Blockchain: Research and Applications 2 (2021) 100027

Contents lists available at ScienceDirect

Blockchain: Research and Applications

journal homepage: www.journals.elsevier.com/blockchain-research-and-applications

Blockchain technology applications for Industry 4.0: A literature-based review

Mohd Javaid [a,*], Abid Haleem [a], Ravi Pratap Singh [b], Shahbaz Khan [c], Rajiv Suman [d]

[a] Department of Mechanical Engineering, Jamia Millia Islamia, New Delhi, 110025, India
[b] Department of Industrial and Production Engineering, Dr B R Ambedkar National Institute of Technology, Jalandhar, Punjab, 144011, India
[c] Institute of Business Management, GLA University, Mathura, Uttar Pradesh, 281406, India
[d] Department of Industrial & Production Engineering, Govind Ballabh Pant University of Agriculture & Technology, Pantnagar, Uttarakhand, 263145, India

ARTICLE INFO

Keywords:
Blockchain
Industry 4.0
Information
Data storage
Manufacturing

ABSTRACT

Industry 4.0 involves innovations with upcoming digital technologies, and blockchain is one of them. Blockchain can be incorporated to improve security, privacy, and data transparency both for small and large enterprises. Industry 4.0 is a synthesis of the new production methods that allow manufacturers to achieve their target more rapidly. Research has been conducted on various Industry 4.0 technologies like Artificial Intelligence (AI), Internet of Things (IoT), Big data, and Blockchain, and how they could create significant interruptions in recent years. These technologies provide various possibilities in the world of manufacturing and supply chain. Blockchain is a technology that has gained much recognition and can enhance the manufacturing and supply chain environment. Various fields now have fascinating insights into the advantages of blockchain. Several research articles on "Blockchain" and "Industry 4.0" from Google Scholar, Scopus, and other relevant sources are identified and reviewed for this study. This paper discusses the major potential of Blockchain in Industry 4.0. Various drivers, enablers, and associated capabilities of Blockchain technology for Industry 4.0 are discussed for insights. Different Industry 4.0 spheres/sub-domains for Blockchain technology realisation are also discussed. Finally, we have identified and studied fourteen significant applications of Blockchain in Industry 4.0. It is a range of new developments and hope for immense opportunities that are changing Industry 4.0. This technology would work to achieve amplified outcomes and work individually to enhance the process.

1. Introduction

In the current scenario, it is necessary to understand blockchain and its value for the effective implementation of Industry 4.0. Some fields have prospective advantages for blockchain, like financial transactions applications in which blockchains can provide trust. Foreign currencies and fiat currency problems are excluded, and a controlled supply transaction may take place. The product itself and its assembly's identification part can also be linked to other areas of Blockchain in Industry 4.0. It provides a reminder where the ability to recognise goods with the defect may be beneficial. Here, blockchain will protect all the details about a product: its sub-assemblies, parts, sales paths, etc. It reduces the expense and interruption of retrieval at any time in the supply chain. New data have been gathered by cameras and sensors that could be used to construct the Blockchains network. It gives us access to more knowledge than a person would gather in a short period [1–3].

In order to maintain end-user support, there must also be a corresponding structural transition within an organisation. Blockchain is one of the most influential technical breakthroughs in various fields [4,5]. This technology is developed remarkably in recent years and provides many applications in manufacturing [6,7]. It is used closely along with terms such as intelligent factories and Industry 4.0. Blockchain refers to a decentralised, encrypted, distributed ledger for filing computers that allow tamper-proof, real-time logs to be created.

In Industry 4.0, several elements are still not well described and not fully understood. This new technology will ensure that the future effects of intelligent manufacturing solutions are amplified. The early sales experiences and the current deployments have been learned a great deal. It provides an inclusive distribution strategy, implementing and incorporating these emerging innovations being promoted and supported as resources to meet broader business goals. It could help SMEs (small and medium enterprises), in particular, to defend their inventions since

* Corresponding author.
E-mail addresses: mjavaid@jmi.ac.in (M. Javaid), ahaleem@jmi.ac.in (A. Haleem), singhrp@nitj.ac.in (R.P. Singh), shahbaz.me12@gmail.com (S. Khan), raje.suman@gmail.com (R. Suman).

https://doi.org/10.1016/j.bcra.2021.100027
Received 1 May 2021; Received in revised form 24 June 2021; Accepted 11 August 2021

blockchain may make the patent environment more straightforward, transparent and less intermediary. This would encourage competition between companies which has more difficulty in accessing the world of patents. It will allow individuals to generate green energy from a freely negotiated arrangement [8–10].

This technology is exceptional and avoids transactions intermediaries, potentially providing an efficient and cost-effective flow of goods and services. This record is connected to the previous block and cannot be changed or altered in the future. An open, participatory space where anyone can read and write transactions, known as non-authorised, is a decentralised forum. In comparison, blockchain is built for particular users with the advantage of reading and writing to an enclosed network. It is the main difference in the position of consumers and incentives to interact with the system among a private and a public blockchain. The supply chain is a dynamic structure comprising multiple businesses that work together to satisfy customers' needs by adding value from the raw material level to the final product. The main chain is supported by the secondary and tertiary chains that co-operate to form an ecosystem, the supplies chain network [11,12]. Transactions and information transactions also create the complexity of the chain are required to balance. It is essential to believe that blockchain provides continuity and traceability across the supply chain. This paper aims to study the significant potential role of Blockchain for Industry 4.0. This article addresses the following research questions:

RQ1: To study major benefits of blockchain in the context of Industry 4.0;

RQ2: To identify and study major drivers & enablers of Blockchain technology for industry 4.0;

RQ3: To study associated blockchain capabilities for successful Industry 4.0 implementation perspectives;

RQ4: To study different Industry 4.0 spheres/sub-domains for Blockchain technology realisation;

RQ5: To identify and study major applications of Blockchain technology for Industry 4.0.

1.1. Need for the study

In Industry 4.0 environment, real-time information is needed to create a smooth manufacturing and service system. The limiting factor is processing time, so proper consideration for real-world applications is needed. To maintain record and information, blockchain is the perfect technology which can fulfil major challenges. So, the need of this study is to identify the potential role of Blockchain in Industry 4.0. In business, it is time for blockchain replenishment to increase transaction efficiency. Blockchain-empowered sustainable manufacturing in the industries helps for product lifecycle management in Industry 4.0. This technology-enhanced smart factory and has the potential to serve information security [8,13]. In manufacturing environments where risks are lesser, this will flourish and provide a better safety level to processes. However, substantial work must be performed with the platform before the organisations accept blockchain for implementation. The risk level can be minimised, and since the technology is continuously evolving, organisational executives must recognise the beneficial impact of this technology on their enterprise. Industry 4.0 involves an improved degree of faith and privacy. Some blockchain studies related to Industry 4.0 are also available but they are focusing on the specific aspect of the industry 4.0. For instance, Leng et al. [14] have conducted a review to discuss how blockchain can overcome potential cybersecurity barriers to achieving intelligence in Industry 4.0. In this study we have focused on various drivers, enablers, and associated capabilities of Blockchain technology for Industry 4.0 that are holistic in nature. Here blockchain comes in to satisfy the industry-specific requirements of Industry 4.0 [15,16].

1.2. Blockchain

Blockchain can be defined as a decentralised, distributed directory driving smart contracts and providing the opportunity to traceability aid, record management, automation for the supply chain, payment applications and other business transactions. Blockchain provides a record of almost real-time replicated between a network of business partners and is unchanging. The process takes information that would have previously been stored in the Enterprise Resource Planning (ERP) of the company. It now makes it available in a distributed network of records across disparate companies. Several benefits of blockchain enable organisations to better understand their customers, particularly on the demand side. Data analytics and Artificial Intelligence (AI) have well-understood cases of application. It can also reach a glass ceiling when it comes to technological viability, but several businesses strive for convenience. It improves the protection and efficiency of procedures and requires more stamina and resilience than accelerated financial consequences [17,18].

In technology circles, the blockchain is used as a permanent distributed directory to record all value transactions. The organisation has total ownership of the blockchain, other than the nodes that make it superior to other data storage technologies. Each node participating in the transaction would have access to the ledger from multiple devices. This enables decentralisation and network-wide autonomy to build trust and confidence in the transaction ecosystem. Participants initially review all transactions connected to the blockchain. Blockchain technology, sometimes known as distributed ledger technology, is a relatively new form of a database for transaction information stored in a decentralised and transparent manner. The database is run by a network of computers called nodes, so there is no single-point-of-failure, and information can be accessed in real-time. The industry is correctly in line with the concept of the influence on the market of blockchain technologies [12,19,20]. It allows users to preserve their exclusive and unchanging identity documents without their permission that nobody can read or view.

2. Industry 4.0 and its significant advancements

Industry 4.0 is the first great transformation that has progressed from a technologically focused to an advanced one and which would rely on different cornerstones, including the openness of knowledge, assistance, and interconnections. Blockchain technology has begun to hit high on the consumer and has also greatly influenced the production sector. In terms of blockchain technologies, there has been much development in the industry and more advantages. Companies are now discussing more composing topics such as creating and producing commodities on demand, dematerialisation, and disintermediation, rather than software, algorithms, and automation robotics. Integration of AI and blockchain will affect various factors, such as safety and transparency. Blockchain can solve a variety of challenges in a modern manufacturing environment. The prevalent distribution of AI and blockchain integration would also stimulate Industry 4.0 [21–23].

Over the decades, there has been automation. The norm is automation in high volumes of manufacturing lines of consumer, pharmaceutical, and other products. Even in areas such as car manufacturing, huge robots are capable of carrying intricate and risky jobs and large final goods. The distinction is that automated monitoring and improves automation. Collaborative robotics operate for employees and are now used to conduct inspection tasks and remove any subjectivity that may otherwise be put into the operation. Visual inspection cameras are now paired with robots. This technology can provide better results than conventional approaches. Industry 4.0 technologies facilitate the role of existing workers in the most efficient installations. The IoT (Internet of Things) is the deployment of sensors of all kinds embedded into the data collection process [24,25].

