of SC architecture with the block chain. The benefits associated with the integration as well as requirements, challenges faced in blockchain based SC ecosystems are discussed. Select example cases of two swiss startups are illustrated.
59	Betti et al (2019)	The paper discusses the application of blockchain, and smart contracts being applied to hyperconnected logistics.
60	Christodoulou et al (2018)	In this work, a smart contract mechanism is presented through blockchain for the advantages in logistics.
61	Cole et al (2019)	In this paper, the application of blockchain in the SCM domain is discussed.
62	Garifova et al (2019)	The authors mention that blockchain can help in reducing cost and errors while moving goods in logistics.
63	Goyat et al. (2019)	The authors present several aspects of blockchain implication in SCM.
64	Hald and Kinra (2019)	The paper deals with the effect of blockchain technology implementation on SC performance. A theoretical approach is used to develop propositions to analyse the performance.
65	Hartley and Sawaya (2019)	It investigates the promise of blockchain and other emerging technologies to forecast their potential for adoption and suggest measures to be taken before adoption of the technologies.
66	Helo and Hao (2019)	It explores the applications of Blockchain technology in operations and SCs as well as designing and building a reference blockchain-based logistics monitoring system (BLMS).
67	Hirsh et al (2018)	The paper describes the current as well as future applications of blockchain technology. It also uncovers the outcomes of research work (Project Chain, Project Novum) completed by the panellists.
68	Hoek (2019c)	The paper presents an empirical research on exploration and implementation of blockchain in SC. It also details multiple pilot case studies of companies pioneering block chain technology adoption in SC.
69	Hoek (2019b)	This research paper highlights the outcome from a workshop, attended by managers working in SC domain, on drivers, barriers and focus areas for blockchain implementation in SCM.
70	Hughes et al (2019)	It shows how blockchain can be of assistance to governments for protecting democratic principles. Management of registries, digitization of land right, secure and lawful execution of voting are some ways in which blockchain can help transform government activities.
71	Hütten (2019)	It shows how blockchain technology helps in government service, enhances global SCs and contributes to transformation of ownership.
72	Kamble et al. (2019b)	From Indian perspective, study is done to analyse how well can Indian SCs adapt to the integration of blockchain in SCs. The study was based on three adoption theories – Technology acceptance model, technology readiness index and the theory of planned behavior.
73	Karamchandani et al (2019)	The article provides an impact analysis of implementation of Enterprise Blockchain (EBC) usefulness in service industry. They validate the hypothesis on six SC dimensions namely, supply uncertainty (only for product SC), information quality, mass customisation, service quality, delivery reliability and customer relationship.
74	Kim and Shin (2019)	In this paper, the effects of blockchain in SC activities on SC performance outcomes like SC partnership growth and efficiency are investigated.
75	Lacity (2018)	This paper explores the reason for blockchain research being mainly proof of concept and not being implemented worldwide. It analyses the managerial and technological implications for the same.
76	Li et al. (2019c)	In this paper, authors applies blockchain for SC traceability and security issues for table grape SC.
77	Liu et al (2019)	The paper adopts a numerical simulation to analyze the risk aversion, weighted proportion and the impact of blockchain on the SC.
78	Longo et al. (2019b)	The paper aims to assess the performance, explore the potential for deploying blockchain technology in SC by recreating a simulation model of block chain integrated SC.
79	Mariappan (2019)	The paper discusses the use of blockchain technology at the global level, the problems incurred during implementation and India's policy on it through data gathering and reviews.
80	Martinez et al (2019)	It shows how blockchain can be effectively used for customer order management in operations and SCs. Th resources, dynamic capabilities required for blockchain implementation are outlined.
81	Narayanaswami et al (2019)	Increasing customer demand leads to complexity in the SC. The paper deals with the proposal of software architecture which also incorporates blockchain into the architecture.
82	O'Leary (2017)	It highlights the utilization of cloud based and private blockchain system for gathering and processing transactions in auditing, accounting, SC and other transaction information types.
83	O'Leary (2018)	The paper investigates open information transactions, its implications on different sectors and the use blockchain to provide a single source of truth for all information flow.
84	Pally and Reddy (2019)	It focuses on creation of a general blockchain network to spread information among the participants across the SC. Use cases relating to implementation of blockchain has been discussed.
