Potential Requirements and Opportunities of Blockchain-Based Industrial IoT in Supply Chain: A Survey

Zhao-Hui Sun, *Member, IEEE*, Zhiyang Chen, Sijia Cao, and Xinguo Ming

***Abstract*— The integration of the industrial Internet of Things (IoT) and blockchain technology is changing the business and management model of the supply chain. Much work is focused on how to promote the application of blockchain-based industrial IoT in the supply chain from both academic research and industrial practice. However, due to the different industrial requirements in industrial scenes, the gap between technology researches and industrial applications is still large. Therefore, the article adopts the mixed method of enterprise survey and literature review to identify the actual industrial requirements in different supply chain scenes. Also, the characteristics and applicable scenarios of industrial IoT and blockchain have been analyzed. Then, the potential application opportunities of blockchain-based industrial IoT in nine scenes are discussed in detail. This study reveals the technical challenges and practical challenges of these applications, which potentially guides research on applying industrial IoT and blockchain technology in the supply chain.**

***Index Terms*— Blockchain, industrial Internet of Things (IoT), scene application, supply chain.**

I. Introduction

SUPPLY chain is an ecosystem that describes the delivery process of products or services from suppliers to consumers [1]. It includes product design, manufacturing and production management, enterprise operation management, and product service. The long supply chain process causes low efficiency and high cost of products. Besides, the quality problems of products are frequently exposed. An efficient and trusted supply chain ecosystem is becoming an emerging requirement among producers and the final consumers [2]. More and more enterprises appeal to the transparency of the supply chain to help the different enterprises timely understand the supply chain information and the requirement of the final consumers.

The premise of supply chain transparency is openness and information security. For an open environment of the supply chain, the industrial Internet of Things (IoT) is introduced in the supply chain. It provides different enterprises with an interactive platform [3], [4]. On the industrial IoT platform, different enterprises could easily obtain the upstream and downstream information of their supply chain and the final consumer information via the standardized interface. There has been a lot of research work on the implementation of industrial IoT in the supply chains of different industries [5]. Although industrial IoT promotes the collaboration of the supply chain from the concept, it seems that few enterprises are willing to actively provide their supply-related information to the platform. Once the equipment and information systems are connected to the platform, the privacy and business secrets of the enterprise will be at great risk [6]. Therefore, the transparency of the supply chain undoubtedly requires powerful information security as its prerequisite [7]. For this proposal, blockchain technology is introduced to the supply chain area to make a trustworthy ecosystem. In addition to the security factor, the distributed ledger and automatic execution characteristics of blockchain are also improving the efficiency and costs of the supply chain.

Through enterprise investigation and literature review, we found the combination of industrial IoT and blockchain could help the supply chain obtain a dynamic balance between the openness of supply information and the privacy protection for the enterprise [8]. Considering the possibility of the combination of the above two technologies to reduce the costs and improve the efficiency of the supply chain [9], this article studies the promising effect and application of blockchain-based industrial IoT platforms for the supply chain. Previous research work mostly focused on the technology or a few case studies discussions. For example, Korpela *et al.* [10] investigated how blockchain technology could be used in supply chains to offer a cost-effective business model. Cole *et al.* [11], through deeply analyzing digital ledger and other technologies about blockchain, found blockchain could reduce the cost of the supply chain by influencing many aspects. Casado-Vara *et al.* [12] proposed a new model of the supply chain via a blockchain-based food supply chain, enabling the concept of circular economy and eliminating many of the disadvantages of the current supply chain. Zhou *et al.* [13] designed an efficient blockchain-based framework for 5G heterogeneous networks to maximize the flow of M2M communication. Lin *et al.* [14] proposed a P2P computing resource transaction system for the Internet-of-Vehicles system in smart cities and combined

Manuscript received June 13, 2021; revised October 12, 2021; accepted November 16, 2021. This work was supported in part by the National Natural Science Foundation of China under Grant 52005218, in part by the Shanghai Decision-Making Advisory Committee under Grant 2018-001-02, and in part by the Industrial Internet Innovation Development Project of the Ministry of Industry and Information Technology of China under Grant TC190A3X8-10. *(Corresponding authors: Zhao-Hui Sun; Xinguo Ming.)*

The authors are with the Department of Industrial Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: zh.sun@sjtu.edu.cn; xgming@sjtu.edu.cn).

Digital Object Identifier 10.1109/TCSS.2021.3129259

TABLE I
INDUSTRIAL REQUIREMENTS OF DIFFERENT PHASES IN THE SUPPLY CHAIN

Phases	Industrial requirements	Descriptions
Product design	Insufficient design resources and high design cost	The design resources of enterprises in the supply chain are limited, so it is difficult to satisfy the personalized product design requirements from customers.
Product manufacturing & production logistics	Difficult to guarantee the manufacturing quality	Due to the complexity of the product manufacturing process, it is difficult to guarantee the quality of raw materials and product processing.
Enterprise operations management	Complex supplier relationship and long purchasing process	Complicated supplier selection and purchasing process leading to the low efficiency of the enterprise supply process.
Product service	Product & service quality and counterfeit products	For the consumer-oriented supply chain, the quality problems of product & service and counterfeit products not only harm the interests of customers but also reduce the reputation and brand effect of the whole supply chain.
Industrial maintenance, repair& operations	High equipment maintenance cost in industrial enterprises	For the maintenance-oriented supply chain, equipment maintenance needs to invest a huge cost.

with blockchain technology to achieve flexible computing resource demand response under the premise of ensuring data security. Different from these previous research works, this article focuses on the analysis of the problems existing in different phases of the supply chain and gives the corresponding potential applications. In the process of the research, we found that, for most industrial enterprises, compared to discussing the specific blockchain application implementation scheme, the potential requirements and application possibilities of the blockchain-based on each phase of the supply chain are the first to be solved. To the best of our knowledge, the systematic discussion of the potential application scenes in different phases of the supply chain is rare. Our study is dedicated to sorting out these potential application scenarios to provide a reference for enterprises to identify the application opportunities of blockchain-based industrial IoT platforms.

The remainder of this article is organized as follows. Section II introduces the research methodology of this article. Then, the key issues in the supply chain are discussed in Section III. To use blockchain, industrial IoT, and platform technologies to solve the industrial requirements in the supply chain, Section IV gives a review and analysis of these key technologies. Next, in Section V, nine scenes in different phases of the supply chain are proposed and analyzed how to solve scene industrial requirements via blockchain-based industrial IoT platform. Section VI discusses the common problems and challenges that the blockchain-based industrial IoT platform needs to face. Future perspectives are given in Sections VII. Finally, the conclusion of our study is drawn in Section VIII.

II. RESEARCH METHODOLOGY

The research methodology includes three steps: enterprise survey, literature review, and scene-oriented analysis. The logic of the research method is given as follows. First, an enterprise survey is conducted; then, a literature review on the requirements of the supply chain obtained from the survey is conducted; and finally, a scene-oriented analysis based on the results of the first two steps is conducted.

A. Enterprise Survey

First, a wide survey of supply chain enterprises and blockchain technology enterprises in Shanghai was conducted sponsored by the Shanghai Decision-Making Advisory Committee of Shanghai. This survey lasted from April 2018 to April 2020. Our survey was mainly based on interviews and seminars with corporate executives. Then, the industrial requirements of different supply chain scenes were sorted out and summarized in Table I.

B. Literature Review

According to our survey of enterprises, the literature review was conducted in the IEEE Xplore, ScienceDirect, Taylor and Francis, and Google Scholar. Three keywords, “blockchain,” “IoT,” and “platform,” were identified for searching related publications. Besides, to narrow the gap between supply chain actual application and advanced technology, different terms in the supply chain, such as product design, manufacturing, supplier, logistics, product service, and maintenance, are tired of searching. Therefore, the searching string is set as “(blockchain AND IoT AND platform) AND (supply chain OR product design OR manufacturing OR supplier OR logistics OR product service OR maintenance).” Then, 230 related articles, from January 2016 to December 2020, were selected for further reading. After the reading, 73 articles were retained. Through the research of these articles, the characteristics and applicable scenarios of industrial IoT, blockchain, and platform technologies have been analyzed.

C. Scene-Oriented Analysis

Scene research mainly focuses on the industrial requirements of the scenes obtained from the enterprise survey. The executives from supply chain enterprises and blockchain enterprises were invited to participate in brainstorming to come up with potential solutions for blockchain-based industrial IoT platforms in different scenes. During the brainstorming, 15 supplementary references were added to make the literature concrete.

According to the above research methodology, this article discusses the actual industrial requirements and the potential blockchain-based industrial IoT potential opportunities in several supply chain scenes. Besides, the technical challenges and practical challenges of these potential applications are identified for future research.

III. Key Issues in the Supply Chain

A. Background

The supply chain is an ecosystem that describes a collaborative network between enterprises [15]. The complexity of products promotes the division of labor in enterprises. It makes it necessary for a large number of enterprises to cooperate to complete the supply process smoothly. From the perspective of the product lifecycle, the supply chain can be roughly divided into five phases, including product design, product manufacturing and product logistics, enterprise operation management, product service, and industrial maintenance and operation. Different enterprises would occupy one or more of the above phases.

The supply chain focuses on customer requirements, supply plan, order delivery, supply process, and reverse. A supply chain is composed of multiple stakeholders who provide products and services for the customers collaboratively. Due to the multiple stakeholders, product quality, supply costs, and delivery time in the supply chain will face great challenges. To analyze the industrial requirements faced by different phases of the supply chain, Table I divides the supply chain into five phases and gives the corresponding industrial requirements in the five phases.

B. Phase: Product Design

Product design is the starting of the supply chain [16]. For the downstream enterprises of the supply chain, the product design proposals mainly come from the collaboration with the individual designer or the design enterprise. The Internet benefits the collaboration process [17]. With the help of the established platform on the Internet, the communication and interaction on the product design between designers and the people on the design demand side are realized. To a certain extent, the Internet has alleviated the lack of design resources. However, the Internet also increases the risk of damage to the designer's interests. The typical collaboration platform is established by the enterprise on the design demand side. Once the product design proposals are uploaded to the platform, the designers cannot guarantee the interests of their work. Therefore, to achieve efficient collaboration in the product design, how to establish the benefit protection mechanism of the designer is worth deep consideration. Besides, different from the collaboration between the individual design and the enterprise [18], how to realize the efficient docking and sharing of design resources among multienterprises is also an important issue in product design. To study how to solve these problems, Sections V-A and V-B discuss the application of blockchain-based industrial IoT platforms in product design.