Industry 4.0 technologies have vast computing and storage capabilities that are detected, authenticated and linked via a cloud server. The high storage and operating costs of integrated cloud providers make these IoT technologies extremely costly. With the rise in IoT and wired computers, these costs are increasing considerably. Not all organisations will also be able to effort IoT cloud solutions. Nevertheless, these problems can easily be solved with a transparent solution like blockchain. In

order to process the tremendous volumes of transactions between connected devices, implementing a structured peer-to-peer connectivity model would reduce the expense of planting and retaining massive consolidated data centres. In addition, it distributes the demands of computing and energy for many IoT computers. The industries are now able to solve various problems with blockchain. Blockchain's transparency will allow all stakeholders to access and control the information related to all phases of the production [26–28].

Industry 4.0 gives us a new economy in which creativity is one of the cornerstones. This new paradigm is built on an entirely digital world that transforms the present business model based on ideas that change the game. The transition to Industry 4.0 has brought with blockchain a range of emerging technologies. This technology helps cyber-physical networks more efficiently and autonomously. It can detect streamline manufacturing processes, amongst other advantages, in order to minimise energy consumption. AI approach will evolve, and a medium where directly involved consumers can share information and interact ultimately to achieve various goals. It was the advances in big data that led to the AI Revolution. It allowed companies to organise a vast dataset into organised components that computers can handle quickly [29,30]. Around the same time, this importance of data has promoted progress in blockchain because its distributed directory is a revolutionary way to store data alternatively and effectively.

3. Drivers & enablers of blockchain technology for Industry 4.0

Smart factories, smart products, supply chains, and smart solutions are some of the quality drivers and enablers been employed to develop blockchain technology for their specific services from industrial perspectives. These conceptualised drivers and enablers are further subcategorised based on the utility of various smart tools and kits: IoT, robotics and AI, cybersecurity, three-dimensional printing concept, and cloud database, augmented/virtual reality, etc. Fig. 1 is showing the various drivers and enablers of blockchain technology in umpteen spheres of industry 4.0. The productivity, quality products, utmost customer satisfaction, precised services, etc., are the significant features of blockchain technology towards Industry 4.0 applications [14,31,32].

Blockchain has many technological implementations and continually introduces innovative applications. There is a growing global interest in the use of blockchain technology in the manufacturing sector. In blockchain applications for supply chain tracking, auditing, and multiple startups are investigating. Initially, blockchain is only one technology that embraces all cryptocurrencies used to understand future requirements. The tremendous improvements would occur in the internet networks themselves after further research. Technology has consistently advanced further, and a blockchain type has developed dramatically. Thus, blockchain has been widely used as a distributed ledger technology; this technology built a chain of information and collected data and validated in the block. These blocks are checked and added in previous blocks to the transaction and knowledge string [33,34].

A new way of thinking and an ambitious and agile strategy are required to unleash blockchain's full potential. Any market leaders in the manufacturing sector should use blockchain's intrinsic features to fix fields that were previously obstacles to technical development. This involves blockchain's intrinsic safety and impossibility to modify some content until it has been authenticated and processed in a block and decentralised workflows to make communication and accountability easier. Intelligent contracts are inserted alongside the ledger on the blockchain network. Smart contracts have many advantages as they allow business processes to begin automatically. Reduction and more accountability can be accomplished by reducing the transaction costs. Databases and conventional applications are available, which can also meet most demands using blockchain. Implementing blockchain technology can be helpful, especially if several transactions connect [35–37].

The public sector is looking at the potential of blockchain to serve as the official registry for citizen-owned assets like buildings, houses, and vehicles. Blockchains could also facilitate voting, reduce fraud, and improve back-office functions like purchasing. This focuses on future business transactions, data management, and how decisions are taken. Furthermore, in every industrial setting, businesses must keep track of the way parts work. In all these cases, blockchain will provide the traceability of the operations and actions of any company. Companies should also optimise the end-to-end management of the supply chain, including commercial logic and data collected from IoT sensors, guarantee the trust and minimisation of fraud [38,39].

An actual supply chain centred on the blockchain is different, since consensus among all stakeholders can be achieved. Without the need for external certifying agents and thus fostering trust between customers and

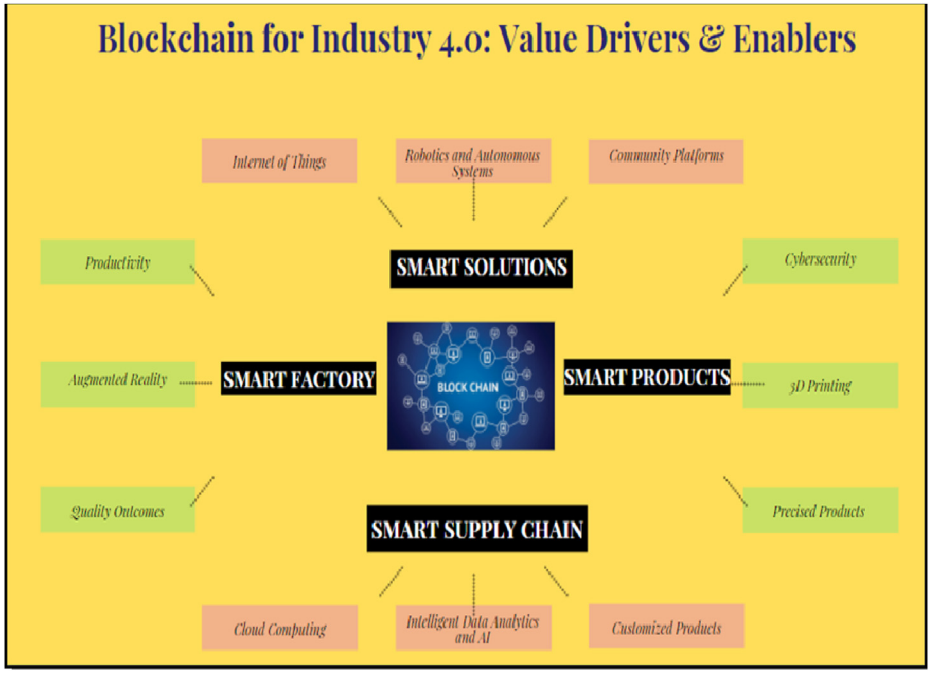

Fig. 1. Various key drivers & enablers of blockchain for Industry 4.0.

stakeholders, data will become a significant asset in this modern industrial process management. There are mechanisms available to ensure, also to establish coordination processes between various factories. With an increasing number of businesses, blockchain is used in various markets and industry sectors. Blockchain technology improves accountability and efficiency across the supply chain. Companies use applications to map and trace content from the source, show authenticity and origin, carry forward recalls, and speed up goods movement in almost every industry. The data is encoded in the blockchain and modified as it passes through the supply chain with new information [40–42].

Demand for blockchain applications is rapidly growing in various industries; the automotive sector is more inclined to introduce blockchain technologies. In current manufacturing methods, the supply chain will operate in many industries and many countries. This will make the innovative approach to increase productivity and pursue individual events more complex. The linked essence of Industry 4.0 makes the copyrighted digital design data easy to share, improving production processes consistency. Intelligent contracts carry out pre-programmed orders, provided that a series of terms and conditions previously negotiated are complied with. Blockchain enables smart businesses to reduce high transaction costs and considerably speed up turnaround times in the Industry 4.0 business [43,44].

In Industry 4.0, the programme, computer, and machines are typically highly related. Protection of sophisticated industrial networks and simplified physical access systems is a top priority because cyber-attack also threatens them. The traditional network isolation and central compliance cyber-security models need to be replaced by distributable, rigorous, scalable, and adaptive models using stable, public-key encryption schemes and data-safety hash algorithms. Blockchain provides edge protection and allows authentication of the machine to machine and human-machine, stable data share, life cycle management, access control compliance of devices, and self-sustaining operations [45, 46].

Thus, to establish a solid underlying direction and mechanism that can connect the whole supply system from source to consumer and beyond, the blockchain can provide some reasonable solutions. It would allow the recall of a commodity to be stock and at the customer end with pinpoint accuracy. It provides distributors with a clear line for communication or call-back to the user. Till now, it was not feasible to provide direct contact. New methods of loyalty and automated voucher management are feasible with blockchain. A few of this technology's other essential implementation fields are reverse logistics, guarantee control, and product monitoring [47,48].

4. Associated blockchain capabilities for successful Industry 4.0 implementation perspectives

Fig. 2 is exemplifying the various associated blockchain capabilities for booming Industry 4.0 implementation perspectives. There is a broad education domain, healthcare services, extensive support in logistics and transportation, and government agencies. The overall blockchain conceptualisation focused on enhancing these spheres from basics to achieve all the heights practically in Industry 4.0. The data privacy, effective care, avoiding fraudulent cases, ease of record maintaining, effective procurement, cost and time saving, improved transparency, etc. are the detailed sub-spheres that ultimately helps and supports blockchain capabilities to practice them more precisely for Industry 4.0 implementation in various sectors [49–51].