85	Pankowska (2019)	It explores how blockchain helps interchain management, improves project management, and enhances interchain sustainability, relationship modelling and interchain coordination in different sectors globally.

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Table 8 (*continued*)

No.	Authors	Major scope/study purpose of the paper
86	Queiroz and Fosso Wamba (2019)	It recommends that blockchain technology has enormous potential of managing the current business models in SCs and logistics because all transactions with blockchain are efficient, safer, economic, more transparent and traceable but the adoption is at a nascent stage which is influenced mainly by performance expectancy.
87	Rahmanzadeh et al. (2019)	In this paper, authors use blockchain and fuzzy sets theory to design the ideas registering and tactical decision making of SC.
88	Roeck et al. (2019)	This paper exemplifies through an empirical study that application of DLT in SC has dual effect. While cost saving and dependency-reduction are benefits, the loss in bargaining power (torpedo effect) might prove to be a disadvantage.
89	Schmidt and Wagner (2019)	The paper presents a transaction cost theory perspective of how blockchain might influence SC relations and limits opportunistic behavior, impact of environmental uncertainty.
90	Sheel and Nath (2019)	It states that blockchain adoption can create competitive advantage for a firm by enhancing SC parameters like agility, adaptability and alignment. Empirical study which connects the blockchain with the above SC parameters and competitive advantage of firm fits the model.
91	Tönnissen and Teuteberg (2019)	The paper develops an explanatory model to explore whether blockchain technology leads to disintermediation and what all-intermediary task can be replaced by Blockchain technology in the logistics industry.
92	Wong et al (2019)	It investigates the effect of different factors like complexity, cost, market dynamics, managerial support, relative advantage, competitive pressure and regulatory support on the adoption of blockchain by the SMEs of Malaysia.
93	Xu et al. (2019)	Here, they show how the blockchain can help electronic products SC for its traceability and security for in forward and return management process.
94	Zelbst et al (2019)	This article validates the untapped potential of multiple technologies (RFID, IIoT and Blockchain) utilized in tandem with each other for advancement in SCM through an empirical study.

Table 9
Summary of the papers studied: Blockchain technology for different industries and social sectors.

No.	Authors	Major scope/study purpose of the paper
Blockchain in food and agriculture supply chains		
95	Astill et al (2019)	The paper illustrates the application of Block chain as one of the enabling technology for increasing the transparency, traceability and sustainability in Food SCs. The requirements to be addressed and challenges faced during the implementation are also highlighted.
96	Bumblauskas et al (2019)	The paper illustrates an implementation of traceability in egg distribution SC using blockchain and IoT.
97	Chan et al (2019)	The paper develops a framework for making the agri-food sector SC more traceable and transparent. It also recommended the use of permissioned blockchain above permission less one.
98	Galvez et al (2018)	Food traceability is one of the major steps for building customer trust and upholding the quality standards. The article focuses on the future implementation and challenges which could arise by using blockchain for improving the source traceability in food SC.
99	Kamble et al. (2019a)	The paper identifies 13 enablers that encourage the adoption of the blockchain in agriculture SCs and establishes the causal relationships between them using Interpretive Structural Modelling (ISM) and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methodology.
100	Kittipanya-ngam and Tan (2020)	The article explores the procedures, barriers and benefits faced by food manufacturers in digitizing their SC. It also provided a framework for digitisation and provides the impact analysis of the same.
101	Kshetri (2019)	It focuses on how blockchain can be used to address food safety issues. It can be used to track products, exchange information between parties and handle critical situations.
102	Leng et al (2018)	In this paper, blockchain is implemented on a double chain structure which helps increase openness and security of transactions, privacy of enterprise information and can achieve seeking and matching of resources for all the stakeholders in agriculture sector.
103	Lin et al (2019)	It highlights that blockchain is a necessary technology for food SC to efficiently detect and prevent safety issues and trace the accountability. Blockchain enhances food security due to its features like smart contract, consensus algorithm and irreversible time vector.
104	Longo et al. (2019a)	The paper proposes for design and frequency of updating of the data to be stored on an Ethereum blockchain for traceability and explores the cost in a transaction from dairy farms to end consumers in a fresh milk processing SC.
105	Mao et al (2018)	This paper aims to solve the problem of information asymmetry by proposing a credit evaluation based on blockchain system which will improve the management and supervision in food SC.