C. Phase: Product Manufacturing and Production Logistics

Product quality is deeply related to product manufacturing and production logistics [19]. From the perspective of warehousing, although many large enterprises have multiple workshops and warehouses, in actual business, to prevent quality problems from being traced and the high logistics costs due to materials allocation, most workshops would rather waste time purchasing from other suppliers than adopting warehousing allocation. Therefore, how to promote low-cost and traceable allocation between warehouses is a problem that large enterprises are facing. Besides, from the perspective of manufacturing, the distributed manufacturing of complex products is facing quality problems that cannot be discovered in time due to the long supply chain. It is also causing a lot of cost and time waste in the entire manufacturing chain. To study how to solve these problems, Sections V-C and V-D discuss the application of blockchain-based industrial IoT platforms in the production and warehousing collaboration and the distributed manufacturing quality control, respectively.

D. Phase: Enterprise Operations Management

Supplier management is the core of industrial enterprise operations management [20]. For manufacturing, the purchasing of production materials and timely replenishment are the keys to maintaining continuous production. However, in the actual purchasing process, it is often difficult to find some specific materials. Even if the material is found, it is difficult to effectively evaluate the quality of the supplier [21]. It will affect whether to purchase from the supplier. Besides, the article contract is big trouble in operations management due to its inconvenience and easy to fake [22]. Electronic contracts are becoming the development trend of contracts due to their high efficiency, convenience, and environmental protection [23]. The adoption of electronic contracts will effectively simplify the procedures in the purchasing process, thereby improving procurement efficiency. The supply and demand contract involves the detailed information of the materials; it also includes the legal terms and the business of the parties. Up until today, since the electronic contract is easy to tamper with, the article contract has not been completely replaced. To study how to solve these problems, Sections V-E and V-F discuss the application of blockchain-based industrial IoT platforms in industrial purchasing and electronic contracts, respectively.

E. Phase: Product Service

The customer focuses on the product quality. The appearance of product quality problems usually leads to a decline in customer satisfaction. In response to this problem, the usual approach is to improve the quality control of the supply chain product manufacturing and delivery process. However, quality problems are sometimes inevitable. Therefore, from the point of view of service, if the product occurs the quality problem, how to quickly trace the quality problem in the supply chain needs to be solved [24]. Besides, in recent years, counterfeit products in the product supply market are forcing the interests of enterprises in the high-quality supply chain to be harmed. Therefore, the problem of counterfeit products is also a problem that the supply chain needs to solve [25]. It can be seen that how to improve the traceability of product quality [26] and combat counterfeit products are the two issues in the supply chain. To study how to solve these problems, Sections V-G and V-H discuss the application

of blockchain-based industrial IoT platforms in product traceability and product verification, respectively.

F. Phase: Industrial Maintenance, Repair, and Operations

In addition to production materials, industrial enterprises also need spare parts to support the maintenance of their equipment [27], [28]. Different from production materials, the purchasing of spare parts for maintenance has the characteristics of small batches. Also, as the equipment spans multiple production lines, the varieties of spare parts are different. It leads to higher costs when enterprises purchase these spare parts. To make matters worse, due to unfamiliarity with the mechanism of equipment degradation, many enterprises intend to equip a large inventory of spare parts to meet maintenance needs. It will not help industrial enterprises reduce maintenance inventory [29]. To study how to solve the above problems, Section V-I discusses the application of blockchain-based industrial IoT platforms in purchasing collaboration platforms for maintenance.

IV. Industrial IoT and Blockchain Technology

A. Industrial IoT

As the infrastructure of industrial interconnection, industrial IoT uses smart sensors and automation technology to improve operational efficiency. The ubiquitous industrial integration for man, machine, and cybernetics is developed by the industrial IoT. From the perspective of technology, industrial IoT is the product of a set of technologies, including communication technology, network technology, and intelligent computing. For example, communication technologies, such as 5G and the future 6G, provide information transmission channels for industrial IoT to perceive people and equipment [30]. The increase in network nodes in industrial scenarios provides an interconnection method for industrial IoT to achieve business automation and collaboration. Edge computing [31], [32], fog computing [33], [34], and cloud computing [35] provide intelligent computing for industrial IoT to the hierarchical perception.

The combination of these technologies gives three important characteristics for the industrial IoT: 1) ubiquitous interconnection between industrial elements [36]; 2) distributed perception [37]; and 3) information digitization and potential business automation [38]. These characteristics together create the underlying implementation mechanism and operation logic of digital transformation for industrial scenarios. It provides a digital foundation for operational efficiency improvement and model innovation in the industry.

B. Blockchain Technology

Blockchain technology [45] is a new fusion technology that is widely used in social and economic fields [46]. It includes key technologies in Table II. From the perspective of the network structure, the blockchain-based network is quite different from the traditional Internet. Internet is a typical centralized network. Initially, the Internet is designed to establish a P2P network data structure. However, due to the emergence of large servers, it gradually moves toward network concentration. Blockchain emphasizes the dual distribution of data generation and storage. That is, data are backed up on any node, and any node can be used as the source of data. Therefore, in the network constructed by the blockchain, it is completely decentralized [47]. Its design effectively prevents the network from converging to the center. From the perspective of the network environment, the task of the Internet mainly establishes a transmission channel between data; there are deviations and untrustworthy elements in the transmission of information and data. Its core idea is to use technology integration and innovation to provide a credible and safe environment for value transfer [48].

TABLE II
Key Technologies of Blockchain

Technologies	Industrial requirements	Refs
P2P Network	Realize dynamic networking, dynamical join and exit mechanism for nodes	[39]
Distributed Ledger	Realize distributed storage of data to help each participant transparently obtain data backup	[40]
Cryptography	Utilize technologies (such as digital signature and hash algorithm) to ensure the non-tampering of data	[41]
Consensus Mechanism	Ensure the consistency of data	[42]
Smart Contract	Use the automatic trigger mechanism to achieve business automation	[43]
Game Theory	Use game thinking to eliminate the centralization that P2P may cause	[44]

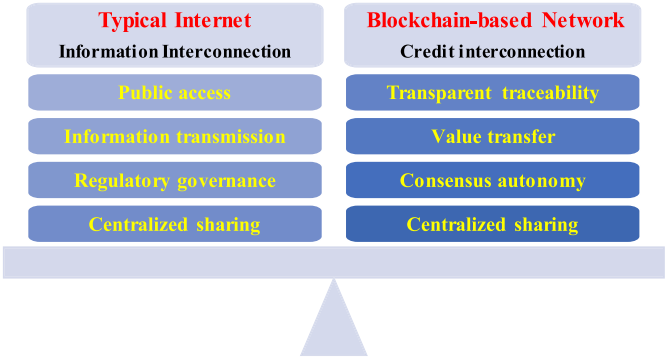

Fig. 1. Comparison of the blockchain-based network and typical internet.

Based on the above comparative analysis, it can be found that the essence of the Internet is to use network technology to complete information processing, storage, and transmission, thereby completing the digitization of information resources. The essence of the blockchain-based network is a credible and safe interconnection [49]. It uses technology integration to form a credible interconnection chain to realize the transfer of value. Fig. 1 gives the comparison of the blockchain-based network and typical Internet.

Through comparison, Table III concludes the three salient features of blockchain and their corresponding potential application scenarios.

C. Platform Technology

The platform is an open organizational structure that integrates physical entities and IoT devices on the network.

TABLE III
SALIENT FEATURES OF BLOCKCHAIN AND POTENTIAL APPLICATION SCENARIOS

Salient Features	Descriptions	Potential Scenarios	Refs
Enhance trustworthiness	Provide a natural and credible distributed ledger without the additional third-party intermediaries	Achieve the trust from multiple parties in a weak trust environment	[50]
Potential possibility of enhancing safety	Provide a high safety and reliable environment of information	Carry out reliable audit management and account liquidation to reduce crime and resist various risks	[51]
Multi-party cooperation	Adapt to multi-party participation in an equal environment	Realize collaborative value creation under multi-role participation and long business process	[52]

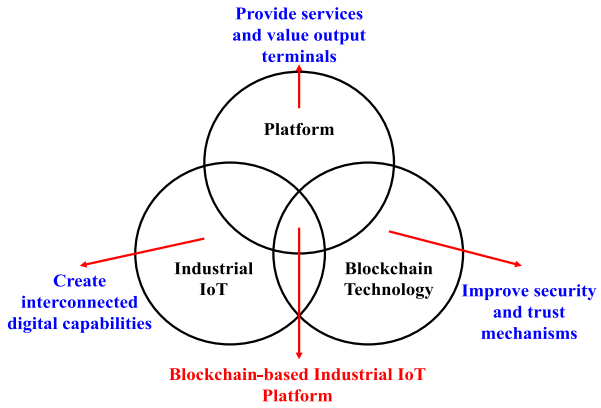

Fig. 2. Concept of the blockchain-based industrial IoT platform.

The lower layer of the platform connects edge devices with specific coding and analysis protocols through communication technology and sensor technology; the middle layer of the platform provides industrial operating systems and reusable and rapid development tools, such as data analysis tools, and microservice components; the upper layer of the platform is based on the capacity reserve of the middle layer and the ubiquitous data interconnection of the lower layer to provide a quick response and processing interface for different business operations and application innovations. Therefore, the platform technology is the sum of the technologies implemented in the abovementioned platform. For detailed platform technology, please refer to the Industrial Internet Architecture from the Industry IoT Consortium of America[1] and the Alliance of Industrial Internet of China.[2]

D. Blockchain-Based Industrial IoT Platform

Industrial IoT provides the underlying operating mechanism for industrial operations by creating interconnected digital capabilities in industrial scenarios [53]. The blockchain helps improve security and trust mechanisms for multiparty cooperation [54]. As shown in Fig. 2, the industrial IoT and blockchain technology together provide opportunities for industrial value creation from the technical level. As the service interface, the platform provides external services by integrating the two technologies.