Blockchain is a novel technology with implementations in various established sectors like finance, property, the supply chain, vote and energy storage. This technology can not only be used to safely and immutably store financial transactions, but it may also be used to store some other kind of data and generate an incorruptible distributed record that is also safer than conventional databases. It will also help secure IP and artistic multimedia goods, such as e-books, songs, images, etc. It can also be used for car or land registration as well as the transition of the

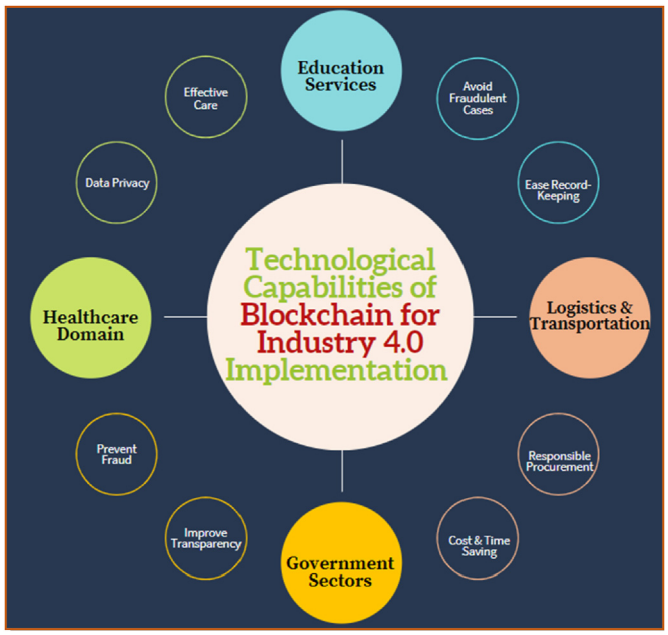

Fig. 2. Capabilities of blockchain implementation in several industrial spheres.

fund. The entire payment system is encrypted through blockchain [52, 53]. All data from digital safe transactions are used in blockchain agreements, and the smart contract will be entered automatically if the networks comply with the terms and conditions. Blockchain is a storage technology better than the standard ones; it analyses the data to make estimates and projections, which helps solve the problems in Industry 4.0. Customers can have access to a certain degree of blockchain info. Instance gives a client access by supplying consumers with an authorisation form. For instance, data exchange generates accountability and gradually builds trust and lifelong relationships with the client [54–56].

Blockchain can make trade faster and more effective for new product trading firms. Vendor results and payments may be extracted directly from authenticated blockchain transactions, reducing the need for human involvement and testing. With blockchain integrated with IoT software and sensors, products' logical and actual flow over the entire value cycle provides unprecedented accessibility and productivity gains. Transport and logistics in business make the most use of blockchain and IoT's combined strengths. An intelligent contract allows pick-ups, drops, or contractual arrangements over physical product features or payments that may be made instantaneously by these technologies [57,58].

The promise of blockchain helps us to adjust a modern business paradigm that is more effective, scalable and optimised, focused on the protection of Industry 4.0. Blockchain is, therefore, a vital partner in industry-related growth. This technology further reduces the intermediary to help businesses and get more out of it. Blockchain helps businesses to verify and conduct secure transactions more directly. Deals with judges, bankers, traders and other intermediaries may be made in principle. Moreover, these solutions are made more interactive so that changes in data can be made and then interpreted and checked by anyone in the chain. Each computer in the digital network may see a transaction registered on a single computer or node [43,59,60].

This technology reduces risk and bribery and creates trust. Blockchain is distributed, and its encrypted nature makes it impossible to access. It shows hope for IoT protection for enterprises and the internet. Blockchain is a genuine peer network that eliminates dependency on certain kinds of intermediaries. This improves the efficiency of operations and reduces the chance of data entry errors and processing fees. Blockchain automatically allows actions, events, and payments to be activated after conditions have been met. It will speed up multi-party process execution and allow quicker transactions. Blockchain technologies are being

applied cautiously in the supply chain world due to existing technological limitations, lack of digital capabilities, and enterprises' lack of enterprises. These problems affect acceptance, reputation and possible strategies of organisational development. With numerous start-up firms set up to create an ecosystem of applications, the blockchain world evolves quickly. Understanding this technology is also still emerging within a supply chain environment [61–63].

Blockchain has made the processes of peer transfers easier in the context of blockchain wallets. This technology has demonstrated the ability to transform the public transit landscape and the economy of ride-sharing. Blockchain enhances the logistics and supply chain management situation. This technology helps businesses to trace all transactions and processes in decentralised blocks spanning from production through selling, storage and shipping. In this way, the probability of mistakes, human errors and related expenses would be reduced. Inside blockchain deployments, intelligent agreements are rapidly becoming a pillar in the mass implementation of blockchain, providing a framework for a functional technological interface for blockchain transaction communication. The breakthrough of intelligent contracts makes it possible to codify rules and regulations that will theoretically create trust-based ecosystems [64,65].

Blockchain is an open and verifiable framework that transforms people's thinking about exchanging value and goods, contract enforcement, and data sharing. Software is a supplier, but a mutual, protected transaction directory spread over a computer network using Industry 4.0. One of blockchain's major advantages is that it lets us overcome people and things identities within supplier chains and actual products that move them. Blockchain has since simplified the supply chain and the authentication process for the drugs and healthcare sectors. It enabled stakeholders in the medical field to make payments with crypto wallet, modify the medication design model and provide patients and medical practitioners with a customised yet trustworthy experience. This technology has facilitated the process of certificate record-keeping and authentication [66–68]. It implemented verifiable open badges principles that permit students to permanently register their qualifications and records and convey them to prospective employers. It also simplified public funding for students and families.

5. Different Industry 4.0 spheres/sub-domains for blockchain technology realisation

Fig. 3 is reflecting about the numerous Industry 4.0 spheres/sub-domains for blockchain technology realisation practically. The major sectors or sub-domains of blockchain fruition are e-commerce, manufacturing industries, healthcare service sector, agriculture industries, security and privacy facts, drone industries for tracking, power sectors, etc. These dimensions are further sub-categorised: data transparency, security, repair and maintenance, sustainable ecosystems, agri-food traceability, Hyperledger blockchain scenario, efficient and effective control operations, drug detection, and care units, etc. [69,70]. With the proper following-up with these sub-domains/sub-dimensions of blockchain tools, the realisation of a booming and powerful Industry 4.0 philosophy is possible for overall growth and development.

Blockchain can affect almost all industries. It allows many partners to securely work on the same data and information without requesting a review and authorisation from a third party. This eliminates repetitive work and minimises time spent on the market. Moreover, blockchain facilitates proof of possession of assets, reduces counterfeiting and makes it possible for purchasers and sellers to contract on the free market. Manufacturers have a broad network of suppliers. A network like a blockchain will put more supply chain members into one network that offers full component traceability and parts traceability, allowing the process to be paid faster. This helps to increase the level of automation by codifying market provisions between blockchain supply chain members, reducing human interference and errors [54,71–73]. Enterprises need to follow an agile strategy in this age of fierce global competition where only the fittest succeed. AI can process IoT and other data sets for different scenarios like predictive system repair and assembly line.

Blockchain gives smaller companies a chance, as it enables individuals and MSMEs to negotiate with company giants and develop a level playing field. With its transformative force, blockchain would help develop a sense of independence and inclusion. The fundamental requirement of the blockchain network is that the knowledge in a distributed board environment is immutable and verifiable. Nevertheless, the developers will have to consider data storage and privacy concerns as technology advances and the scientific progress in implementing this technology beyond the crypto domain. Blockchain technology also offers convergence problems with legacy networks. It could lead to integration problems in extended supply chains [74–76].

The potential for future disruption of blockchain technology is the first foray into food, pharmaceuticals, and aerospace, requiring mandatory traceability and transparency. With creative applications, this technology environment is overgrowing. It is also necessary to remember that an extensive, dynamic supply chain is not a simple factory situation; a blockchain solution would be helpful. Blockchain acceptance would

Fig. 3. Major Industry 4.0 sub-domains for blockchain technology realisation.

focus on the implementation of several variables. More developers, interoperability, increased skills growth, and effective deployment stories are expected in the field. Blockchain is too much a revolution because it also updates the fundamental principles of transferring capital to remove corruption, minimise the possibility of theft, and build new income sources and business models [77,78]. In order to motivate intelligent production models, blockchain helps one to visualise the main processes around the industrial IoT industry. The function of blockchain in promoting transaction efficiency during the product life cycle must be crucial.

This helps manufacturers automate product migration, maintain copyright and IP rights, and facilitate IoT system data storage and items like documents. A blockchain is primarily a digital transaction database, repeated and replicated over the whole data network. All businesses have been digitalised. Today, car companies use IoT-enabled sensors to build fully autonomous cars. In addition, the automobile industry is inclined to incorporate IoT-enabled blockchain technology vehicles so that more people can quickly and rapidly share valuable details. The industry conveniently uses blockchain IoT in independent vehicles, smart car parks and automatic traffic management. The conventional centralised solution lacks security requirements and data ownership to share information created by IoT devices [79–81]. By removing constraints on centralised networks, blockchain could increase Smart Homed protection. It has been implemented to ensure that none of the data taken from clever devices can be manipulated.

Today, several companies working in many countries issue multiple invoices using various payment methods in the dynamic global supply chains. Processing that takes hours or days is often drawn over weeks or months solely because a single, readily accessed data collection is unavailable. This challenge can be easily takeover by the application of this technology. Regardless of the commodity, human error, shortages and additional costs of plague supply chains, blockchain's accountability bid has created much interest. Blockchain can manage from source to manufacturer to sell any trade, arrangement or tracking mechanism. It can refer to everything from the self-running procurement contracts to the automatic operation of the cold chain in the supply chain. Blockchain will also reduce the cost of digital twins and be developed for a wider range of sectors. Using blockchain in conjunction with digital twins will give a safe, cost-effective, and scalable system, combining digital identification and data tracking via blockchain traceability. Furthermore, this technology will assist businesses in guaranteeing that the huge amounts of information being processed are held discreetly at their internal servers [82,83].

6. Blockchain technology applications for Industry 4.0

In different processing phases, blockchain allows for decentralised transactions and knowledge sharing in Industry 4.0 within a trustworthy framework that marks all transactions and timescales. Blockchain allows companies to not only work with confidence but also to test their confidence. It became gradually embraced and promoted the ecosystem. For manufacturers, digital transformation was a slow development process, but it cannot continue to neglect the efficiencies, competitiveness and agility of digitalisation. Critical insights can be used to optimise systems and manufacturers to produce considerable savings by using data obtained from sensors and machinery. With the addition of blockchain technologies, the current digital revolution will bring innovation. The consumer goods sector is perhaps the most interactive in providing, producing, and retailing [84,85].

Blockchain's effective intelligent contracts can bind all parties and guarantee that all parties adhere. Blockchain can prove to be very successful in preventing counterfeiting, which traceability in all supply chain segments plagues the electronics, luxury and lifestyle sectors. The equipment suppliers can earn sales in the warehouses where they use the equipment. The continued growth of the automobile industry has been counterproductive to safety issues regarding the alleged hacking of connected vehicles. Many issues can be dealt with via blockchain [86,87]. Major applications of blockchain technology for Industry 4.0 are discussed in Table 1.