106	Mondal et al (2019)	The paper discusses a “proof-of-object“ authentication protocol, blockchain based IoT for a food chain. The blockchain provides authenticate history of products, which can then be used by the interested parties to gain the correct information.
107	Pearson et al (2019)	The authors propose that blockchain DLT technique can be used to securely link all the actors of the entire food SC from the source to the consumer. This can help eliminate food adulteration, ensure high resolution of food safety issues, improve management of quality issues and reduce the social chaos caused by uncoordinated issues.
108	Reddy et al (2019)	It recommends that blockchain as a solution improves the visibility across the SC from farm to store thereby improving the quality, eliminating the intervention of middlemen and improving the efficiency in Indian agricultural economy.
109	Salah et al (2019)	The paper proposes a solution leveraging Ethereum blockchain and smart contracts to improve transparency and traceability in Soya bean SC in a secure, reliable and efficient manner.
110	Sander et al (2018)	Blockchain implementation is assessed through survey reports from customers with a team of the firm's retail manager and the blockchain provider to understand the feasibility of its implementation.

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No.	Authors	Major scope/study purpose of the paper
111	Scuderi et al (2019)	This article states that the agri SC developed today is extremely complex and needs to be digitized and improved with blockchain. Blockchain will bring not only transparency but also help to maintain fair relationship between the small farmers and big buyers and democratize the supply process.
112	Thiruchelvam et al (2018)	The paper analyses the potential of blockchain for providing secure, accurate and real-time cost-efficient SC that will help in fair trade of coffee SC.
Blockchian in healthcare supply chains		
113	Clark and Burstall (2018)	It states that blockchain can be used for enforcing anti-counterfeit manufacturing/ distribution of drugs using traceability and authenticity of pharma SC. Also, its application involves IP protection and registration in pharmaceutical industries to authenticate licensing and provide evidence in case of a legal battle.
114	Drosatos and Kaldoudi (2019)	This study focuses on various issues in the biomedical domain and how they can be solved using blockchain.
115	Jamil et al (2019)	The paper discusses the use of hyperledger fabric based on blockchain to enhance the medical SC and drug records. Smart records are used to maintain transparency. Hyperledger caliper is used to benchmark the system designed.
116	Jayaraman et al (2019)	The authors claim that fragmented nature of the healthcare SC sector causes errors and difficulties in maintaining transparency in processes. IoT and blockchain combined can help to track products in a better and efficient manner.
117	Kirkner (2018)	It states that blockchain technology improves data management by providing faster access to more secure data and ensuring privacy of data, improves patient experience by providing individualistic advices, protects against counterfeit and fraud and helps make the healthcare system more robust.
118	Mackey and Nayyar (2017)	It states how blockchain can help solve the problem of trade in fake medicines in the pharmaceutical industry.
119	Mackey et al (2019)	Adoption challenges for blockchain technology in healthcare sector are studied and found to be interoperability, scalability, managing storage capabilities, social acceptance and standardization challenges.
120	Mattke et al. (2019)	In this paper, authors provide several examples on how blockchain is helping pharmaceutical SC and subsequent benefits for the healthcare industry.
121	Padmavathi and Rajagopalan (2019)	In this paper, authors propose a framework for using blockchain technology for cold chain pharmaceutical products.
122	Radanović and Likić (2018)	Blockchain is used to improve patient outcomes, lower costs, enhance compliance and ensure security, transparency and better use of healthcare data.
123	Srivastava et al (2019)	The focus of this paper is on blockchain implementation and applications in pharmaceutical industry based on detailed secondary research.
124	Sylim et al (2018)	The paper focuses on the development and testing of a pharma surveillance blockchain system which will enhance sharing of information across drug distribution network.
125	Tseng et al (2018)	This paper aims to create transparent drug transaction data using a Gcoin blockchain with inputs from all the stakeholders in the entire SC.
126	Yong et al (2019)	Here, blockchain implementation with machine learning technology is utilized to create a “vaccine blockchain” that could help in countering issues like vaccine expiration and record fraud.
Blockchain in shipping and maritime		
127	Gausdal et al (2018)	The paper explores the feasibility, challenges and possibilities of applying blockchain technology to enhance maritime experience.
128	Grzelakowski (2019)	In this paper, authors discuss the use of blockchain for container shipment in maritime industry.