[1]https://www.iiconsortium.org/IIRA.htm

[2]https://www.miit.gov.cn/cms_files/filemanager/oldfile/miit/n973401/n5993937/n5993968/c7886657/part/7886662.pdf

Currently, more and more supply chain management processes are using "industrial IoT + blockchain + platform technology" to solve the bottlenecks (See Table I) that are facing in the supply chain. The platform here means the integration of blockchain and IoT-related technologies to form an architecture that can be quickly developed, reused, and expanded. Therefore, the research of blockchain-based industrial IoT platforms is necessary. It will be discussed in detail in the following Section IV.

V. BLOCKCHAIN-BASED INDUSTRIAL IOT PLATFORM FOR SUPPLY CHAIN MANAGEMENT

This section discusses the potential solutions of blockchain-based industrial IoT platforms in nine supply chain scenarios. These scenarios come from the investigation of multiple blockchain-based supply chain projects and, on the other hand, come from the investigation of supply chains and blockchain technology enterprises. The research results are summarized, classified, and discussed in detail by brainstorming methods of the members of the research team to ensure the integrity of the scene. Considering that the platform and industrial IoT, respectively, constitute the service output of the platform and the underlying operation logic of the platform, they are merged into the industrial IoT platform for discussion in the following. Despite the differences in scenarios, these solutions all describe the industrial IoT platform and blockchain applications in detail. In each scene, it will be divided into two parts: scene description and solution to discuss the application of industrial IoT platform and blockchain.

A. Mass Innovation-Based Product Design

1) Scene Requirement: Considering the personalized needs, the product design mode based solely on a single or few design enterprises will gradually fail to meet the customer needs. Mass innovation-based product design is helping the product design process more efficiently [55]. With individual designers as the new stakeholder of product design [56], their interests are difficult to guarantee due to their weak position [57]. To better meet customer needs, more and more huge enterprises are opening up their design platforms for the designers to participate [56], [58]. The problem that the open design platform should solve is the opacity of the design platform. Once designers upload their works to the platform, it is hard for the designers to trace their works and protect their copyrights. Faced with the risk of works being stolen, individual designers cannot safely participate in the product design.

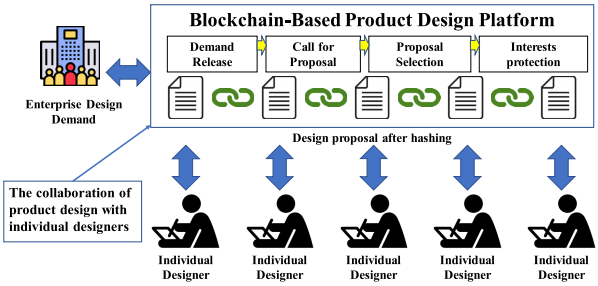

Fig. 3. Blockchain-based product design platform.

2) Potential Opportunity: The openness determines whether huge enterprises attract designers and integrate their design abilities for product design. To this end, the establishment of the industrial IoT platform will help enterprises expand their openness of product design. As a huge enterprise, there are many design tools and design resources. According to the development of interface on Software-as-a-Service (SasS) of industrial IoT platform, the internal design process can be shared with individual designers.

The bottleneck of mass innovation-based product design is how to provide designers with a design platform based on trustworthiness. The anxiety of designers stems from the risk of leakage and illegal use of their works by huge enterprises [59]. Blockchain technology will solve this problem by creating a unique unmodifiable record for each design proposal [60]. For the individual designers, after complete design proposals, they may generate a unique hash value for each design proposal. Then, upload the hash value to the design platform. Since the probability of hash collisions is almost 0, it is possible to guarantee to the greatest extent that only the original design proposal can calculate the same hash value. Since the original information cannot be reversed from the hash value, large enterprises cannot restore the designer's original proposal through the hash value. Due to the characteristics of the distributed ledger of the blockchain, even if the enterprise suspends its design platform, the blockchain ledger will still be retained. The mass innovation-based product design, therefore, could generally be operated by an enterprise or a business alliance that has a large demand for design solutions. The government and legal institutions supervise as third-party institutions and back up the hash data of the distributed blockchain for mediating legal disputes. The designer can confirm the rights of his works by holding the original design proposal and the corresponding hash value. Once the illegal use of the design proposal occurs, the blockchain ledger can be used to protect the rights of the designer. Since only (or almost only) the same original information can get the same hash value with the same hash function, the original design proposal and the corresponding hash value can be used as evidence of the legal prosecution. At present, governments and legal institutions in various countries confirm the legal effect of blockchain rights' confirmation.

Fig. 3 gives the schematic of the blockchain-based product design platform. The product design demands of the enterprise's first release on the open design platform. Then, the design demands generate the call for proposal automatically via the demand release tools. The individual designers can respond to those design demands that they want to participate in through the enterprise design platform and further conduct the design process via the open design resource and tools. Here, the SaaS (Software as a Service) layer of the industrial IoT platform helps the integration of individual designers. Next, the design proposal made by the individual designer uses the hashing operation to generate a unique hash value, which can be uploaded to the design platform. Whether the enterprise chooses the design proposal, the individual designer keeps the original proposal and corresponding hash value for copyright protection. Once the design proposal is stolen, the retained hash value and distributed ledger of blockchain will become important evidence to protect the interests of the individual designer.

B. Design Resource Docking and Sharing

1) Scene Requirement: Considering operation cost, the enterprise intends to use the least resource to accomplish the maximum product design tasks. Such a streamlined resource setting helps enterprises realize efficient management. However, the rapid changing of product design needs is making it different for enterprises to cope with these changes with streamlined resources. To this end, more and more enterprises start to seek resource complementary cooperation. Through the cooperation of design resources, the enterprise can use the design resources of other enterprises at a low cost [61]. The enterprise can also open its resources for sharing to get an extra income. The problems in design resource sharing are given as follows.

1) Where to seek the design resources and where to open the design resources of the enterprise?
2) How to ensure the privacy of open resources?
3) How to manage open resources?

2) Potential Opportunity: The docking and sharing of the design resources between enterprises are based on trust. With blockchain as a machine for keeping the evidence, its existence naturally generates trust. Therefore, the use of blockchain for authentication mechanism of design resources will help enterprises confirm the copyrights of their resources [62]. Besides, the smart contract technology of the blockchain with the authorization mechanism of enterprises by blockchain will automatically trigger resource authentication for enterprises that meet the platform requirements [63]. Through the combination of the above mechanism of the blockchain technology, the trust mechanism between enterprises finally can be built.

Design resource docking and sharing platforms could generally be established by third-party service enterprises or industry alliances to provide services for platform enterprises through unified certification and transparent resource sharing mechanisms. The Platform-as-a-Service (PasS) layer of the developed platform needs to provide different enterprises with a development environment to share their design resources in different forms. For example, the enterprise could give information on its designers to other enterprises in the form of a designer introduction. For these private resources

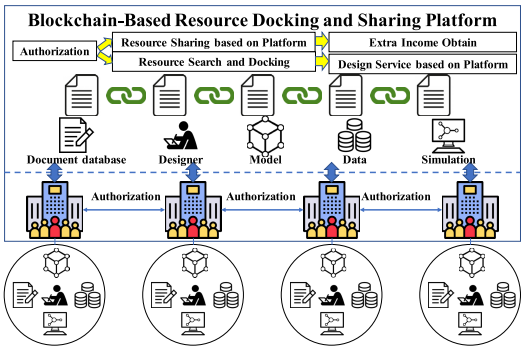

Fig. 4. Blockchain-based resource docking and sharing platform.

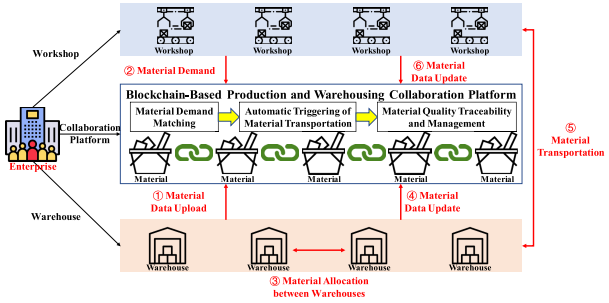

Fig. 5. Blockchain-based production and warehousing collaboration platform.

(computing resources, simulation software, and so on), the enterprise could provide a service interface of resources to other enterprises.

Fig. 4 gives the schematic of the blockchain-based resource docking and sharing platform. Different from the enterprise design platform (see Section V-B), the resource docking and sharing between multienterprises first should solve the problem of mutual and consensus. The introduction of blockchain help enterprises confirm their resources and quickly join the platform. The built trust mechanism benefits resource docking and sharing. It makes enterprises willing to open their design resources for exchange. Then, the opened resources upload on the platform by the appropriate forms for sharing. So far, problem 1) can be solved. For problem 2), the enterprise can evaluate the privacy degree of the resource and open it up in an appropriate way. For example, the simulation tools of enterprises may involve internal mechanisms that the enterprise would not want to disclose. The service interface may be an appropriate form to avoid the leakage of core design secrets. Besides, the identity management mechanism of industrial IoT can help enterprises dynamically manage the opening of their resources to other enterprises. This management mechanism will solve problem 3). The mutual trust and consensus of blockchain and the resource sharing and management of industrial IoT provide an efficient platform for enterprises to exchange their design resources.

C. Multiwarehouse Material Allocation

1) Scene Requirement: For the large group enterprise, it may include many workshops and warehouses in different places. Typically, one workshop corresponds to several fixed warehouses, while one warehouse services for several fixed workshops. In the actual production, the material should be transported from the warehouse to the workshop. Once the shortage of materials occurs in the corresponding warehouses of one workshop, the production task of the workshop may be interrupted. Under normal circumstances, the workshops are not willing to use the material of other warehouses. It is because, although all warehouses belong to one enterprise, the quality of materials is no guarantee. Besides, consider the small demand for the shortage of materials in most cases; it is expensive to find temporary logistics for transportation. For the consistency of the product quality and the high cost of transportation, most workshops would rather purchase materials from other suppliers nearby than conduct the allocation between warehouses from their group enterprises.

