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Application of blockchain in the field of intelligent manufacturing: Theoretical basis, realistic plights, and development suggestions

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Abstract Blockchain technology is considered one of the promising technologies of the information technology era. The core features of blockchain, such as decentralization, transparency, high security, and tamper-proof nature, bring great convenience for large-scale social cooperation and data sharing. Blockchain has a broad application prospect in the field of intelligent manufacturing. The key issues of this field, such as distributed collaborative production, industrial big data sharing and security, transparent logistics, and supply chain, are naturally consistent with the core characteristics of the blockchain technology. This study aims to analyze the application of blockchain in the field of intelligent manufacturing. First, we introduce the basic connotation and applications of blockchain. Then, we propose the theoretical basis for the application of blockchain in the field of intelligent manufacturing. Finally, we point out the realistic plights and provide some suggestions to promote the application of blockchain in the field of intelligent manufacturing.

Keywords blockchain technology, intelligent manufacturing, networked collaborative manufacturing, full life-cycle management, manufacturing model innovation

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1 Introduction

Blockchain is a new technology that is characterized by decentralization, transparency, and high security (Mettler, 2016). The concept of blockchain originated from Bitcoin, the digital cryptocurrency system, and was introduced by Nakamoto (2008). In essence, blockchain is a shared database, in which the data and information stored have certain features, such as unforgery, traceability, public transparency, and collective maintenance (Wüst and Gervais, 2018). The blockchain technology has established a solid foundation of “trust” on the basis of these features, thus creating a reliable “cooperation” mechanism with a broad application prospect. The blockchain technology is widely used in various fields, such as finance and medical fields.

In recent years, many scholars have studied the application of the blockchain technology in intelligent manufacturing fields, such as supply chain (Angrish et al., 2018) and Internet of Things (Bahga and Madiseti, 2016). The blockchain technology plays a key role in data sharing, distributed collaborative manufacturing, and life-cycle management, and has an important influence on the development of intelligent manufacturing. This study proposes a four-stage model to analyze the theoretical basis of the blockchain application in the field of intelligent manufacturing. In the model, we expound the potential value of blockchain for the development of intelligent manufacturing from four levels: Industrial big data integration, networked collaborative manufacturing, full life-cycle management, and manufacturing model innovation.

The rest of this paper is organized as follows. Section 2 describes the basic connotation of blockchain. Section 3 introduces the theoretical basis of the blockchain application for intelligent manufacturing. Section 4 discusses the challenges and suggestions. Section 5 presents the contributions.

2 Basic connotation and application of blockchain

2.1 Basic structure of blockchain

Blockchain data are stored in different blocks, which are connected end-to-end by a special Hash function value to form a chain of data that increases over time (Buterin, 2014). The structure of each block and the blockchain are shown in Fig. 1. A block is mainly composed of the block header and body. The block header basically stores the Hash value of the previous block header. The Hash value is a hashed value, such as “ahdhdhdhdhdh2333hheh”, with fixed digits (such as 128 or 256 bits), generated by the previous block after the overall data are encrypted by the Hash function. The block body mainly stores the core data in the block, including the transaction list and timestamp. The transaction order is essentially a data record in our relational database, recording the operational data that take place between the principals of the blockchain system (Yaga et al., 2018). Figure 1 shows that the block header of each block records the Hash function value of the previous block. In this way, each block forms a chain data storage structure connected in turn. The new transactions and data are generated over time, and the new blocks are also simultaneously created.

2.2 Basic features of blockchain

(1) Decentralization and joint maintenance

Each node of the blockchain system has the same chain database and participates in the data record and update of the database. The node relies on a core technology called peer-to-peer (P2P) network. The chain database of the blockchain system is transferred and processed through each node on the basis of the P2P network transmission technology. Blockchain data are the category of distributed data storage. Figure 2 shows that the traditional centralized data service pattern requires a centralized data storage center, and all the data of the users come from the unified centralized server. Once the centralized server fails, data

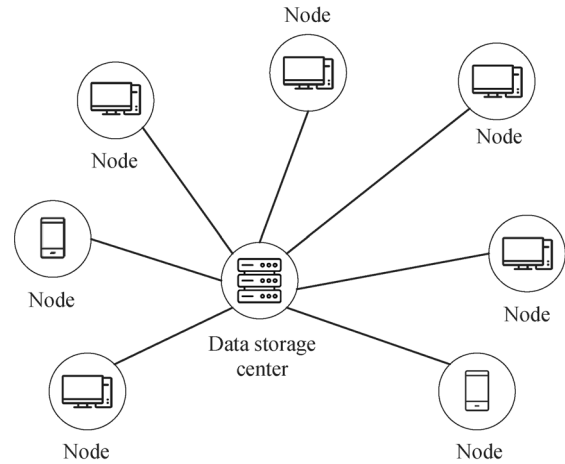


Fig. 2 Traditional centralized data service pattern.