129	Hasan et al (2019)	The authors propose that block chain-based solution with IoT enabled smart containers; Smart contracts can be used to manage shipments, automate payments, track violations and make the whole SC efficient.
130	Jugović et al (2019)	In this paper, authors show that the possible application and advantages of blockchain in maritime industry.
131	Komathy (2018)	It states that blockchain can be incorporated in the cargo shipping sector to create a verifiable and distributed blockchain shipping system to integrate and interconnect all the business activities (finance, banking, IoT, SC, manufacturing, insurance) in the view of a shipment.
132	Philipp et al (2019)	The paper discusses how blockchain technology enables the Small and Medium Enterprises (SME's) to be integrated into the complex multimodal and transnational SC.
133	Yang (2019)	This paper studies the potential applications, future improvements and factors influencing the intentions to adopt blockchain-based technologies in maritime shipping SCs.
Integration with IoT and industry 4.0		
134	Benčić et al. (2019)	In this paper, authors use the amalgamation of distributed ledger technology and IoT in SCM.
135	Cho et al (2017)	It introduces an efficient method of rule-based voting for non-dependent transaction to overcome low throughput of transactions and block generation rate.
136	Gromovs and Lammi (2017)	This paper talks about the need to revamp logistics education to include emerging technologies like blockchain and IoT.
137	Kshetri (2017b)	It says IoT can be improved by application of blockchain due to its tamper-proof nature and efficient identity and access management.
138	Maiti et al. (2019)	The article determines the benefit of blockchain implementation for measuring service quality in an IIoT monitoring infrastructure, using a finite series blockchain.
139	Qiao et al (2018)	The paper investigates the ability of blockchain to enhance security in dynamic data storage, to reject tampering by unauthorized users and ensure safe and traceable transactions.
140	Rejeb et al (2019)	The paper provides propositions on how blockchain technology can affect IoT. With the increase in the complexity of the SC, the verification of the source and transparency of products become problematic. Pairing of blockchain technology and IoT can better the SC performance.
141	Tang and Veelenturf (2019)	In this paper, authors mention how different technologies including blockchain can help improving industry 4.0 and other logistics services.

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No.	Authors	Major scope/study purpose of the paper
Blockchain in finance sector		
142	Alkhodre et al (2019)	This article discusses the blockchain implementation for developing the new VAT structure for Kingdom of Saudi Arabia.
143	Bogucharskov et al (2018)	It shows how blockchain implementation in trade finance can help reduce processing time for documents, increases number of participants, enhances transparency and reduces transaction costs.
144	Notheisen et al (2017)	It proposes that the transaction of assets like cars, lemons etc can be automated and transparent, tamper-proof records of all information can be achieved using blockchain.
145	Wamba et al (2018)	This article analyses the applications, the advantages and the predicaments of Blockchain in Fintech SC.
Sustainability in supply chain		
146	Kouhizadeh and Sarkis (2018)	The paper tries to understand the feasibility of integration blockchain with green SC and help advance the discussion.
147	Kouhizadeh et al (2019)	Linkages exist between blockchain, circular economy and product deletion. Therefore, information stored on blockchain can be used by companies to analyze circular economy implementation and product deletion practices.
148	Manupati et al (2019)	The paper proposes a blockchain based approach for optimizing both emission levels and operational cost within a multi-echelon SC under a carbon taxation policy for an optimal SC
149	Meyer et al. (2019)	This paper uses the physical internets using decentralized approach of blockchain technology for sustainable logistics.
150	Shen and Pena-Mora (2018)	In this paper, authors explore three espects of city sustainability, namely, social, economic and environment, using blockchain technology.
Blockchain in retail sector		
151	Choi et al. (2020a)	In their study, the authors provide a blockchian enabled service SC for rental platform using product information disclosure game.
152	Miraz et al (2019)	The article proposes a blockchain solution that would increase customer delight and improve performance of retail SC. The article also promised to enable SC managers to perform their tasks more effectively and aid them in decision making processes regarding blockchain implementation in their respective retail SC.
Blockchain in SMEs		
153	Nayak and Dhaigude (2019)	It proposes that the blockchain technology can be utilized in SMEs to transform their SCM into sustainable SCM.
154	Prause and Boevsky (2019)	Blockchain and smart contracts application is explained using empirical study to promote development in rural SCs.