Most businesses change digitally today, but disruption of manufacturing is much more noticeable. Industry 4.0 undergoes profound improvements, expands virtual data and processes. The transition has begun and is expected to have a considerable effect. Throughout the entire production ecosystem, technical, economic and social improvements are anticipated. As a result, workers start moving from offshoring to nearshoring. The Industry 4.0 revolution has several factors like 3D printing, robotics and automation, intelligent IoT, computer education, and digitalisation of supply chains [149–151]. Blockchain is the next technology that can help to upgrade the level of the digital revolution. Wherever different parties in a business network need to transact, exchange, and transfer data whilst retaining a trusted atmosphere, blockchain can also add value to Industry 4.0.

Many other fields may be used by blockchain, such as smart metering for more effective use of electricity or to ensure the energy efficiency certificate of a building is managed safely. Its operating standards are based on protection, documentation and making them permanent. In Industry 4.0, blockchain technology provides us with a whole series of possibilities as an intelligent network. Blockchain transactions promise a higher degree of automation, interparty frictions, thereby reducing costs and accelerating operations due to network flexibility [157–159]. It can be applied to various supply chain systems in various ways to deliver tremendous advantages to everyone involved. Consumers have a high degree of freedom, and companies can find their way more competitive by managing supplies and demand in real-time [152–154]. Efficient use of the label characteristics of immutability, traceability, safety, robustness, and openness shows the effectiveness achieved in commercial processes.

7. Challenges of industry 4.0 undertaken by blockchain

There are various challenges of Industry 4.0 that can be easily undertaken by blockchain technology. This technology can store all data digitally for the enhancement of manufacturing processes. Only with the correct staff will business models be able to incorporate new technology while still continuing to operate successfully. This technology can solve data privacy issues with proper implementation. Many businesses can easily share their data and facilitate cross-organisational data exchange. Another major worry is the threat of current and emerging vulnerabilities in production. Blockchain comprises smart factories that enable real-time interoperability. This technology can connect to single or multiple networks. Flaws in any of those pieces of equipment could leave the system vulnerable to attack. Industry 4.0 can deal with various security issues [115,122,155].

8. Discussion on the study

The collection and verification of the data for accuracy is a great challenge. The data would traditionally be gathered by several trackers and sent to an authentication facility until data scientists were contacted for analysis. Using blockchain and intelligent agreements to ensure the reliability and possession of data gathered, the information may be submitted to the data scientists using the data for developing machine learning models directly from the driver. Blockchain addresses some key problems, namely scalability, anonymity and trustworthiness. Blockchain software can be an incredible way to track and control many connected devices so that transfers between connected devices can be shared and processed. It will also remove single points of failure by decentralising and create an environment that would make computer operating robust. Blockchain can promote safe and stable IoT network cooperation among connected devices.

Blockchain and AI have, over the last couple of years, formed their ways with a slight overlap of themselves. There is a direct link in the form

Table 1
Blockchain technology applications for Industry 4.0

S No	Application areas	Description	References
1	Finance	Blockchain's main emphasis is on financial-sector applications. The management of financial transactions can be done through the use of blockchains. Via blockchains, foreign currency problems could be resolved, and a controlled spectrum could be reached in the supply transaction. At present, the finance and payments sector tend to act as a crucial corporate of blockchain and the pace of adoption in many other industries.	[88–91]
2	Manufacturing data protection	The underlying encryption of a blockchain is also a possible use for data protection in Industry 4.0. This can prevent unwanted viewing of some data transmitted through a public network. Blockchain may be used in several ways within the space of intellectual property for proof of copyright, registers and clear rights, keeping a record, monitoring and tracking distribution rights, setting up IP contracts and even managing the purchase of the rights in the context of Industry 4.0.	[92–94]
3	Identifications of products and assemblies	Blockchains provide information for the identification of products and assemblies. This could contribute to quantifying and resolving high-specific quality issues. Blockchain provides all information about a commodity, subassemblies, components and business delivery direction. This technology is used to collect data at each stage, which can significantly minimise reminder costs and disruptions in the current context. This is the perfect way to manage products and their assemblies. In Industry 4.0, blockchain can add value in various other fields.	[95–98]
4	Automotive	Blockchain can be used by all various kinds of initiatives and partners in the automotive sector. Its value for production is promising with the continuous increase of Industry 4.0. Blockchain has an important impact on many sectors worldwide. In a blockchain, the purchasing and other data can be stored digitally in the automotive industry.	[99–103]
5	Information and security	All information provided by blockchain is digitally stored, such as how goods are produced, how they begin to ship and how data are managed, and much more. Blockchain inherent security qualities using the structure of data. It provides accurate monitoring and tracking capabilities if the data is persistent and conveniently exchanged with the appropriate information, and it includes invoices, deals and exchanges timely. In a traditional security system, this can be easily hacked by anybody and hence risky. Blockchain preserves knowledge more securely using the best cryptographic approaches rather than conventional methods. So, industries choose blockchain networks for better management solutions and cyber-attacks.	[104–107]
6	Digital purchasing	Blockchain takes the next step of property. This technology has opened new opportunities for future buyers in the real estate economy worldwide. Blockchain has particular benefits in the market, such as authenticating digital purchases and building trust in the solution for purchasing and selling properties both on the industrial and residential front. Blockchain technology has proved to be more than a groundless hype in the healthcare sector.	[108–112]
7	Business	This technology has moved beyond the financial services world in recent years, with businesses in a wide range of sectors. It starts to explore its possible role in developing infrastructure. It initiates the process by establishing a bar validated on the internet and attached to a series by thousands of computers. The network is configured to periodically upgrade itself to access reliable information in real-time from any party. It is also incredibly transparent, effective and flexible, and highly stable to the business purposes.	[113–115]
8	Supervision	In the area of crowdfunding and investment capital, blockchain has implemented the principle of smart contracts. This contributed to improving the supervision of each affiliated agency's individual campaigns and reducing the possibility of fraud. Blockchain has allowed users to monitor their donations accurately. It gave them the ability to stay up to date and added a sense of responsibilities and accountability, and helped charities deal with the increasing challenges of donated funds for other purposes.	[116–119]
9	Transaction recording	Blockchain is a decentralised transaction recording system. The transactions are registered in a global blockchain booklet held on thousands of computers worldwide. Transactions are registered and organised into blocks in the ledger. Blockchain holds the previous block hash, and it is quickly detected and avoided to modify or to forge transactions. This helps people to transmit and receive electronically, is the best-known use of blockchain technology.	[120–124]
10	Supply chain	Several emerging innovations enhance the way industrial companies operate with their supply chain management. The supply chain industry will undoubtedly search for tangible ways of openness, accountability, and productivity as blockchain technology evolves. Combined with real-time data alerts, the centralisation of ERP applications provides Industry 4.0 companies complete control of their in-house activities and lets them decide about the future data-oriented.	[125–130]
11	Data storage	Blockchain involves the network used to transfer the data from the sensor to the storage and then to the analysis device. There is a slight risk where the data is moved across a private network. The cloud provides many benefits, such as low-cost computing capacity and payment. However, the data is placed on a shared network as a vulnerability by using the cloud. This technology can also reduce the risk with the help of a good data sharing and storage system.	[131–134]
12	Proper management	For blockchain implementations and advantages, various fields are more applicable to Industry 4.0. This allows proper management and product details required by the market more efficiently. With the latest information gathered by cameras and sensors, blockchain can be built to collect more information than a person can potentially collect in a short time. The underlying encryption of a blockchain is also a possible use. In some instances, hackers can use and confiscate any of the designs on the public network. Blockchain could help secure digital design authors' IP. This technology can also be used to handle financial transfers but also to monitor digital property use.	[135–139]
13	Integration of system	Blockchain technologies can involve its partners, clients, and supply chains through an organisation, providing more possibilities for integration beyond the ecosystem of a business. This helps to make anyone aware of the operation. Industry 4.0 can equally access data so that the risk of data being withheld and distorted is minimised. Manufacturers can create beneficial results with the successful implementation of this technology. This is the beginning of the outcome market, which is intended for the revolutionisation of business models and the development to promote larger businesses.	[140–143]
14	Digital directory	A blockchain is a decentralised digital directory, which archives public and private peer-to-peer transactions. All properties are embedded and maintained in open, distributed libraries in digital code. Each transaction contains a unique digital signature that the entire network identifies and validates, protects against revocation, manipulation and revision. As such, blockchain has the capacity to exclude intermediaries and central from the new method of data exchange and asset transfer. The identity can be used for the identification of commodities and persons to trace items in Industry 4.0.	[144–148]

of data between the two technologies. The future of banks and insurance firms is primarily ordered to move away from the connection between blockchain and distributed AI. Connecting one or more chain blocks to banks and insurance firms would speed up transfers, enhance protection and openness and optimise data control. Conversely, in the embryonic process of technological progress, which has been increasingly used to deploy at a crucial level. AI and blockchain are in places where they can help each other and assist each other in the next phase of the fourth industrial revolution. If a customer needs explained details about a specific subject or has a particular request, a chatbot can handle customer service. The solution would certainly be more satisfactory and quicker as chatbots are powered by machine learning and algorithms.

Information in the database shall be encrypted, such that the contract related to a particular collection of data may only be signed by a specified

receiver having private keys. Blockchain can share information requested with others through secure, encrypted end-to-end communication with each other. Businesses have increased leverage of data security and data exchange using blockchain technologies. A wide variety of records, from leases, land deeds, logistics manifests and virtually everything else, can contain blockchain ledgers. Big data information can be exchanged in a multi-verification environment and is ideal for reliable information shared in real-time.

Sensors can track acceleration, heat, pressure, humidity or moisture and vibration. In the form of batches of statistically important amounts, the information can be compiled, processed and analysed in real-time. The sensors are pretty cheap, and all of them can be mounted without the existing capital equipment being disabled. These devices into the current networks can be challenging. Considerations must be provided for the expense of storing and processing the data obtained. Blockchain is used for ERP and parts supplier and plant's cyber-physical infrastructure, machines that can safely and autonomously order their replacement components. In addition, blockchain's ability to allow frictionless and open financial transactions between any number of smart machines makes it essential for industry 4.0's economic shifts.