2) Potential Opportunity: The difficulties of the multiwarehouse material allocation are original from the material quality and the transportation cost. For workshops, the quality of materials cannot be traced. Once the quality problems occur on the allocated materials, they cannot be traced back to the original suppliers. Industrial IoT improves the process [64]. Considering that all the workshops and warehouses are belonging to the same group enterprise, it is easy to establish a collaboration platform between workshops and warehouses. The transparent material using and warehousing information helps workshops know the inventory status of each warehouse in advance and helps warehouses know the material demands of each workshop. Once the workshop finds that the fixed warehouses cannot meet the material demand according to the material prediction, it can entrust a suitable fixed warehouse for material allocation from other warehouses. Firstly, the entrusted warehouse transports the materials that the workshop needed in the future from other warehouses to its place for temporary storage. Once the workshop needs these materials, the entrusted warehouse then transfers them from its temporary storage location to the workshop. Since the warehouses are normally equipped with transportation tools, the transportation cost is lower than the temporary logistics to achieve the purpose of saving transportation costs. Besides, the established platform improves the traceability of material quality. The combination with blockchain technology makes all the purchasing recordings with the original supplier information be kept. Every purchase and circulation of materials will be recorded on the blockchain. Once the material quality problem occurs, even if the material is circulated in multiple warehouses and multiple workshops, the material circulation record containing supplier information will be retained to support the supplier tracking.

Fig. 5 gives the schematic of the blockchain-based production and the warehousing collaboration platform. The platform connects workshops and warehouses through industrial IoT. The industrial IoT timely uploads the material information from warehouses and workshops, respectively. The transparency of the information of materials helps the workshop understand the overall distribution of the materials. Once the fixed warehouses of the workshop cannot meet the material demand of this workshop, this workshop can further

let one warehouse carry out the material allocation between warehouses through negotiation. Then, the information of the material allocation can be uploaded to the blockchain-based collaboration platform for the material information update. Then, the typical material transportation can be conducted between the workshop and the warehouse. Next, the material using the information in the workshop will be uploaded to the platform. Once the quality problem occurs to the material, the material circulation record can support the supplier tracking.

D. Manufacturing Quality Control

1) Scene Requirement: The partition of the manufacturing division promotes the distribution of manufacturing. As small as different processing machines are responsible for different processing contents, as large as different enterprises are responsible for different processing parts. Distributed manufacturing involves collaboration across various business activities of suppliers and manufacturers [65]. For the complex product, its manufacturing chain is long. The quality problems of the manufacturing in the previous step may affect the next step, and the accumulated manufacturing problems may spread to the next manufacturing process. Due to the untransparent of distributed manufacturing, it is difficult for downstream manufacturing to determine the source of the quality problem. Therefore, quality problems can usually be found in the final testing. The unqualified products will cause the cost and time waste of the entire manufacturing chain.

2) Potential Opportunity: The untransparent manufacturing chain causes less understanding of each other between different processes. Therefore, for the distributed manufacturing, after receiving the semifinished product manufactured in the previous step, only a sample and fixed quality inspection will be performed on it, and then, the next step of manufacturing will start. The simple and fixed quality inspection is typically based on manual experience and several key parameters.

Enterprises that are closer to product sales are expected to establish the manufacturing quality control platform. Therefore, the product original equipment manufacturers (OEMs) closest to consumers are the best to take the lead in establishing the platform. The platform is required to connect the key manufacturing parameters on the untransparent manufacturing chain. The blockchain-based industrial IoT platform can be used for collecting the key parameters of the entire manufacturing chain. On the one hand, blockchain technology effectively guarantees the authenticity of upload parameters in the manufacturing chain. The parameters collected help the next step of manufacturing simplify the inspection process of key parameters. On the other hand, the complete manufacturing information of products can improve the product quality in the entire manufacturing chain. The complete manufacturing information helps the establishment of a more complete quality control and evaluation system for the final testing. Based on the gradually formed evaluation system, the quality problem of the product can be further decomposed into the specific manufacturing link and corresponding manufacturing parameters based on the complete manufacturing information. For example, if one quality problem of the product is decomposed into several parameters of the mth manufacturing process, then, through the analysis of the information given by the testing process, the $m + 1$th manufacturing process can add these parameters to the quality control evaluation for the product from the mth manufacturing process.

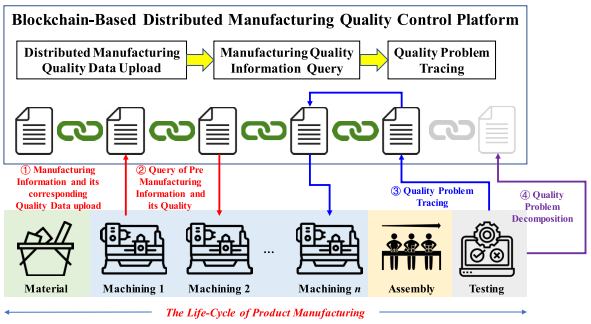

Fig. 6. Blockchain-based distributed manufacturing quality control platform.

Fig. 6 gives the schematic of the blockchain-based distributed manufacturing quality control platform. The material and manufacturing information is first uploaded to the platform. Then, the subsequent processing can use the manufacturing chain information for fast quality inspection. When all the manufacturing processes are done, the testing conducts the final inspection to guarantee the product quality. Once the quality problem of the products occurs, the recording of manufacturing information can be used for quality problem tracing and quality problem decomposition.

E. Purchasing and Replenishment

1) Scene Requirement: Purchasing is one of the core activities for enterprises in the supply chain. For the huge enterprise, due to the huge purchasing demand, a supply chain platform is typically established to provide a standardized process for negotiating with supply providers. For the small enterprise, due to the unstable purchasing demand, its supplier selection is more flexible. The scattered purchasing will not be able to effectively establish a stable supplier partnership. Due to the limitation of the purchasing volume, it is difficult to accumulate an effective evaluation of suppliers. Such a predicament leads enterprises to treat every purchase with caution. In this case, the purchasing process is time-consuming and labor-intensive.

2) Potential Opportunity: Blockchain-based industrial IoT will improve the purchasing process [66]. As the above scene description, the difficulty of purchasing is how to select trustworthy suppliers. The deep-seated reason is that it is difficult to establish an evaluation system for suppliers through a small amount of purchasing records. Once several enterprises on the demand side are cooperated to establish the industrial purchasing platform, the overall purchasing volume will become large enough. The cooperative enterprises can release their demands on the collaborative purchasing platform and call for suppliers. In the initial stage of platform establishment, cooperative enterprises invite their suppliers to the platform to respond to their demands. The platform established by

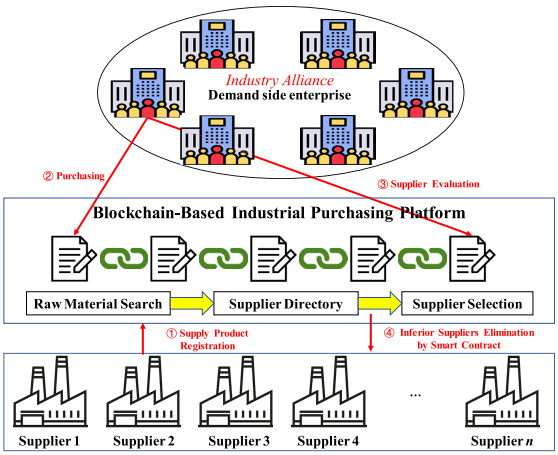

Fig. 7. Blockchain-based industrial purchasing platform.

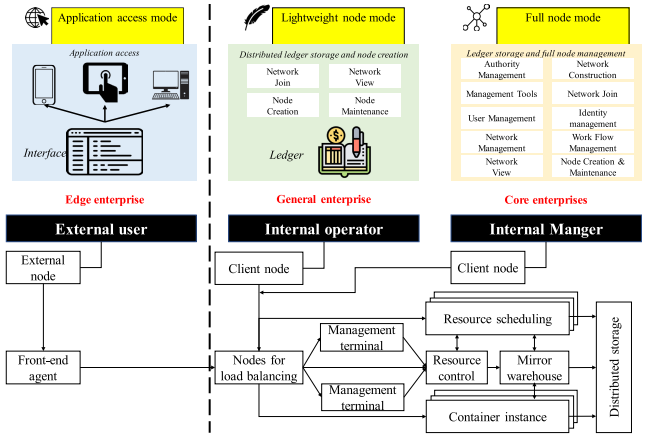

Fig. 8. Reference of enterprise authorities and data storage deployment plan.

the demand side means a broader supply market. For high-quality suppliers, it will also be willing to enter the platform to accumulate its credit value. When the platform matures, the accumulated credit will directly affect the evaluation of sustainable suppliers [67]. Through evaluation, the supplier finally realizes the survival of the fittest.

Fig. 7 gives the schematic of the blockchain-based industrial purchasing platform. After the establishment of the platform, suppliers are asked to register for the products (materials) that they provided. Then, the enterprises from the demand side purchase on the platform according to their demands. The purchasing records will be written to the blockchain. When the purchased goods are used, the supplier evaluation information will be written to the blockchain. Furthermore, to enable the platform to have high-quality suppliers, the demand side can use smart contract technology to formulate supplier access standards. For example, once the supplier's evaluation is below a certain standard, its platform access qualification will be automatically canceled.

When constructing the collaborative purchasing platform, the actual purchasing needs of different enterprises should be considered. Different enterprises in the alliance can be roughly divided into three categories, edge enterprises, general enterprises that do business with core enterprises, and core enterprises. For edge enterprises, application access mode can be adopted. The enterprise does not maintain the blockchain nodes but directly uses the nodes of other enterprises. For general enterprises, the lightweight node mode can be adopted. The enterprise maintains a blockchain node, but it does not own the platform. It relies on the platform established by the core enterprise of the supply chain. For the core enterprises, the full node mode is adopted. They are deeply involved in the construction of the alliance and the construction of the blockchain-based industrial IoT platform. Since different enterprises have different degrees of participation in the platform, they have different platform authorities. The upper part of Fig. 8 shows the authorities owned by enterprises with different participation modes. Besides, how to store the data generated by blockchain is also vital to the collaboration platform established by the alliance. To provide a reference for the data storage, the lower part of Fig. 8 shows a basic framework of data storage in our practice. The internal general enterprises and core enterprises use the client node to join the blockchain network. The external enterprises connect to the blockchain network platform through front-end agents. These agents are the subnodes of the client nodes of internal enterprises. The data are generated in an internal network composed of general enterprises and core enterprises and are stored in each internal network node in a distributed storage manner.

The above data storage deployment plan can prevent core enterprises from forming advantages and barriers to other supply chain enterprises via data storage. Also, it enhances the flexibility of edge and general enterprises and reduces their equipment and management costs. The plan takes into account platform neutrality and practical feasibility.