Blockchain in manufacturing sector		
155	Gunasekaran et al. (2019)	This article highlights the integration of emerging technologies like IoT, blockchain, big data analytics for agility in manufacturing practices.
156	Kennedy et al (2017)	It solves the problem of counterfeit products in additive manufacturing by linking chemical signature information using blockchain.
157	Ko et al (2018)	It states that blockchain helps to incorporate the shift to shared and distributed systems in manufacturing ecosystems using a cross enterprise framework which enables higher level of knowledge sharing, saves money, gives more security and builds a scalable and flexible business.
158	Westerkamp et al. (2019)	This paper presents a new methodology to trace the product along with their components using blockchain for manufacturing sector. The products are represented by "tokens", which can be utilized to track the entire journey of a product from its raw material to consumer doorstep.
Blockchain in automotive idustry		
159	Sharma et al (2018)	In this paper, blockchain based solution for creating a distributed framework model is created for automotive industry as it fulfils the requirements like SCM, unparalleled security, evidence integrity and secure storage, mobility solution for resource sharing, automated maintenance services, ability to audit records, transparency, execution speed and cost reduction.
160	Surjandy et al (2019b)	The paper presents a simulation test for a new and robust blockchain integrated SCM system and its benefits in Automotive component tracing.
Blockchain in entertainment and tourism sector		
161	Liao and Wang (2018)	In integrates casinos and entertainment sectors, the major challenges are to leverage traffic, demand and storage allocation which is resolved through the decentralized system of blockchain.
162	Mofokeng and Matima (2018)	The paper explores the capabilities of using distributed ledger technology for advancement in tourism marketing through virtual environments system.
163	Plant (2017)	It highlights on the improvement in digital content infrastructure using blockchain for trust, transparency and efficient management.
Blockchain in analytics		
164	Choi et al (2020b)	In this paper, authors explore how the blockchain helps in enhancing social media analytics for SCM in practices.
165	Dillenberger et al (2019)	It deals with the value analytics on data contained in blockchain. The analytics engine can provide dashboards, predictive models and compliance checking in which AI can be further used on this data.
Blockchain in e-commerce and online advertising		
166	Choi et al (2020a)	Here, authors deploy blockchain technology for optimal pricing strategy in an on-demand service platform by assessing the proportion of risk (seeker, neutral and averse) taking attitude of customers.
167	Isikdag (2019)	It shows that, by using blockchain, the e-procurement expands the marketplace, lowers cost of availability and improves options for both suppliers and buyers.
168	Li et al. (2019b)	In this work, the use of blockchain for e-commerce logistics service integrating with infrastructure support is shown.
169	Parssinen et al (2018)	It investigates the two-fold integration of blockchain with online advertising.
Blockchain in aviation industry		
170	Choi et al (2019)	In this paper, authors highlight the application of Mean-Variation theory to analyse risks associated with SCs in air logistics.

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No.	Authors	Major scope/study purpose of the paper
171	Santonino et al (2018)	The paper explores the feasibility of using RFID in aviation sector for improving component management, tracking parts and enhancing logistics management.
172	Vaio and Varriale (2019)	It analyses the link between the blockchain, operation management, and sustainability issues in SCM.
Blockchain in energy sector		
173	Park et al (2018)	The paper investigates in creating a secure, transparent and trustworthy P2P trading environment for electrical energy transaction.
Blockchain in fashion industry		
174	Choi and Luo (2019)	This paper investigates the role of blockchain and decentralized SC as one of the factor along with government sponsors to enhance fashion industry SC operations.
Blockchain in education sector		
175	Novotny et al (2018)	It shows that blockchain can play a major role in academic publishing through decentralized distribution of data, trust, data immutability and ability of function without intermediary. These characteristics make it suitable to solve the problems of reputation, productivity, peer review processes and predatory publishing.
Blockchain in construction industry		
176	Xiong et al. (2019)	Main objective of this paper is to reduction of delay in information sharing, effective utilization of constraints and payment security in construction SC.
Blockchain in postal service		
177	Yanovich et al (2018)	The paper investigates the ability of blockchains to resolve problems faced by postal service clients who include losses due to stamp fraud with the help of digital assets based crypto stamp.
Blockchain in packaging industry		
178	Yi (2019)	The authors propose a blockchian based logistics model with decentralized and distributed platform in data security and personal privacy for packaging delivery business.

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