corruption or other problems may occur, and the entire system will be down (Wu and Duan, 2019). The distributed shared database model of the blockchain system allows it to have the great advantage of decentralization (Fig. 3). Data loss or failure of one or more system nodes will not affect the operation of the entire system. Even if a data failure occurs in a single or multiple nodes, the other nodes will still keep the same network-wide consistent database (Pinna and Ruttenberg, 2016). This feature is the decentralization of blockchain.

(2) Creation of trust, openness, and transparency

Each node of the blockchain system can download and own a chain database consistent with the whole network, although different nodes can only view and command the relevant data with permissions related to themselves. Accordingly, the blockchain database becomes open and transparent. A trust relationship between the nodes of the system can be realized by blockchain, not depending on subjective social relationship, but through reliable mathematical algorithms. Figure 4 shows that the algorithm used to realize trust between nodes is called the “consensus algorithm” of blockchain. For example, the famous Bitcoin and all other types of similar cryptocurrencies apply the

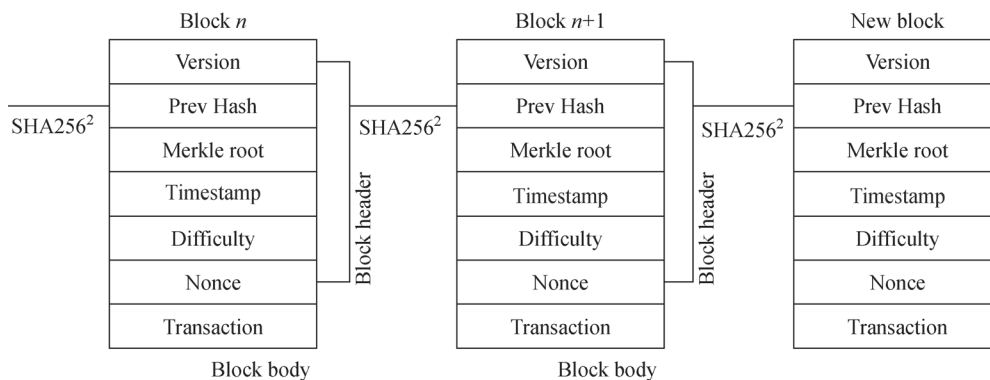


Fig. 1 Block and blockchain structure.