In the working environment, the use of alarms, scanners and barcodes will help ensure that employees and materials have proper registration and location using blockchain. Feedback should be provided before the correct positions have been reached. Industry 4.0 has a roadmap and a way to become a fully digital production system. In order to accomplish this transition, further advancements in blockchain and sensor technologies, automation devices, applications, AI and machine learning would be needed. Blockchain improves the protection of IoT devices and guarantees openness within the IoT ecosystems. IoT enables intelligent devices to send data to the private blockchain ledges, including other tamper-resistant data used in popular transactions.

Blockchain and IoT combinations allow organisations to securely exchange IoT data within their private networks without central control and management structures. With IoT-enabled computers, businesses can trace the movement of shipments at all stages. Blockchain ensures that the whole process is transparent. IoT sensors can provide info on shipping status. This information is then processed in the blockchain accountability network, with all supply chain stakeholders identified in Smart Contracts accessing information in real-time until the data is stored on the blockchain network. The stability and traceability of the supply chain network can be improved with blockchain.

9. Future of blockchain

Blockchain will help us rethink commercial finance, supply chain activities, operations management and more associated areas. This would help to resolve disputes quickly through customisation. This will minimise the enormous manual work now being made by financial services organisations. Any inconsistencies or crucial errors in the text can also be found in the AI process to help decision-makers with approvals and refusals. Many organisations seek to promote the relationship between IoT and blockchain. In order to help companies use blockchains, such as the company has developed a way to integrate the power of connected devices with secure, accurate digital data archives. This technology will store and consistently share data. When blockchain is involved, it will make the path of goods smarter as well as secured, thus tracking the exposure of products in real-time. The blockchain contains holistic and lasting knowledge about each transaction data in the supply chain process. It will allow linking to any vendors, manufacturing locations and fulfilment centres in the supply chain. Blockchain will change corporate procedures in many industries in the future, but its adoption will take time and effort. This technology will help to improve financial and public services in the near future. Data is saved in blocks that are all linked to one another, are timestamped, and are unforgeable. Blockchain will allow users to view a product's whole history, whether it is new or used. As Leng et al. [156] proposed a ManuChain that is a bi-level hybrid intelligence model to adopt holistic planning along with individualized manufacturing systems. This type of application of blockchain can reduce the inconsistency between the planning and execution in Industry 4.0 environment in the upcoming future. This type of interconnection is required for the success of the Industry 4.0 and researchers need to pay attention to such issues. Further, the identified drivers, enablers and challenges need to be addressed in a quantitative way so that policy planners and managers can adopt the blockchain and move a step forward in the direction of Industry 4.0.

10. Conclusion

The growth and increase of the blockchain in this decade are probably going to occur in different ways. Digitalisation is one of Industry 4.0's main factors, as it allows companies to benefit from efficiency in all aspects, from management and technology consultancy to supply chain strategy and solutions. Many industries see the promise of this blockchain, which can be very helpful in addition to others. Banks now use this technology to accelerate and reduce the related costs of payments and transactions. Implementation of blockchain is not just restricted to the financial system, but it also provides information. This unchanging ledger confirms the commodity production through the correct process and resources, and that approval is provided against this process. Blockchain guarantees stable and efficient data sharing, and in addition, an unchangeable database of all messages exchanged by various connected smart devices is established. Identity protection is another excellent application of blockchain. This technology enables consumers to build their own safe and trustworthy digital identity because it is manipulative. For several items, from basic acts to apps, software or signing digital signatures, people would be allowed to use their blockchain identities. By offering a trustworthy source of high-quality transactional knowledge to smaller companies and vendors, blockchain may be the solution to facilitate this step. Furthermore, a retailer needs to maintain the consistency of goods in its supply chain.

Author contributions

Mohd Javaid: Writing (original draft), investigation, review; **Abid Haleem:** Conceptualization, supervision, validation, review & editing; **Ravi Pratap Singh:** Formal analysis, investigation, writing (review & editing); **Shahbaz Khan:** Writing (review & editing); **Rajiv Suman:** Writing (review & editing).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] V. Chang, P. Baudier, H. Zhang, et al., How blockchain can impact financial services–The overview, challenges and recommendations from expert interviewees, Technol. Forecast. Soc. Change 158 (2020), 120166.
[2] C.S. Tang, L.P. Veelenturf, The strategic role of logistics in the industry 4.0 era, Transport. Res. E Logist. Transport. Rev. 129 (2019) 1–11.
[3] C.M.S. Ferreira, R.A.R. Oliveira, J.S. Silva, et al., Blockchain for machine to machine interaction in Industry 4.0.. In: Blockchain technology for Industry 4.0, Springer, Singapore, 2020, pp. 99–116.
[4] J. Huang, L. Kong, G. Chen, et al., Towards secure industrial IoT: blockchain system with credit-based consensus mechanism, IEEE Transactions on Industrial Informatics 15 (6) (2019) 3680–3689.
[5] L. Faramondi, G. Oliva, R. Setola, et al., Iiot in the hospital acenario: hospital 4.0, blockchain and robust data management. In: Security and Privacy Trends in the Industrial Internet of Things, Springer, Cham, 2019, pp. 271–285.
[6] G. Epiphaniou, H. Daly, H. Al-Khateeb, Blockchain and healthcare. In: Blockchain and Clinical Trial, Springer, Cham, 2019, pp. 1–29.
[7] P. Sandner, A. Lange, P. Schulden, The role of the CFO of an industrial company: an analysis of the impact of blockchain technology, Future Internet 12 (8) (2020) 128.

[8] X.L. Liu, W.M. Wang, H.Y. Guo, et al., Industrial blockchain based framework for product lifecycle management in industry 4.0, Robot. Comput. Integrated Manuf. 63 (2020), 101897.

[9] B. Esmaeilian, J. Sarkis, K. Lewis, et al., Blockchain for the future of sustainable supply chain management in Industry 4.0, Resour. Conserv. Recycl. 163 (2020), 105064.

[10] J.J. Sikorski, J. Haughton, M. Kraft, Blockchain technology in the chemical industry: machine-to-machine electricity market, Appl. Energy 195 (2017) 234–246.

[11] A. Kapitonov, I. Berman, S. Lonshakov, et al., Blockchain based protocol for economical communication in Industry 4.0. 2018 Crypto Valley Conference on Blockchain Technology (CVCBT); 20-22 Jun 2018; Zug, Switzerland, IEEE, Piscataway, NJ, USA, 2018, June, pp. 41–44.

[12] T.M. Fernández-Caramés, O. Blanco-Novoa, M. Suárez-Albela, et al., A UAV and blockchain-based system for Industry 4.0 inventory and traceability applications. Multidisciplinary Digital Publishing Institute Proceedings vol. 4, 2018, p. 26.

[13] J.W. Leng, G. Ruan, P. Jiang, et al., Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: a survey, Renew. Sustain. Energy Rev. 132 (2020), 110112.

[14] J. Leng, S.D. Ye, M. Zhou, et al., Blockchain-secured smart manufacturing in industry 4.0: *a survey*, IEEE Transactions on Systems, Man, And Cybernetics: Systems 51 (1) (2021) 237–252, https://doi.org/10.1109/tsmc.2020.3040789.

[15] U. Bodkhe, S. Tanwar, K. Parekh, et al., Blockchain for industry 4.0: a comprehensive review, IEEE Access 8 (2020) 79764–79800.

[16] T. Alladi, V. Chamola, R.M. Parizi, et al., Blockchain applications for industry 4.0 and industrial IoT: a review, IEEE Access 7 (2019) 176935–176951.

[17] C. Lin, D.B. He, X.Y. Huang, et al., BSeIn: a blockchain-based secure mutual authentication with fine-grained access control system for industry 4.0, J. Netw. Comput. Appl. 116 (2018) 42–52.

[18] W. Viriyasitavat, L.D. Xu, Z. Bi, et al., Blockchain-based business process management (BPM) framework for service composition in industry 4.0, J. Intell. Manuf. (2018) 1–12.

[19] J. Lee, M. Azamfar, J. Singh, A blockchain enabled Cyber-Physical System architecture for Industry 4.0 manufacturing systems, Manufacturing Letters 20 (2019) 34–39.

[20] R. Ashima, A. Haleem, S. Bahl, et al., Automation and manufacturing of smart materials in Additive Manufacturing technologies using Internet of Things towards the adoption of Industry 4.0, Mater. Today: Proceedings 45 (6) (2021) 5081–5088.

[21] T. Kumar, E. Harjula, M. Ejaz, et al., BlockEdge: blockchain-edge framework for industrial IoT networks, IEEE Access 8 (2020) 154166–154185.

[22] D. Mehta, S. Tanwar, U. Bodkhe, et al., Blockchain-based royalty contract transactions scheme for Industry 4.0 supply-chain management, Inf. Process. Manag. 58 (4) (2021), 102586.

[23] K.N. Khaqqi, J.J. Sikorski, K. Hadinoto, et al., Incorporating seller/buyer reputation-based system in blockchain-enabled emission trading application, Appl. Energy 209 (2018) 8–19.

[24] M. Singh, Blockchain technology for data management in Industry 4.0. In: Blockchain Technology for Industry 4.0, Springer, Singapore, 2020, pp. 59–72.

[25] G. Rathee, M. Balasaraswathi, K.P. Chandran, et al., A secure IoT sensors communication in industry 4.0 using blockchain technology, Journal of Ambient Intelligence and Humanized Computing 12 (1) (2021) 533–545.

[26] Y. Kayikci, N. Subramanian, M. Dora, et al., Food supply chain in the era of Industry 4.0: blockchain technology implementation opportunities and impediments from the perspective of people, process, performance, and technology, Prod. Plann. Contr. (2020) 1–21.

[27] D.V. Lypnytskyi, Opportunities and challenges of blockchain in industry 4.0, Economy of Industry 1 (85) (2019) 82–100.