F. Electronic Contract

1) Scene Requirement: The supply and demand parties sign the contract that is an important issue in the typical supply process [68]. The contract includes not only the provided material information but also the related law and business information. Besides, the document of the contract should be encrypted. Considering the law meaning of the contract, contract documents in the form of the article still occupy the dominant position. This is because electronic documents are more likely to be forged. Therefore, its endorsement ability as legal evidence is weak. It is still difficult to promote the electronic contract.

2) Potential Opportunity: The blockchain-based IoT platform provides a potential solution for electronic contracts. For the enterprise, contract management requires standardization. To make the contract more standardized, the establishment of the corresponding contract template library will help business departments choose the appropriate template for different business processes. It provides the potential business space for platform service providers to establish an electronic contract service industrial IoT platform. By developing the SaaS layer of industrial IoT platforms, defined contract service components, such as template selection, and information filling, the contract generation could provide the user with a quick and

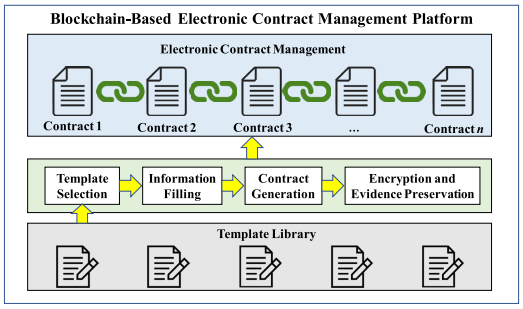

Fig. 9. Blockchain-based electronic contract management platform.

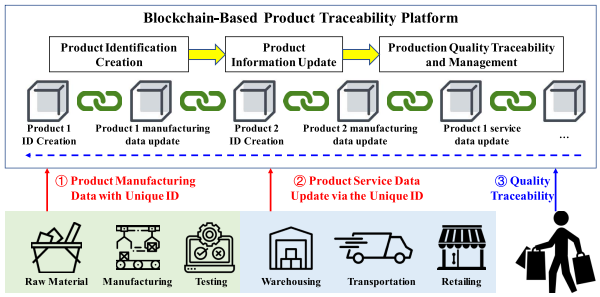

Fig. 10. Blockchain-based product traceability platform.

credible electronic contract generation scheme. The encryption technology of blockchain will improve the privacy of the contract. Once the contract is signed by both parties, the hashing technology is used to enhance the unforgeability of the contract. Finally, the electronic contract is uploaded to the blockchain for evidence preservation. Due to the distributed and transparent characteristics of blockchain, the information can be shared with the law and judicial institutions in real time to reserve the initial evidence for possible legal problems in the future [69].

Fig. 9 gives the schematic of the blockchain-based electronic contract management platform. The Industrial IoT platform provides a contract management system with functions used for quickly generating the contract. Blockchain technology helps improve the privacy of the contract and reserve the evidence of a possible contract dispute.

G. Product Traceability

1) Scene Requirement: Product traceability refers to the traceability where the quality problem occurred after the customer bought the product through the sales channel [70]. The existing traceability methods in the supply chain include the barcode, radio frequency identification (RFID) technology, QR code, and so on [71]. Among various traceability methods, a centralized model is general used to manage the supply information uniformly. It makes data easy to be tampered with. Besides, the label of traceability information mainly relies on manual processing. It causes difficulty in ensuring the authenticity of traceable data.

2) Potential Opportunity: The blockchain-based IoT platform integrates the entire process information flow. Once the manufacturing of one product starts, immediately bind the product with a unique digital ID based on the blockchain. Next, real-time manufacturing information is obtained through IoT equipment and uploaded to the blockchain to ensure the transparency and credibility of the data. After being tested by the industrial product appraisal department, the test and appraisal report information is encrypted and stored in the blockchain for product quality traceability in the future. To protect the data privacy of the enterprise testing information to the greatest extent, the access authority of the testing report can be set as only the designated verifier has the right to view the report. Besides, for industries with mature logistics information technology, such as food and medical, sensors are used to monitor temperature, humidity, and other data in real time to ensure that the products are within a reasonable range. The dynamic upload of these logistics status information, geographic location information, certificates, and other data to the blockchain will provide more complete product supply process information for product traceability [72]. Generally speaking, the platform could be jointly constructed by the third-party platform provider and the consumer-end enterprise. By establishing a model of typical high-quality products for consumers, more enterprises in the middle link of other products will be promoted to add their information to the chain.

Fig. 10 gives the schematic of the blockchain-based product traceability platform. According to the order of the supply chain, the manufacturing and service data of the product is created with the product ID and recorded to the blockchain-based product traceability platform through IoT equipment. Then, the product is purchased by customers through the sales network. Once the quality problem occurs, the product ID can be used for quality traceability. Since the regulatory authorities have the authority to view the product manufacturing information and testing reports of the entire supply process, the quality traceability and accountability of the supply process can be efficiently carried out.

H. Counterfeit Products' Elimination

1) Scene Requirement: The counterfeit product is a common problem in the supply chain process [73], [74]. When it comes to the topic of counterfeit products, the first thing that comes to mind is that upstream product providers provide counterfeit products to the downstream to obtain illegal benefits. However, the new paradox of the platform economy is spawning a reverse flow of counterfeit products, that is, the downstream product buyers seek illegal benefits by purchasing certified products but returning counterfeit products. Taking an example of the e-commerce platform, one buyer purchases two products: one certified product with a high price and one counterfeit product with a low price. The two products belong to the same product type. Then, by returning the counterfeit one to the seller who sells the certified one, the certified one can be purchased at a low price. Such behavior is illegal. However, since the distributors of the e-commerce platform are self-employed, the lack of the ability to judge counterfeit products causes such deceptions to often occur.

2) Potential Opportunity: The key problem of counterfeit products is the untransparent product supply information.

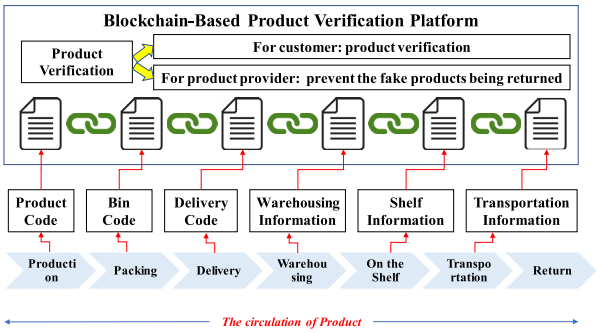

Fig. 11. Blockchain-based product verification platform.

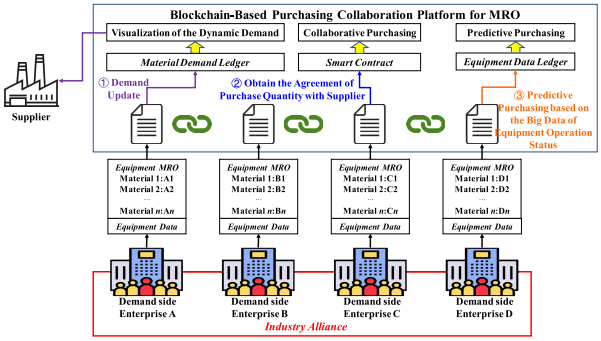

Fig. 12. Blockchain-based purchasing collaboration platform for MRO.

Different from the quality traceability of the product, product verification focus on how to use the basic supply chain information to identify the authenticity of products [75]. In response to counterfeit products, the blockchain-based product verification platform can be established.

Fig. 11 gives the schematic of the blockchain-based product verification platform. The product supply information, such as the product code, the bin code of the product, the warehousing information, the shelf information, and the transportation information, can be obtained automatically and uploaded to the blockchain through the IoT equipment. Then, the blockchain-based platform is used to verify the product at any time based on the distributed storage of product supply information. Due to the unique ID of the product, the supply chain information stored in the blockchain will be incremental. Thus, even if the product is purchased and returned multiple times, it can also be verified through the backtracking of the supply chain.

I. Maintenance Purchasing

1) Scene Requirement: Maintenance, repair, and operations (MRO) have been widely concerned by industry in recent years [76]. MRO usually refers to the materials and services that do not directly be used for manufacturing but are only used for maintenance, repair, and operations of equipment. The purchased industrial products of MRO are quite different from the bill of material (BOM). The categories of MRO products are complex and span all production lines. It is, therefore, a big challenge for enterprise supply chain management [28]. Besides, suppliers of MRO materials generally have the following problems: 1) small supply scale; 2) full of fake goods; 3) few kinds of products; 4) less standardized management; 5) shortage of funds; 6) untransparent product price; 7) high warehousing investment costs; and so on. Therefore, how to improve the efficiency of the supply chain and reduce the cost of the manufacturing industry has become the core problem.

2) Potential Opportunity: Considering that similar equipment often has a similar operation mechanism, enterprises in the same industry can establish an alliance to realize MRO material purchasing collaboration. On the one hand, MRO has the characteristics of a small batch. Through negotiation, the enterprises in the alliance could jointly establish a collaborative purchasing mechanism. Each enterprise at the demand side uploads its MRO material demand to the blockchain. Once the set collaborative purchasing cycle or purchasing quantity is reached, the demand of all enterprises will be counted and integrated. Then, the procurement will be initiated to the MRO material suppliers. Different enterprises upload their requirements at different times; the material demand quantity in a certain period is dynamic. Due to the transparency of blockchain, MRO material suppliers can forecast the demand for the MRO material according to the dynamic changes of demand. Also, the increase in purchasing quantity is helpful to reduce the purchase cost. On the other hand, by using multiparty secure computings, homomorphic encryption, and other privacy protection technologies in cryptography, under the premise of ensuring the business privacy of enterprises, each enterprise at the demand side can query the data of the equipment in the alliance. It realizes the reliable and low-cost sharing of the equipment data. The accumulation of these credible and big data can realize the knowledge accumulation of similar equipment in the service cycle and maintenance time through the intelligent algorithm. Besides, the equipment maintenance forecast helps enterprises in the alliance optimize the purchasing of MRO materials.