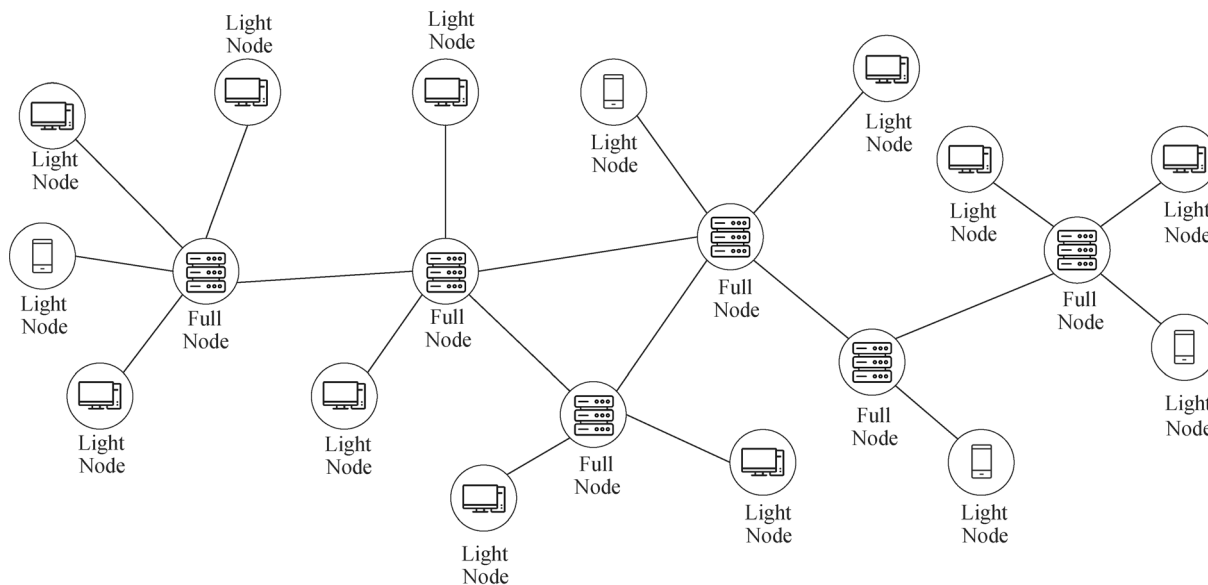


Fig. 3 Decentralized data service pattern of blockchain.

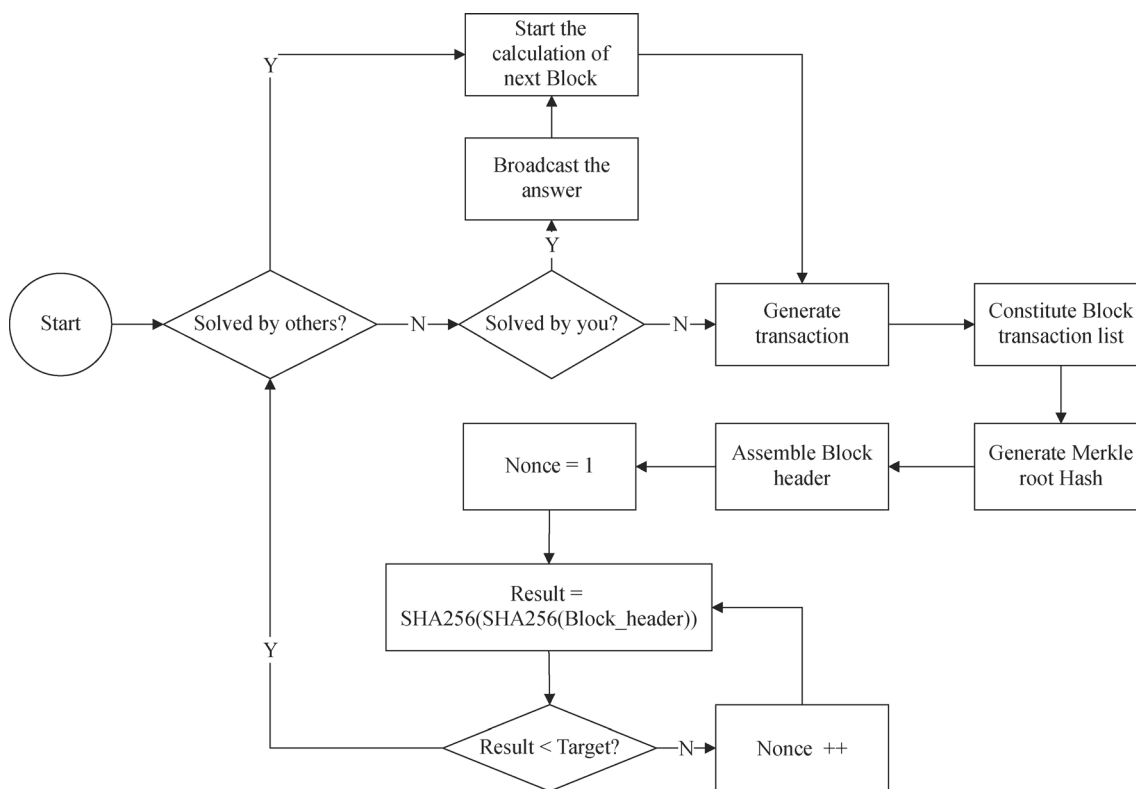


Fig. 4 The process of POW algorithm.

Proof of Work (POW) algorithm (Gervais et al., 2016), while the Ethereum platform uses the Proof of Stake (POS) algorithm (Vasin, 2014). Many classical consensus algorithms, such as the Practical Byzantine Fault Tolerance, are proposed (Sukhwani et al., 2017). Accordingly, blockchain gradually breaks away from cryptocurrency and is

increasingly used in finance, manufacturing, energy, medical, and other fields.