[28] P. Mukherjee, D. Singh, The opportunities of blockchain in health 4.0. In: Blockchain Technology for Industry 4.0, Springer, Singapore, 2020, pp. 149–164.

[29] T.B. da Silva, E.S. de Morais, L.F.F. de Almeida, et al., Blockchain and industry 4.0: overview, convergence, and analysis, Blockchain Technology for Industry 4 (2020) 27–58, 0.

[30] R. Gupta, S. Tanwar, S. Tyagi, et al., Habits: blockchain-based telesurgery framework for healthcare 4.0. 2019 International Conference on Computer, Information and Telecommunication Systems (CITS); 28–31 Aug 2019; Beijing, China, IEEE, Piscataway, NJ, USA, 2019, pp. 1–5.

[31] P. Christodoulou, K. Christodoulou, A. Andreou, A decentralised application for logistics: using blockchain in real-world applications, Cyprus Rev. 30 (2) (2018) 181–193.

[32] M. Çağlıyangil, S. Erdem, G. Özdağoğlu, A blockchain based framework for blood distribution. In: Digital Business Strategies in Blockchain Ecosystems, Springer, Cham, 2020, pp. 63–82.

[33] Y. Lu, Blockchain and the related issues: a review of current research topics, Journal of Management Analytics 5 (4) (2018) 231–255.

[34] A.E.C. Mondragon, C.E.C. Mondragon, E.S. Coronado, Exploring the Applicability of Blockchain Technology to Enhance Manufacturing Supply Chains in the Composite Materials Industry. 2018 IEEE International Conference on Applied System Invention (ICASI); 13–17 Apr 2018; Chiba, Japan, IEEE, Piscataway, NJ, USA, 2019, pp. 1300–1303.

[35] J.E. Kasten, Engineering and manufacturing on the blockchain: a systematic review, IEEE Eng. Manag. Rev. 48 (1) (2020) 31–47.

[36] C. Alcaraz, J.E. Rubio, J. Lopez, Blockchain-assisted access for federated Smart Grid domains: coupling and features, J. Parallel Distr. Comput. 144 (2020) 124–135.

[37] H.F. Anjum, S.Z.A. Rasid, H. Khalid, et al., Mapping research trends of blockchain technology in healthcare, IEEE Access 8 (2020) 174244–174254.

[38] S. Hartmann, S. Thomas, Applying blockchain to the Australian carbon market, Econ. Pap.: A journal of applied economics and policy 39 (2) (2020) 133–151.

[39] W. Viriyasitavat, D. Hoonsopon, Blockchain characteristics and consensus in modern business processes, Journal of Industrial Information Integration 13 (2019) 32–39.

[40] X.B. Zhu, J. Shi, S. Huang, et al., Consensus-oriented cloud manufacturing based on blockchain technology: an exploratory study, Pervasive Mob. Comput. 62 (2020), 101113.

[41] A. Haleem, M. Javaid, Additive manufacturing applications in industry 4.0: a review, Journal of Industrial Integration and Management 4 (4) (2019), 1930001.

[42] S. Perera, S. Nanayakkara, M.N.N. Rodrigo, et al., Blockchain technology: is it hype or real in the construction industry? Journal of Industrial Information Integration 17 (2020), 100125.

[43] Y. Zuo, Making smart manufacturing smarter–a survey on blockchain technology in Industry 4.0, Enterprise Inf. Syst. (2020) 1–31.

[44] S. Tanwar, K. Parekh, R. Evans, Blockchain-based electronic healthcare record system for healthcare 4.0 applications, Journal of Information Security and Applications 50 (2020), 102407.

[45] S.V. Akram, P.K. Malik, R. Singh, et al., Adoption of blockchain technology in various realms: opportunities and challenges, Security and Privacy 3 (5) (2020) e109.

[46] M. Javaid, A. Haleem, R. Vaishya, et al., Industry 4.0 technologies and their applications in fighting COVID-19 pandemic, Diabetes & Metabolic Syndrome: Clin. Res. Rev. 14 (4) (2020) 419–422.

[47] R. Gupta, S. Tanwar, N. Kumar, et al., Blockchain-based security attack resilience schemes for autonomous vehicles in industry 4.0: a systematic review, Comput. Electr. Eng. 86 (2020), 106717.

[48] P.W. Khan, Y.C. Byun, N. Park, IoT-blockchain enabled optimized provenance system for food industry 4.0 using advanced deep learning, Sensors 20 (10) (2020) 2990.

[49] C. Zhang, Y. Chen, A review of research relevant to the emerging industry trends: industry 4.0, IoT, blockchain, and business analytics, Journal of Industrial Integration and Management 5 (1) (2020) 165–180.

[50] I. Jovović, S. Husnjak, I. Forenbacher, S. Maček, Innovative application of 5G and blockchain technology in industry 4.0, EAI Endorsed Transactions on Industrial Networks and Intelligent Systems 6 (18) (2019).

[51] A.G. Khan, A.H. Zahid, M. Hussain, et al., A journey of WEB and blockchain towards the industry 4.0: an overview. 2019 International Conference on Innovative Computing (ICIC); 1–2 Nov 2019; Lahore, Pakistan, IEEE, Piscataway, NJ, USA, 2019, pp. 1–7.

[52] Q. Wang, X. Zhu, Y. Ni, et al., Blockchain for the IoT and industrial IoT: a review, Internet of Things 10 (2020), 100081.

[53] T. Ahram, A. Sargolzaei, S. Sargolzaei, et al., Blockchain technology innovations. 2017 IEEE Technology & Engineering Management Conference (TEMSCON); 8–10 Jun 2017; Santa Clara, CA, USA, IEEE, Piscataway, NJ, USA, 2017, pp. 137–141.

[54] C.T.B. Garrocho, M.C. Silva, C.M.S. Ferreira, et al., Real-time systems implications in the blockchain-based vertical integration of industry 4.0, Computer 53 (9) (2020) 46–55.

[55] T.M. Fernández-Caramés, O. Blanco-Novoa, I. Froiz-Míguez, et al., Towards an autonomous industry 4.0 warehouse: a UAV and blockchain-based system for inventory and traceability applications in big data-driven supply chain management, Sensors 19 (10) (2019) 2394.

[56] J. Lohmer, R. Lasch, Blockchain in operations management and manufacturing: potential and barriers, Comput. Ind. Eng. 149 (2020), 106789.

[57] B.C.A. Petroni, J.Z. Reis, R.F. Gonçalves, Blockchain as an Internet of services application for an advanced manufacturing environmentF. Ameri, K. Stecke, G. von Cieminski (Eds.), in: IFIP International Conference on Advances in Production Management Systems, Springer, Cham, 2019, pp. 389–396.

[58] P.F. Borowski, Digitisation, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector, Energies 14 (7) (2021) 1885.

[59] R. Rajmohan, T.A. Kumar, M. Pavithra, et al., Blockchain: Next-generation technology for Industry 4.0.. In: Blockchain Technology Fundamentals, Applications, and Case Studies, CRC Press, Boca Raton, FL, USA, 2020, p. 177.

[60] A. Upadhyay, S. Mukhuty, V. Kumar, et al., Blockchain technology and the circular economy: implications for sustainability and social responsibility, J. Clean. Prod. 293 (2021), 126130.

[61] F. Chiacchio, D. D'urso, L. Compagno, et al., Towards a blockchain based traceability process: A case study from pharma industryF. Ameri, K. Stecke, G. von Cieminski (Eds.), in: Advances in Production Management Systems. Production Management for the Factory of the Future, IFIP International Conference on Advances in Production Management Systems, Springer, Cham, 2019, pp. 451–457.

[62] U. Hacioglu, Digital business strategies in blockchain ecosystems, Springer (2020).

[63] Y. Pan, X. Zhang, Y. Wang, et al., Application of blockchain in carbon trading, Energy Procedia 158 (2019) 4286–4291.

[64] I. Yaqoob, K. Salah, M. Uddin, et al., Blockchain for digital twins: recent advances and future research challenges, IEEE Network 34 (5) (2020) 290–298.

[65] V. Puri, R. Kumar, C. Van Le, et al., A vital role of blockchain technology toward Internet of vehicles. In: Handbook of Research on Blockchain Technology, Academic Press, 2020, pp. 407–416.

[66] J. Al-Jaroodi, N. Mohamed, Blockchain in industries: a survey, IEEE Access 7 (2019) 36500–36515.