Fig. 12 gives the schematic of the blockchain-based purchasing collaboration platform for MRO. Enterprises in the same alliance can upload their demands for MRO materials on the blockchain and connect their equipment to the blockchain-based platform. Once the set collaborative purchasing cycle or purchasing quantity is reached, the release of purchase demand will be triggered automatically through the smart contract [77]. Furthermore, if enterprises in the alliance realize the equipment data securely sharing based on the blockchain, the equipment data leger can be established for predictive purchasing. Finally, the blockchain-based purchasing collaboration platform for MRO will help optimize MRO purchasing for a low cost and a reasonable purchase plan while helping MRO suppliers dynamically predict the material demand.

VI. Challenges

The blockchain-based supply chain application has only been gradually developed in the last ten years, so it is still in the early stage of exploration. Technology and practice have encountered a lot of challenges. The former is the bottleneck of blockchain's own performance, which is closely related to the level of technological development and depends on further

TABLE IV
TECHNICAL CHALLENGES FACED BY THE BLOCKCHAIN

Technical challenges	Descriptions	Refs
Consensus algorithm	According to the CAP theory (Consistency, Availability, Partition tolerance) [78], based on satisfying the tolerance of network partition, strong consistency cannot coexist with availability. The performance is precisely the embodiment of availability. To meet the massively distributed data consistency requirements of the supply chain, the distributed consensus protocol needs to be optimized.	[79]
Data storage model	To cope with the massive amount of data generated by a large number of IoT equipment, the bottom layer of the blockchain must be optimized to support the dynamic expansion of storage. In actual operation, how to build an asynchronous data submission model and use the distributed cache, message queue, and local cache-based asynchronous storage together to solve storage optimization problems is an urgent problem.	[80]
Encryption algorithm	The construction of the supply chain platform involves a large number of enterprises and equipment. Due to different IoT equipment, different data encryption algorithms may be different. Therefore, it is necessary to adopt a set of architecture solutions compatible with multiple cryptographic algorithms.	[81]
Blockchain performance	Considering a large number of transactions and the intensive data interaction under the industrial IoT platform, it faces higher challenges to many performance indicators of the blockchain itself. For example (1) Blockchain node indicators (number of blocks produced, number of transactions processed, processing time, completion time, etc.); (2) P2P subsystem indicators (number of hit/miss requests, number of active users, the amount and structure of P2P traffic, etc.); (3) System node indicators (CPU, memory, storage, network, etc.).	[82]

TABLE V
PRACTICAL CHALLENGES FACED BY THE BLOCKCHAIN-BASED INDUSTRIAL IOT PLATFORM

Practical challenges	Descriptions	Refs
Business ledger storage	A large number of IoT equipment generate massive amounts of data. The sequential execution and storage of data specific to the blockchain have a direct conflict with performance. How to maintain stable performance under massive data storage is an urgent issue that needs to be considered.	[84]
Contract writing rule	The storage organization of smart contract transactions and status data in the blockchain is binary data. It is easy to recognize and process by software but difficult for users to understand. The blockchain-based platform is also difficult to interpret smart contract data in different fields and application scenarios as information that is easy for users to understand. It is urgent to study to improve the understandability of blockchain data, including application binary interface (ABI) and blockchain data specifications.	[85]
Blockchain performance testing method	The increase in equipment access also places extremely high requirements on the concurrency of the blockchain-based platform. In response to the requirements of high concurrency, the three problems need to be further explored, including how to establish various testing models to simulate extreme scenarios, conduct the pressure test to the platform, and find potential problems.	[86]

theoretical development, such as limited data throughput. The latter is the degree of matching between blockchain and specific business scenarios, mainly reflected in how blockchain meets the characteristics and needs of different scenarios, which mainly depends on the accurate abstraction of the scenarios and the adjustment of the specificity of blockchain.

A. Technology Challenges

Although blockchain technology has been widely used in the supply chain, it is still in the early stages of the application so that there are many technical bottlenecks, including consensus algorithm, data storage model, encryption algorithm, and blockchain performance. Table IV describes the technical challenges faced by blockchain. In the running time of blockchain, a large number of IoT equipment connect and generate data to the blockchain. Since the blockchain requires data consistency, the upload of massive data must be carried out in order. It restricts the data throughput capacity of the blockchain. The problem of blockchain throughput may be solved by exploring parallel technology in the future. Besides, due to different data forms of IoT equipment, it is required to be compatible with different encrypted data.

B. Practical Challenges

In the face of specific business scenarios in practice, the application of a blockchain-based industrial IoT platform for the supply chain faces the following practical challenges, including business ledger storage, contract writing rules, and blockchain performance testing methods. Table V gives the detailed descriptions. The business ledger focuses on the development of the distributed storage scheme for data in the real scenario [83]. The contract writing rule focuses on how to solve the interpretability problem caused by the difference between machine language and human language in the use of the smart contract. Blockchain performance testing method focuses on how to design a reasonable blockchain performance test method to evaluate whether the designed blockchain scheme can meet practical needs.

Besides, the integration of platforms and technology is a difficult task. In the actual platform construction process, the integration of IoT equipment and platform, the integration of blockchain and platform, and the integration of IoT equipment and blockchain need to be considered.

VII. FUTURE PERSPECTIVES

Although there are technical and practical challenges in applying the blockchain-based industrial IoT platform to solve the problems faced by the supply chain, academic exploration and industry practices in this area have also achieved certain development results. To provide a reference for the follow-up work, the article also proposes future research directions.

A. Consensus Algorithm

The consensus agreement is a key technology to realize data distributed consistency and decentralization, and avoid

multiple payment problems [87]. The existing consensus agreements are generally inefficient and cumbersome. Therefore, the lightweight consensus algorithm needs to be explored [88].

B. Cybersecurity

Cybersecurity involves the entire supply chain application process, starting from data collection via IoT, recording information to the blockchain, and then to application services. Only if there is a data leakage in this process, then the established data privacy protection will no longer exist [49]. Therefore, it is very necessary to explore cybersecurity issues in the full lifecycle of data.

C. Technical System and Standards

The blockchain-based industrial IoT platform is the fusion of multiple technologies, including blockchain, IoT technology, and platform technology. Each technology includes its technology system. It will be a great but very difficult thing to organically combine the three technologies and establish a unified and self-consistent technical system. For industrial applications, the establishment of platform architecture requires reference to the technical system. Therefore, the standardization of the technical system will be an urgent matter, and it is worthy of academic research to be further studied.

VIII. Conclusion

The article explores the potential requirements and opportunities of blockchain-based industrial IoT in the supply chain. To the best of our knowledge, this article is the first to systematically discuss the potential application of blockchain-based industrial IoT under various potential scenes in the supply chain. Through analyzing the industrial requirements of the supply chain, corresponding application opportunities are studied. Then, the challenges of blockchain-based industrial IoT faced by technology and practice are summarized. Furthermore, urgent research directions are proposed. We hope that our research could inspire industrial enterprises to explore the blockchain-based industrial IoT application in the supply chain and also look forward to providing a reference for academic research.

References

[1] N. Bakhtadze and A. Suleykin, "Industrial digital ecosystems: Predictive models and architecture development issues," *Annu. Rev. Control*, vol. 51, pp. 56–64, 2021.

[2] R. Azzi, R. K. Chamoun, and M. Sokhn, "The power of a blockchain-based supply chain," *Comput. Ind. Eng.*, vol. 135, pp. 582–592, Sep. 2019.

[3] F. Fraile, T. Tagawa, R. Poler, and A. Ortiz, "Trustworthy industrial IoT gateways for interoperability platforms and ecosystems," *IEEE Internet Things J.*, vol. 5, no. 6, pp. 4506–4514, Dec. 2018.

[4] M. Ben-Daya, E. Hassini, and Z. Bahroun, "Internet of Things and supply chain management: A literature review," *Int. J. Prod. Res.*, vol. 57, nos. 15–16, pp. 4719–4742, Aug. 2019.

[5] C. Garrido-Hidalgo, T. Olivares, F. J. Ramirez, and L. Roda-Sanchez, "An end-to-end Internet of Things solution for reverse supply chain management in Industry 4.0," *Comput. Ind.*, vol. 112, Nov. 2019, Art. no. 103127.

[6] W. Zhou, Y. Jia, A. Peng, Y. Zhang, and P. Liu, "The effect of IoT new features on security and privacy: New threats, existing solutions, and challenges yet to be solved," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1606–1616, Apr. 2019.

[7] A. Boiko, V. Shendryk, and O. Boiko, "Information systems for supply chain management: Uncertainties, risks and cyber security," *Proc. Comput. Sci.*, vol. 149, pp. 65–70, 2019.

[8] D. Mazzei *et al.*, "A blockchain tokenizer for industrial IoT trustless applications," *Future Gener. Comput. Syst.*, vol. 105, pp. 432–445, Apr. 2020.

[9] P. K. Sharma, N. Kumar, and J. H. Park, "Blockchain technology toward green IoT: Opportunities and challenges," *IEEE Netw.*, vol. 34, no. 4, pp. 263–269, Jul. 2020.

[10] K. Korpela, J. Hallikas, and T. Dahlberg, "Digital supply chain transformation toward blockchain integration," in *Proc. 50th Hawaii Int. Conf. Syst. Sci.*, 2017, pp. 1–10.

[11] R. Cole, M. Stevenson, and J. Aitken, "Blockchain technology: Implications for operations and supply chain management," *Supply Chain Management: Int. J.*, vol. 24, no. 4, pp. 469–483, Jun. 2019.

[12] R. Casado-Vara, J. Prieto, F. De la Prieta, and J. M. Corchado, "How blockchain improves the supply chain: Case study alimentary supply chain," *Proc. Comput. Sci.*, vol. 134, pp. 393–398, Aug. 2018.

[13] Z. Zhou, X. Chen, Y. Zhang, and S. Mumtaz, "Blockchain-empowered secure spectrum sharing for 5G heterogeneous networks," *IEEE Netw.*, vol. 34, no. 1, pp. 24–31, Jan./Feb. 2020.

[14] X. Lin, J. Wu, S. Mumtaz, S. Garg, J. Li, and M. Guizani, "Blockchain-based on-demand computing resource trading in IoV-assisted smart city," *IEEE Trans. Emerg. Topics Comput.*, vol. 9, no. 3, pp. 1373–1385, Jul. 2021.

[15] L. Chen, X. Zhao, O. Tang, L. Price, S. Zhang, and W. Zhu, "Supply chain collaboration for sustainability: A literature review and future research agenda," *Int. J. Prod. Econ.*, vol. 194, pp. 73–87, Dec. 2017.