(3) Security, confidentiality, and tamper-proof nature Blockchain applies cryptography and security technology to ensure the reliability of data transmission, storage, and other aspects. These technologies mainly

include asymmetric encryption technology, digital signature technology, and the design of the storage structure of the blockchain (Yuan and Wang, 2016). The asymmetric encryption technology is a type of encryption technology with different keys during encryption and decryption. Each user has a group of key pairs, including public and private keys. The data encrypted by the public key need to be decrypted by the corresponding private key. Meanwhile, the data encrypted by the private key need to be decrypted by the public key (Simmons, 1979) (Fig. 5). Everyone's public keys are generally public, while private keys are private. The digital signature technology is a comprehensive application of the asymmetric encryption and digital digest technologies. Such a technology solves the problem of determining whether the data sent by User A have not been tampered with in the midway. Blockchain can ensure that data cannot be tampered with during transmission by the digital signature technology (Kravitz, 1993). The data stored on the blockchain cannot be tampered with also due to the design of the chain storage structure of the blockchain. The basic principle is that each data block contains the Hash encryption value of the previous block. When any data block on the blockchain is tampered with, the Hash value of the subsequent block will change. With the Hash calculation, we can easily verify whether the data of the blockchain have been changed on each node of the blockchain; specifically, once the data of the blockchain have been modified, they can be immediately found by each node (Ateniese et al., 2017). The blockchain have the advantages and features of security, confidentiality, and tamper-proof nature mainly owing to the comprehensive application of the above-mentioned main encryption technologies.

(4) Smart Contract with automatic execution

The concept of Smart Contract is not new. Computer scientist and cryptographer Nick Szabo first proposed this concept in 1994 (i.e., earlier than the birth of the concept of blockchain) (Huh et al., 2017). A Smart Contract is a special protocol designed to provide, validate, and enforce contracts. Specifically, the blockchain Smart Contract refers to the application of the blockchain technology to store the electronic contract and related operations (in the form of program code) into the blockchain block; thus, the electronic contract cannot be tampered with and can be automatically executed (Alharby and van Moorsel, 2017)

(Fig. 6). The Smart Contract ensures the decentralization of the blockchain system, thereby allowing us to execute traceable, irreversible, and secure transactions without a third party. The Smart Contract contains all the information about the transaction. The result operation can be performed only after the requirements are satisfied. The difference between the Smart Contract and the traditional paper contract is that the former is generated by computer program and code (Macrinici et al., 2018), which explains the obligations of the parties involved. The intelligent contract agreed by the computer code can be automatically and safely executed, due to the high security and tamper-proof nature of blockchain (Zhang and Wen, 2017).

2.3 Blockchain applications

Blockchain was first applied to the digital currency Bitcoin and labeled as Blockchain 1.0. The Smart Contract was used to define some trigger terms. The contract was automatically executed when the terms were satisfied; this task expanded the application space of blockchain and laid the foundation for the rapid development of blockchain, which was then labeled as Blockchain 2.0. Besides the application of blockchain in currency, finance, and market, it was gradually implemented in other sectors, thereby changing our society and life in various aspects, which was then labeled as Blockchain 3.0 (Efanov and Roschin, 2018; Angelis and Ribeiro da Silva, 2019). To date, blockchain has been gradually established in various sectors, such as finance, supply chain, energy, medical care, and social governance (Akins et al., 2014; Armknecht et al., 2015; Peters et al., 2015; Kuo et al., 2017; Liang et al., 2017; 2019; Tanaka et al., 2017; Fernando et al., 2018; Werbach, 2018) (Fig. 7).

The combination of blockchain and supply chain enables supply chain enterprises to operate transparently, and further innovates and develops the supply chain industry (Korpela et al., 2017). For example, Provenance is an American blockchain technology company that provides supply chain traceability services for all types of enterprises. Provenance can record the whole process of information of the global retail supply chain in the blockchain, so that consumers can search in real time and improve the information transparency of the supply chain. The tracking of Provenance is made throughout the

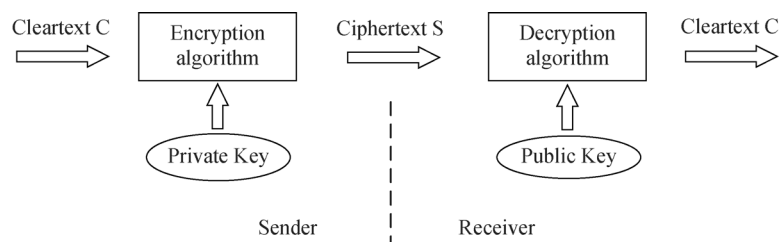


Fig. 5 Asymmetric encryption algorithm flow.