[67] J. Wu, M. Dong, K. Ota, et al., Application-aware consensus management for software-defined intelligent blockchain in IoT, IEEE Network 34 (1) (2020) 69–75.
[68] Y. Lu, Blockchain: a survey on functions, applications and open issues, Journal of Industrial Integration and Management 3 (4) (2018), 1850015.
[69] K. Sabri-Laghaie, S.J. Ghoushchi, F. Elhambakhsh, et al., Monitoring blockchain cryptocurrency transactions to improve the trustworthiness of the fourth industrial revolution (industry 4.0), Algorithms 13 (12) (2020) 312, https://doi.org/10.3390/a13120312.
[70] M. Li, D. Hu, C. Lal, et al., Blockchain-enabled secure energy trading with verifiable fairness in industrial internet of things, IEEE Transactions on Industrial Informatics 16 (10) (2020) 6564–6574.
[71] I. Froiz-Míguez, P. Fraga-Lamas, J. Varela-Barbeito, et al., LoRaWAN and blockchain based safety and health monitoring system for Industry 4.0 operators 42, Multidisciplinary Digital Publishing Institute Proceedings, 2019, p. 77.
[72] N. Kawaguchi, Application of blockchain to supply chain: flexible blockchain technology, Procedia Computer Science 164 (2019) 143–148.
[73] M. Kouhizadeh, Q. Zhu, J. Sarkis, Blockchain and the circular economy: potential tensions and critical reflections from practice, Prod. Plann. Contr. 31 (11–12) (2020) 950–966.
[74] E. Tijan, S. Aksentijević, K. Ivanić, et al., Blockchain technology implementation in logistics, Sustainability 11 (4) (2019) 1185.
[75] U. Bodkhe, P. Bhattacharya, S. Tanwar, et al., BloHosT: blockchain enabled smart tourism and hospitality management. 2019 International Conference on Computer, Information and Telecommunication Systems (CITS); 28–31 Aug 2019; Beijing, China, IEEE, Piscataway, NJ, USA, 2019, pp. 1–5.
[76] V. Hargaden, N. Papakostas, A. Newell, et al., The role of blockchain technologies in construction engineering project management. 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC); 17–19 Jun 2019; Valbonne Sophia-Antipolis, France, in: 2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), IEEE, Piscataway, NJ, USA, 2019, pp. 1–6.
[77] F. Ullah, F. Al-Turjman, A conceptual framework for blockchain smart contract adoption to manage real estate deals in smart cities, Neural Comput. Appl. (2021) 1–22.
[78] W. Viriyasitavat, L.D. Xu, Z.M. Bi, et al., Blockchain and internet of things for modern business process in digital economy—the state of the art, IEEE Transactions on Computational Social Systems 6 (6) (2019) 1420–1432.
[79] C.T.B. Garrocho, E. Klippel, A.V. Machado, et al., Blockchain-based machine-to-machine communication in the Industry 4.0 applied at the industrial mining environment charles.. 2020 X Brazilian Symposium on Computing Systems Engineering (SBESC); 24–27 Nov 2020; Florianopolis, Brazil, IEEE, Piscataway, NJ, USA, 2020, pp. 1–8.
[80] M.H. Miraz, Blockchain of Things (BCoT): the Fusion of Blockchain and IoT Technologies. In: Advanced Applications of Blockchain Technology, Springer, Singapore, 2020, pp. 141–159.
[81] W. Liang, Y.K. Fan, K.C. Li, et al., Secure data storage and recovery in industrial blockchain network environments, IEEE Transactions on Industrial Informatics 16 (10) (2020) 6543–6552.
[82] D. Guo, S. Ling, H. Li, et al., A framework for personalised production based on digital twin, blockchain and additive manufacturing in the context of Industry 4.0.. 2020 IEEE 16th International Conference On Automation Science And Engineering (CASE); 20–21 Aug 2020; Hong Kong, China, IEEE, Piscataway, NJ, USA, 2020, pp. 1181–1186.
[83] Y. Issaoui, A. Khiat, A. Bahnasse, et al., Smart logistics: study of the application of blockchain technology, Procedia Computer Science 160 (2019) 266–271.
[84] M. Ammar, A. Haleem, M. Javaid, et al., Improving material quality management and manufacturing organisations system through Industry 4.0 technologies, Mater. Today: Proceedings 45 (6) (2021) 5089–5096.
[85] J. Hathaliya, P. Sharma, S. Tanwar, et al., Blockchain-based remote patient monitoring in healthcare 4.0.. 2019 IEEE 9th International Conference On Advanced Computing (IACC); 13–14 Dec 2019; Tiruchirappalli, India, IEEE, Piscataway, NJ, USA, 2019, pp. 87–91.
[86] B. Fu, Z. Shu, X. Liu, Blockchain enhanced emission trading framework in fashion apparel manufacturing industry, Sustainability 10 (4) (2018) 1105.
[87] M. Swami, D. Verma, V.P. Vishwakarma, Blockchain and industrial internet of things: applications for industry 4.0. In: Proceedings of International Conference on Artificial Intelligence and Applications, Springer, Singapore, 2021, pp. 279–290.
[88] A.N. Hidayanto, H. Prabowo, The latest adoption blockchain technology in supply chain management: a systematic literature review, ICIC Express Letters 13 (10) (2019) 913–920.
[89] P. Fraga-Lamas, T.M. Fernández-Caramés, A review on blockchain technologies for an advanced and cyber-resilient automotive industry, IEEE Access 7 (2019) 17578–17598.
[90] S. Sajid, A. Haleem, S. Bahl, et al., Data science applications for predictive maintenance and materials science in context to Industry 4.0, Mater. Today: Proceedings 45 (6) (2021) 4898–4905.
[91] L. Zhang, Y.P. Xie, Y. Zheng, et al., The challenges and countermeasures of blockchain in finance and economics, Syst. Res. Behav. Sci. 37 (4) (2020) 691–698.
[92] Y. Guo, C. Liang, Blockchain application and outlook in the banking industry, Financial Innovation 2 (1) (2016) 1–12.
[93] Y. Lu, The blockchain: state-of-the-art and research challenges, Journal of Industrial Information Integration 15 (2019) 80–90.
[94] J. Dai, N. He, H. Yu, Utilising blockchain and smart contracts to enable Audit 4.0: from the perspective of accountability audit of air pollution control in China, J. Emerg. Technol. Account. 16 (2) (2019) 23–41.
[95] M. Li, K.L. Zhang, J.M. Liu, et al., Blockchain-based anomaly detection of electricity consumption in smart grids, Pattern Recogn. Lett. 138 (6) (2020) 476–482.
[96] S.B. ElMamy, H. Mrabet, H. Gharbi, et al., A survey on the usage of blockchain technology for cyber-threats in the context of industry 4.0, Sustainability 12 (21) (2020) 9179.
[97] Q. Zhu, M. Kouhizadeh, Blockchain technology, supply chain information, and strategic product deletion management, IEEE Eng. Manag. Rev. 47 (1) (2019) 36–44.
[98] Y. Issaoui, A. Khiat, A. Bahnasse, et al., Smart logistics: blockchain trends and applications, J. Ubiquitous Syst. Pervasive Networks 12 (2) (2020) 9–15.
[99] B. Putz, M. Dietz, P. Empl, et al., Ethertwin: blockchain-based secure digital twin information management, Inf. Process. Manag. 58 (1) (2021), 102425.
[100] P. Pinheiro, M. Macedo, R. Barbosa, et al., Multi-agent systems approach to Industry 4.0: enabling collaboration considering a blockchain for knowledge representation. In: International Conference on Practical Applications of Agents and Multi-Agent Systems, Springer, Cham, 2018, pp. 149–160.
[101] J.M. Song, J. Sung, T. Park, Applications of blockchain to improve supply chain traceability, Procedia Computer Science 162 (2019) 119–122.
[102] A. Adiyanto, R. Febrianto, Authentication of transaction process in E-marketplace based on blockchain?? technology, Aptisi Transactions on Technopreneurship (ATT) 2 (1) (2020) 68–74.
[103] G.Q. Zhao, S.F. Liu, C. Lopez, et al., Blockchain technology in agri-food value chain management: a synthesis of applications, challenges and future research directions, Comput. Ind. 109 (2019) 83–99.
[104] H.R. Hasan, K. Salah, R. Jayaraman, et al., A blockchain-based approach for the creation of digital twins, IEEE Access 8 (2020) 34113–34126.
[105] O. Bouachir, M. Aloqaily, L. Tseng, et al., Blockchain and fog computing for cyberphysical systems: the case of smart industry, Computer 53 (9) (2020) 36–45.
[106] G.D. Martins, R.F. Gonçalves, B.C. Petroni, Blockchain in manufacturing revolution based on machine-to-machine transaction: a systematic review, Brazilian Journal of Operations & Production Management 16 (2) (2019) 294–302.
[107] I. Mistry, S. Tanwar, S. Tyagi, et al., Blockchain for 5G-enabled IoT for industrial automation: a systematic review, solutions, and challenges, Mech. Syst. Signal Process. 135 (2020), 106382.
[108] Y. Madhwal, P.B. Panfilov, Industrial case: blockchain on aircraft's parts supply chain management, in: American Conference on Information Systems 2017 Workshop on Smart Manufacturing Proceedings vol. 6, 2017, pp. 1–6.
[109] A.H. Sodhro, S. Pirbhulal, M. Muzammal, et al., Towards blockchain-enabled security technique for industrial internet of things based decentralised applications, J. Grid Comput. 18 (2020) 615–628.
[110] B. Zareiyan, M. Korjani, Blockchain technology for global decentralized manufacturing: challenges and solutions for supply chain in fourth industrial revolution, Int. J. Adv. Robot. Autom 3 (2) (2018) 1–10.
[111] E.A. Carey, N. Subramanian, An Exploratory Study on Blockchain Application in a Food Processing Supply Chain to Reduce Waste.. In: Research Anthology on Blockchain Technology in Business, Healthcare, Education, and Government., IGI Global, Hershey, PA, USA, 2019, pp. 61–85.
[112] M. Kouhizadeh, J. Sarkis, Blockchain characteristics and green supply chain advancement. In: Global Perspectives on Green Business Administration and Sustainable Supply Chain Management, IGI Global, Hershey, PA, USA, 2020, pp. 93–109.
[113] T. Zheng, M. Ardolino, A. Bacchetti, et al., The applications of Industry 4.0 technologies in manufacturing context: a systematic literature review, Int. J. Prod. Res. (2020) 1–33.
[114] M.S. Kumar, R.D. Raut, V.S. Narwane, et al., Applications of industry 4.0 to overcome the COVID-19 operational challenges, Diabetes & Metabolic Syndrome: Clin. Res. Rev. 14 (5) (2020) 1283–1289.
[115] D. Schönle, K. Wallis, J. Stodt, et al., Industry use cases on blockchain technology. In: Industry Use Cases on Blockchain Technology Applications in IoT and the Financial Sector, IGI Global, Hershey, PA, USA, 2021, pp. 248–276.
[116] A. Boudguiga, N. Bouzerna, L. Granboulan, et al., Towards better availability and accountability for IoT updates by means of a blockchain. 2017 IEEE European Symposium on Security and Privacy Workshops (EuroS&PW); 26–28 Apr 2017; Paris, France, IEEE, 2017, pp. 50–58.
[117] A. Sulkowski, Industry 4.0 era technology (AI, big data, blockchain, DAO): why the law needs new memes, Kan. JL & Pub. Pol'y Online 29 (2019) 1.
[118] A. Haleem, M. Javaid, Industry 4.0 and its applications in dentistry, Indian J. Dent. Res. 31 (5) (2020) 824.
[119] E. Aghamohammadzadeh, O.F. Valilai, A novel cloud manufacturing service composition platform enabled by blockchain technology, Int. J. Prod. Res. 58 (17) (2020) 5280–5298.
[120] A. Dolgui, D. Ivanov, S. Potryasaev, et al., Blockchain-oriented dynamic modelling of smart contract design and execution in the supply chain, Int. J. Prod. Res. 58 (7) (2020) 2184–2199.
[121] N. Mohamed, J. Al-Jaroodi, S. Lazarova-Molnar, Leveraging the capabilities of industry 4.0 for improving energy efficiency in smart factories, IEEE Access 7 (2019) 18008–18020.
[122] C.H. Lim, S. Lim, B.S. How, et al., A review of industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach, Renew. Sustain. Energy Rev. 135 (2021), 110223.