[16] X. L. Liu, W. M. Wang, H. Guo, A. V. Barenji, Z. Li, and G. Q. Huang, "Industrial blockchain based framework for product lifecycle management in Industry 4.0," *Robot. Comput.-Integr. Manuf.*, vol. 63, Jun. 2020, Art. no. 101897.

[17] Y.-W. Jung, Y.-K. Lim, and M.-S. Kim, "Possibilities and limitations of online document tools for design collaboration: The case of Google docs," in *Proc. ACM Conf. Comput. Cooperat. Work Social Comput.*, Feb. 2017, pp. 1096–1108.

[18] R. Winkler, R. O. Briggs, G.-J. De Vreede, J. M. Leimeister, S. Oeste-Reiss, and M. Sollner, "Modeling support for mass collaboration in open innovation initiatives—The facilitation process model 2.0," *IEEE Trans. Eng. Manag.*, early access, Mar. 16, 2020, doi: 10.1109/TEM.2020.2975938.

[19] H. M. Stellingwerf, L. H. C. Groeneveld, G. Laporte, A. Kanellopoulos, J. M. Bloemhof, and B. Behdani, "The quality-driven vehicle routing problem: Model and application to a case of cooperative logistics," *Int. J. Prod. Econ.*, vol. 231, Jan. 2021, Art. no. 107849.

[20] S. Lechler, A. Canzaniello, and E. Hartmann, "Assessment sharing intra-industry strategic alliances: Effects on sustainable supplier management within multi-tier supply chains," *Int. J. Prod. Econ.*, vol. 217, pp. 64–77, Nov. 2019.

[21] M. Giannakis, R. Dubey, I. Vlachos, and Y. Ju, "Supplier sustainability performance evaluation using the analytic network process," *J. Cleaner Prod.*, vol. 247, Feb. 2020, Art. no. 119439.

[22] J. Lohmer and R. Lasch, "Blockchain in operations management and manufacturing: Potential and barriers," *Comput. Ind. Eng.*, vol. 149, Nov. 2020, Art. no. 106789.

[23] J.-C. Cheng, N.-Y. Lee, C. Chi, and Y.-H. Chen, "Blockchain and smart contract for digital certificate," in *Proc. IEEE Int. Conf. Appl. Syst. Invention (ICASI)*, Apr. 2018, pp. 1046–1051.

[24] A. Pal and K. Kant, "Using blockchain for provenance and traceability in Internet of Things-integrated food logistics," *Computer*, vol. 52, no. 12, pp. 94–98, Dec. 2019.

[25] Y. Wang, J. Lin, and T.-M. Choi, "Gray market and counterfeiting in supply chains: A review of the operations literature and implications to luxury industries," *Transp. Res. E, Logistics Transp. Rev.*, vol. 133, Jan. 2020, Art. no. 101823.

[26] Q. Lu and X. Xu, "Adaptable blockchain-based systems: A case study for product traceability," *IEEE Softw.*, vol. 34, no. 6, pp. 21–27, Nov./Dec. 2017.

[27] H. Li, S. Mi, Q. Li, X. Wen, D. Qiao, and G. Luo, "A scheduling optimization method for maintenance, repair and operations service resources of complex products," *J. Intell. Manuf.*, vol. 31, no. 7, pp. 1673–1691, Oct. 2020.

[28] X. Zhao, J. Cai, S. Mizutani, and T. Nakagawa, "Preventive replacement policies with time of operations, mission durations, minimal repairs and maintenance triggering approaches," *J. Manuf. Syst.*, vol. 61, pp. 819–829, Jun. 2020.

[29] A. R. Somarin, S. Asian, F. Jolai, and S. Chen, "Flexibility in service parts supply chain: A study on emergency resupply in aviation MRO," *Int. J. Prod. Res.*, vol. 56, no. 10, pp. 3547–3562, 2017.

[30] J. Cheng, W. Chen, F. Tao, and C.-L. Lin, "Industrial IoT in 5G environment towards smart manufacturing," *J. Ind. Inf. Integr.*, vol. 10, pp. 10–19, Jun. 2018.

[31] H. Liao *et al.*, "Learning-based context-aware resource allocation for edge-computing-empowered industrial IoT," *IEEE Internet Things J.*, vol. 7, no. 5, pp. 4260–4277, May 2020.

[32] T. Wang, P. Wang, S. Cai, Y. Ma, A. Liu, and M. Xie, "A unified trustworthy environment establishment based on edge computing in Industrial IoT," *IEEE Trans. Ind. Informat.*, vol. 16, no. 9, pp. 6083–6091, Sep. 2020.

[33] D. A. Chekired, L. Khoukhi, and H. T. Mouftah, "Industrial IoT data scheduling based on hierarchical fog computing: A key for enabling smart factory," *IEEE Trans. Ind. Informat.*, vol. 14, no. 10, pp. 4590–4602, Oct. 2018.

[34] J.-S. Fu, Y. Liu, H.-C. Chao, B. K. Bhargava, and Z.-J. Zhang, "Secure data storage and searching for industrial IoT by integrating fog computing and cloud computing," *IEEE Trans. Ind. Informat.*, vol. 14, no. 10, pp. 4519–4528, Oct. 2018.

[35] G. Wang, M. Nixon, and M. Boudreaux, "Toward cloud-assisted industrial IoT platform for large-scale continuous condition monitoring," *Proc. IEEE*, vol. 107, no. 6, pp. 1193–1205, Jun. 2019.

[36] S. Huang, Z. Zeng, K. Ota, M. Dong, T. Wang, and N. Xiong, "An intelligent collaboration trust interconnections system for mobile information control in ubiquitous 5G networks," *IEEE Trans. Netw. Sci. Eng.*, vol. 8, no. 1, pp. 347–365, Mar. 2020.

[37] D. Hussein, E. Bertin, and V. Frey, "A community-driven access control approach in distributed IoT environments," *IEEE Commun. Mag.*, vol. 55, no. 3, pp. 146–153, Mar. 2017.

[38] I. Mistry, S. Tanwar, S. Tyagi, and N. Kumar, "Blockchain for 5G-enabled IoT for industrial automation: A systematic review, solutions, and challenges," *Mech. Syst. Signal Process.*, vol. 135, Jan. 2020, Art. no. 106382.

[39] J. Li, J. Wu, and L. Chen, "Block-secure: Blockchain based scheme for secure P2P cloud storage," *Inf. Sci.*, vol. 465, pp. 219–231, Oct. 2018.

[40] F. M. Bencic and I. P. Zarko, "Distributed ledger technology: Blockchain compared to directed acyclic graph," in *Proc. IEEE 38th Int. Conf. Distrib. Comput. Syst. (ICDCS)*, Jul. 2018, pp. 1569–1570.

[41] T. M. Fernández-Caramès and P. Fraga-Lamas, "Towards post-quantum blockchain: A review on blockchain cryptography resistant to quantum computing attacks," *IEEE Access*, vol. 8, pp. 21091–21116, 2020.

[42] Z. Zheng, S. Xie, H. Dai, X. Chen, and H. Wang, "An overview of blockchain technology: Architecture, consensus, and future trends," in *Proc. IEEE Int. Congr. Big Data (BigData Congress)*, Jun. 2017, pp. 557–564.

[43] B. K. Mohanta, S. S. Panda, and D. Jena, "An overview of smart contract and use cases in blockchain technology," in *Proc. 9th Int. Conf. Comput., Commun. Netw. Technol. (ICCCNT)*, Jul. 2018, pp. 1–4.

[44] Z. Liu *et al.*, "A survey on applications of game theory in blockchain," 2019, *arXiv:1902.10865*.

[45] J. Kolb, M. AbdelBaky, R. H. Katz, and D. E. Culler, "Core concepts, challenges, and future directions in blockchain: A centralized tutorial," *ACM Comput. Surveys*, vol. 53, no. 1, pp. 1–39, May 2020.

[46] J. Leng *et al.*, "Blockchain-secured smart manufacturing in Industry 4.0: A survey," *IEEE Trans. Syst., Man, Cybern. Syst.*, vol. 51, no. 1, pp. 237–252, Jan. 2020.

[47] Z. Yang, K. Yang, L. Lei, K. Zheng, and V. C. M. Leung, "Blockchain-based decentralized trust management in vehicular networks," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1495–1505, Apr. 2019.

[48] Z. Ren, K. Cong, T. Aerts, B. de Jonge, A. Morais, and Z. Erkin, "A scale-out blockchain for value transfer with spontaneous sharding," in *Proc. Crypto Valley Conf. Blockchain Technol. (CVCBT)*, Jun. 2018, pp. 1–10.

[49] J. Leng, M. Zhou, J. L. Zhao, Y. Huang, and Y. Bian, "Blockchain security: A survey of techniques and research directions," *IEEE Trans. Services Comput.*, early access, Nov. 25, 2021, doi: 10.1109/TSC.2020.3038641.

[50] H. Johng, D. Kim, T. Hill, and L. Chung, "Using blockchain to enhance the trustworthiness of business processes: A goal-oriented approach," in *Proc. IEEE Int. Conf. Services Comput. (SCC)*, Jul. 2018, pp. 249–252.

[51] U. U. Uchibeke, K. A. Schneider, S. H. Kassani, and R. Deters, "Blockchain access control ecosystem for big data security," in *Proc. IEEE Int. Conf. Internet Things (iThings), IEEE Green Comput. Commun. (GreenCom), IEEE Cyber, Phys. Social Comput. (CPSCom), IEEE Smart Data (SmartData)*, Jul. 2018, pp. 1373–1378.

[52] D. Wu and N. Ansari, "A cooperative computing strategy for blockchain-secured fog computing," *IEEE Internet Things J.*, vol. 7, no. 7, pp. 6603–6609, Jul. 2020.

[53] J. Wang, C. Xu, J. Zhang, J. Bao, and R. Zhong, "A collaborative architecture of the industrial internet platform for manufacturing systems," *Robot. Comput.-Integr. Manuf.*, vol. 61, Feb. 2020, Art. no. 101854.

[54] R. D. Raut, A. Gotmare, B. E. Narkhede, U. H. Govindarajan, and S. U. Bokade, "Enabling technologies for Industry 4.0 manufacturing and supply chain: Concepts, current status, and adoption challenges," *IEEE Eng. Manag. Rev.*, vol. 48, no. 2, pp. 83–102, Jun. 2020.