[123] J. Stodt, D. Schönle, C. Reich, et al., Security audit of a blockchain-based industrial application platform, Algorithms 14 (4) (2021) 121.
[124] Q.K. Nguyen, Q.V. Dang, Blockchain technology for the advancement of the future. In: 2018 4th International Conference on Green Technology and Sustainable Development (GTSD); 23–24 Nov 2018; Ho Chi Minh City, Vietnam, IEEE, Piscataway, NJ, USA, 2018, pp. 483–486.
[125] P.T. Duy, D.T.T. Hien, D.H. Hien, et al., A Survey on opportunities and challenges of blockchain technology adoption for revolutionary innovation. SoICT 2018: The Ninth International Symposium on Information and Communication Technology; 6–7 Dec 2018; Danang City Viet Nam, ACM, New York, NY, USA, 2018, pp. 200–207.
[126] N. Mohamed, J. Al-Jaroodi, Applying blockchain in Industry 4.0 applications. 2019 IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC); 7–9 Jan 2019; Las Vegas, NV, USA, IEEE, Piscataway, NJ, USA, 2019, pp. 852–858.
[127] J. Al-Jaroodi, N. Mohamed, Industrial applications of blockchain.. 2019 IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC); 7–9 Jan 2019; Las Vegas, NV, USA, IEEE, Piscataway, NJ, USA, 2019, pp. 550–555.
[128] A. Mushtaq, I.U. Haq, Implications of blockchain in Industry 4.0. 2019 International Conference On Engineering And Emerging Technologies (ICEET); 21–22 Feb 2019; Lahore, Pakistan, IEEE, Piscataway, NJ, USA, 2019, pp. 1–5.
[129] N.V. Vafiadis, T.T. Taefi, Differentiating blockchain technology to optimise the processes quality in Industry 4.0. 2019 IEEE 5th World Forum on Internet of Things (WF-IoT); 15–18 Apr 2019; Limerick, Ireland, IEEE, Piscataway, NJ, USA, 2019, pp. 864–869.
[130] I. Sittón-Candanedo, A new approach: Edge computing and blockchain for Industry 4.0. In: International Symposium on Distributed Computing and Artificial Intelligence, Springer, Cham, 2019, pp. 201–204.
[131] S.H. Jang, J. Guejong, J. Jeong, et al., Fog computing architecture based blockchain for Industrial IoT. Computational Science – ICCS 2019. ICCS 2019. Lecture Notes in Computer Science, in: J. Rodrigues (Ed.) vol 1153, Springer, Cham, 2019, pp. 593–606.
[132] M.M.H. Onik, M.H. Miraz, Performance analytical comparison of blockchain-as-a-service (baas) platforms, in: International Conference for Emerging Technologies in Computing; 19–21 Aug 2019; London, UK, Springer, Cham, 2019, pp. 3–18.
[133] D. Muzylyov, N. Shramenko, Blockchain technology in transportation as a part of the efficiency in Industry 4.0 strategyV. Tonkonogyi (Ed.), in: Advanced Manufacturing Processes. InterPartner 2019. Lecture Notes in Mechanical Engineering, Springer, Cham, 2019, pp. 216–225.
[134] V. Puri, I. Priyadarshini, R. Kumar, et al., Blockchain meets IIoT: an Architecture for privacy preservation and security in IIoT, in: 2020 International Conference on Computer Science, Engineering and Applications (ICCSEA); 13–14 Mar 2020; Gunupur, India, IEEE, Piscataway, NJ, USA, 2020, pp. 1–7.
[135] A.O. Kwok, S.G. Koh, Neural network insights of blockchain technology in manufacturing improvement. 2020 IEEE 7th International Conference on Industrial Engineering and Applications (ICIEA); 16–21 Apr 2020; Bangkok, Thailand, IEEE, Piscataway, NJ, USA, 2020, pp. 932–936.
[136] A. Ossamah, Blockchain as a solution to drone cybersecurity. 2020 IEEE 6th World Forum on Internet of Things (WF-IoT); 2–16 Jun 2020; New Orleans, LA, USA, IEEE, Piscataway, NJ, USA, 2020, pp. 1–9.
[137] F. Dietrich, Y. Ge, A. Turgut, et al., Review and analysis of blockchain projects in supply chain management, Procedia Computer Science 180 (2021) 724–733.
[138] P. Frey, M. Lechner, T. Bauer, T. Shubina, A. Yassin, S. Wituschek, M. Merklein, November). Blockchain for forming technology–tamper-proof exchange of production data, IOP Conf. Ser. Mater. Sci. Eng. 651 (1) (2019), 012046.
[139] A. Jabbar, S. Dani, Investigating the link between transaction and computational costs in a blockchain environment, Int. J. Prod. Res. 58 (11) (2020) 3423–3436.
[140] I. Islam, K.M. Munim, S.J. Oishwee, et al., A critical review of concepts, benefits, and pitfalls of blockchain technology using concept map, IEEE Access 8 (2020) 68333–68341.
[141] C. Zhang, G.H. Zhou, H. Li, et al., Manufacturing blockchain of things for the configuration of a data-and knowledge-driven digital twin manufacturing cell, IEEE Internet of Things Journal 7 (12) (2020) 11884–11894.
[142] G. Rathee, A. Sharma, R. Kumar, et al., A secure communicating things network framework for industrial IoT using blockchain technology, Ad Hoc Netw. 94 (2019) 101933.
[143] B.A. Tama, B.J. Kweka, Y. Park, et al., A critical review of blockchain and its current applications. 2017 International Conference on Electrical Engineering and Computer Science (ICECOS); 22–23 Aug 2017; Palembang, Indonesia, IEEE, Piscataway, NJ, USA, 2017, pp. 109–113.
[144] Y. Yan, B. Duan, Y. Zhong, et al., Blockchain technology in the Internet plus: the collaborative development of power electronic devices. IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society; 29 Oct–1 Nov 2017; Beijing, China, IEEE, Piscataway, NJ, USA, 2017, pp. 922–927.
[145] C. Hennebert, F. Barrois, Is the blockchain a relevant technology for the Industry 4.0?. 2020 2nd Conference On Blockchain Research & Applications For Innovative Networks And Services (BRAINS); 28–30 Sept 2020; Paris, France IEEE, Piscataway, NJ, USA, 2020, pp. 212–216.
[146] M. Javaid, A. Haleem, Industry 4.0 applications in medical field: a brief review, Current Medicine Research and Practice 9 (3) (2019) 102–109.
[147] S.F. Wamba, M.M. Queiroz, Industry 4.0 and the supply chain digitalisation: a blockchain diffusion perspective, Prod. Plann. Contr. (2020) 1–18.
[148] L.D. Xu, E.L. Xu, L. Li, Industry 4.0: state of the art and future trends, Int. J. Prod. Res. 56 (8) (2018) 2941–2962.
[149] A. Haleem, M. Javaid, Medical 4.0 and its role in healthcare during COVID-19 pandemic: a review, Journal of Industrial Integration and Management 5 (4) (2020) 531–545.
[150] N. Teslya, I. Ryabchikov, Blockchain-based platform architecture for Industrial IoT. 2017 21st Conference of Open Innovations Association (FRUCT); 6–10 Nov 2017; Helsinki, Finland, IEEE, Piscataway, NJ, USA, 2017, pp. 321–329.
[151] M. Holland, J. Stjepandić, C. Nigischer, Intellectual property protection of 3D print supply chain with blockchain technology; 17–20 Jun 2018; Stuttgart, Germany, in: 2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), IEEE, Piscataway, NJ, USA, 2018, pp. 1–8.
[152] P. Pinheiro, R. Santos, R. Barbosa, Industry 4.0 multi-agent system based knowledge representation through blockchain. In: International Symposium on Ambient Intelligence, Springer, Cham, 2018, pp. 331–337.
[153] K. Kuhi, K. Kaare, O. Koppel, Ensuring performance measurement integrity in logistics using blockchain. 2018 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI); 31 Jul–2 Aug 2018; Singapore, IEEE, Piscataway, NJ, USA, 2018, pp. 256–261.
[154] S. Saberi, M. Kouhizadeh, J. Sarkis, et al., Blockchain technology and its relationships to sustainable supply chain management, Int. J. Prod. Res. 57 (7) (2019) 2117–2135.
[155] B. Bhushan, C. Sahoo, P. Sinha, et al., Unification of blockchain and Internet of Things (BIoT): requirements, working model, challenges and future directions, Wireless Network 27 (1) (2021) 55–90.
[156] J.W. Leng, D.X. Yan, Q. Liu, et al., ManuChain: combining permissioned blockchain with a holistic optimization model as Bi-level intelligence for smart manufacturing, IEEE Transactions On Systems, Man, And Cybernetics: Systems (2019) 1–11, https://doi.org/10.1109/tsmc.2019.2930418.
[157] S. Khan, R. Singh, Kirti, Critical factors for blockchain technology implementation: a supply chain perspective, Journal Of Industrial Integration And Management (2021), 2150011, https://doi.org/10.1142/s2424862221500111.
[158] J.W. Leng, P.Y. Jiang, Evaluation across and within collaborative manufacturing networks: a comparison of manufacturers' interactions and attributes, Int. J. Prod. Res. 56 (15) (2018) 5131–5146.
[159] H. Zhang, Q. Liu, X. Chen, et al., A digital twin-based approach for designing and multi-objective optimization of hollow glass production line, IEEE Access 5 (2017) 26901–26911, https://doi.org/10.1109/access.2017.2766453.