[55] D. Yin, X. Ming, and X. Zhang, "Sustainable and smart product innovation ecosystem: An integrative status review and future perspectives," *J. Cleaner Prod.*, vol. 274, Nov. 2020, Art. no. 123005.

[56] S. Friesike, C. M. Flath, M. Wirth, and F. Thiesse, "Creativity and productivity in product design for additive manufacturing: Mechanisms and platform outcomes of remixing," *J. Oper. Manage.*, vol. 65, no. 8, pp. 735–752, Dec. 2019.

[57] Q. Lin and S. Wong, "A study of intellectual property protection for mass innovation spaces," in *Proc. Int. Conf. Appl. Syst. Innov. (ICASI)*, May 2017, pp. 973–975.

[58] S. Rahmanzadeh, M. S. Pishvaee, and M. R. Rasouli, "Integrated innovative product design and supply chain tactical planning within a blockchain platform," *Int. J. Prod. Res.*, vol. 58, no. 1, pp. 1–21, 2019.

[59] R. Mehta, N. Kapoor, S. Sourav, and R. Shorey, "Decentralised image sharing and copyright protection using blockchain and perceptual hashes," in *Proc. 11th Int. Conf. Commun. Syst. Netw. (COMSNETS)*, Jan. 2019, pp. 1–6.

[60] Z. Meng, T. Morizumi, S. Miyata, and H. Kinoshita, "Design scheme of copyright management system based on digital watermarking and blockchain," in *Proc. IEEE 42nd Annu. Comput. Softw. Appl. Conf. (COMPSAC)*, Jul. 2018, pp. 359–364.

[61] J. Chen, R. Mo, L. Wu, and S. Yu, "A method of collaborative task allocation for cloud service platform of industrial design," in *Proc. 8th Int. Conf. Intell. Hum.-Mach. Syst. Cybern. (IHMSC)*, vol. 1, 2016, pp. 484–487.

[62] S. K. Dwivedi, R. Amin, and S. Vollala, "Blockchain based secured information sharing protocol in supply chain management system with key distribution mechanism," *J. Inf. Secur. Appl.*, vol. 54, Oct. 2020, Art. no. 102554.

[63] S. Xu, Y. Xin, H. Zhu, S. Luo, and Y. Chen, "A authentication and access authorization mechanism on the PaaS platform," in *Proc. IEEE Symp. Ser. Comput. Intell. (SSCI)*, Dec. 2019, pp. 893–900.

[64] M. I. S. Assaqty *et al.*, "Private-blockchain-based industrial IoT for material and product tracking in smart manufacturing," *IEEE Netw.*, vol. 34, no. 5, pp. 91–97, Sep. 2020.

[65] Y. Zhang, P. Zhang, F. Tao, Y. Liu, and Y. Zuo, "Consensus aware manufacturing service collaboration optimization under blockchain based industrial internet platform," *Comput. Ind. Eng.*, vol. 135, pp. 1025–1035, Sep. 2019.

[66] H. Yao, T. Mai, J. Wang, Z. Ji, C. Jiang, and Y. Qian, "Resource trading in blockchain-based industrial Internet of Things," *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3602–3609, Jun. 2019.

[67] Z. Chen, X. Ming, T. Zhou, and Y. Chang, "Sustainable supplier selection for smart supply chain considering internal and external uncertainty: An integrated rough-fuzzy approach," *Appl. Soft Comput.*, vol. 87, Feb. 2020, Art. no. 106004.

[68] A. Dolgui, "Blockchain-oriented dynamic modelling of smart contract design and execution in the supply chain," *Int. J. Prod. Res.*, vol. 58, no. 7, pp. 2184–2199, 2019.

[69] L. X. Downey, F. Bauchot, and J. Röling, "Blockchain for business value: A contract and work flow management to reduce disputes pilot project," *IEEE Eng. Manag. Rev.*, vol. 46, no. 4, pp. 86–93, Dec. 2018.

[70] R. Schuitemaker and X. Xu, "Product traceability in manufacturing: A technical review," *Proc. CIRP*, vol. 93, pp. 700–705, 2020.

[71] C. Zhuang, J. Gong, and J. Liu, "Digital twin-based assembly data management and process traceability for complex products," *J. Manuf. Syst.*, vol. 58, pp. 118–131, Jan. 2021.

[72] I. J. Orji, S. Kusi-Sarpong, S. Huang, and D. Vazquez-Brust, "Evaluating the factors that influence blockchain adoption in the freight logistics industry," *Transp. Res. E, Logistics Transp. Rev.*, vol. 141, Sep. 2020, Art. no. 102025.

[73] S. J. Trenfield *et al.*, "Track-and-trace: Novel anti-counterfeit measures for 3D printed personalized drug products using smart material inks," *Int. J. Pharmaceutics*, vol. 567, Aug. 2019, Art. no. 118443.
[74] R. Kumar and R. Tripathi, "Traceability of counterfeit medicine supply chain through blockchain," in *Proc. 11th Int. Conf. Commun. Syst. Netw. (COMSNETS)*, Jan. 2019, pp. 568–570.
[75] N. Kshetri, "Blockchain and the economics of customer satisfaction," *IT Prof.*, vol. 21, no. 1, pp. 93–97, Jan. 2019.
[76] J. Chen, O. Gusikhin, W. Finkenstaedt, and Y.-N. Liu, "Maintenance, repair, and operations parts inventory management in the era of Industry 4.0," *IFAC-PapersOnLine*, vol. 52, no. 13, pp. 171–176, 2019.
[77] Y. Wang, M. Singgih, J. Wang, and M. Rit, "Making sense of blockchain technology: How will it transform supply chains?" *Int. J. Prod. Econ.*, vol. 211, pp. 221–236, May 2019.
[78] S. D. Angelis, L. Aniello, R. Baldoni, F. Lombardi, and V. Sassone, "Pbft vs proof-of-authority: Applying the cap theorem to permissioned blockchain," in *Proc. Italian Conf. Cybersecurity*, 2017, pp. 1–11.
[79] S. Li, S. Zhao, P. Yang, P. Andriotis, L. Xu, and Q. Sun, "Distributed consensus algorithm for events detection in cyber-physical systems," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 2299–2308, Apr. 2019.
[80] M. Xu, G. Feng, Y. Ren, and X. Zhang, "On cloud storage optimization of blockchain with a clustering-based genetic algorithm," *IEEE Internet Things J.*, vol. 7, no. 9, pp. 8547–8558, Sep. 2020.
[81] Y. Shoukry *et al.*, "Privacy-aware quadratic optimization using partially homomorphic encryption," in *Proc. IEEE 55th Conf. Decis. Control (CDC)*, Dec. 2016, pp. 5053–5058.
[82] Q. Zhou, H. Huang, Z. Zheng, and J. Bian, "Solutions to scalability of blockchain: A survey," *IEEE Access*, vol. 8, pp. 16440–16455, 2020.
[83] R. K. Raman and L. R. Varshney, "Dynamic distributed storage for blockchains," in *Proc. IEEE Int. Symp. Inf. Theory (ISIT)*, Jun. 2018, pp. 2619–2623.
[84] L. Xu, L. Chen, Z. Gao, Y. Lu, and W. Shi, "CoC: Secure supply chain management system based on public ledger," in *Proc. 26th Int. Conf. Comput. Commun. Netw. (ICCCN)*, Jul. 2017, pp. 1–6.
[85] G. Governatori, F. Idelberger, Z. Milosevic, R. Riveret, G. Sartor, and X. Xu, "On legal contracts, imperative and declarative smart contracts, and blockchain systems," *Artif. Intell. Law*, vol. 26, no. 4, pp. 377–409, Dec. 2018.
[86] B. Farahani, F. Firouzi, and M. Luecking, "The convergence of IoT and distributed ledger technologies (DLT): Opportunities, challenges, and solutions," *J. Netw. Comput. Appl.*, vol. 177, Mar. 2021, Art. no. 102936.
[87] Y. Hao, Y. Li, X. Dong, L. Fang, and P. Chen, "Performance analysis of consensus algorithm in private blockchain," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2018, pp. 280–285.
[88] S. Biswas, K. Sharif, F. Li, S. Maharjan, S. P. Mohanty, and Y. Wang, "PoBT: A lightweight consensus algorithm for scalable IoT business blockchain," *IEEE Internet Things J.*, vol. 7, no. 3, pp. 2343–2355, Mar. 2020.

Zhao-Hui Sun (Member, IEEE) is currently pursuing the Ph.D. degree in industrial intelligent systems with the Department of Industrial Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China.

He has authored or coauthored more than 15 research articles in top-tier refereed international journals and conferences, such as the IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT and the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS. His current research interests include blockchain, evolutionary optimization, neuroergonomics, brain-inspired intelligence, cognitive computing, complex network, nonparametric machine learning, operations research, knowledge automation, and their applications in industrial or medical problems.

Mr. Sun is a member of the IEEE Computational Intelligence Society and Association for Computing Machinery. He also has been severing as the reviewer for several top-tier international journals and conferences in his research field.

Zhiyang Chen received the B.S. degree in industrial engineering from Shanghai Jiao Tong University, Shanghai, China, in 2021, where he is currently pursuing the M.S. degree in industrial engineering with the School of Mechanical.

His current research interests include logistics and supply chain management, continuous finite comparative decision theory, production and operation management, complex systems modeling, and intelligent control of complex systems.

Sijia Cao received the B.S. degree in mechanical engineering from the Chongqing University of Posts and Telecommunications, Chongqing, China, in 2019. She is currently pursuing the master's degree in industrial engineering with the Department of Industrial Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China.

Her current research interest is production plan and control, service-oriented scheduling, and intelligent transportation systems.

Xinguo Ming received the Ph.D. degree in computer-aided process planning from Shanghai Jiao Tong University, Shanghai, China, in 1995.

He was a Research Scientist with the Singapore Institute of Manufacturing Technology, Nanyang, Singapore. He is currently a Full Professor of industrial engineering with the Department of Industrial Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University. He is also the Director of the Shanghai Research Center for Industrial Informatics, Shanghai. He has published more than 100 research articles in refereed international journals and conferences. His research focuses mainly on the industrial Internet, product-service systems, and innovation ecosystem.