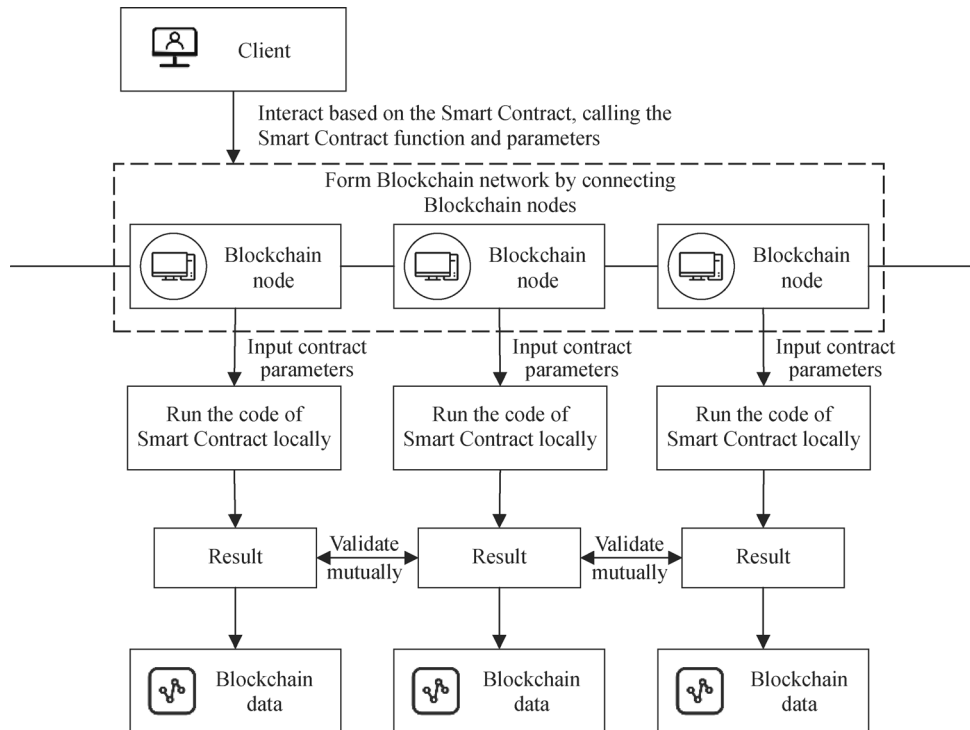


Fig. 6 Smart Contract process.

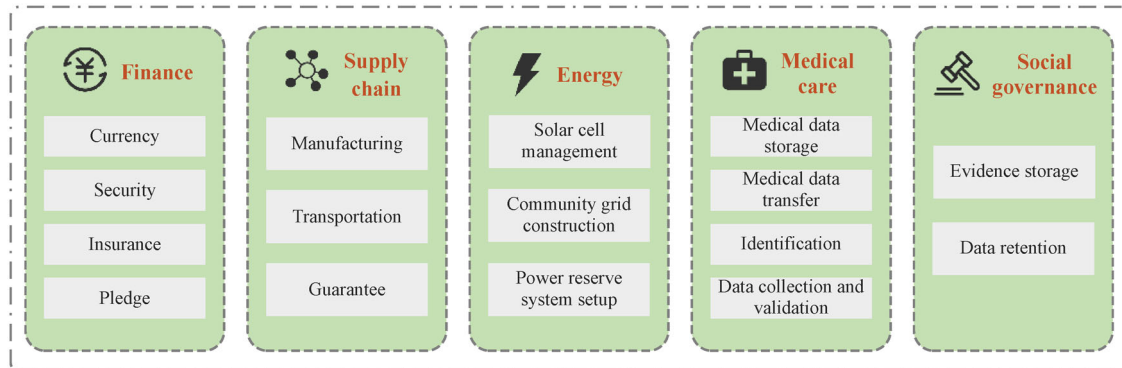


Fig. 7 Application scenarios of blockchain.

product life-cycle. Users can monitor the target with Internet-connected devices, tracking the origin of goods and the intermediate transactions of the entire process in a transparent manner. The applications of blockchain in the field of supply chain are shown in Fig. 8.

3 Theoretical basis for the application of blockchain in intelligent manufacturing

The blockchain technology can create trust, realize value sharing, and enable the realization of large-scale collaboration and data sharing. The comprehensive technical features of blockchain support its wide application in the

field of intelligent manufacturing. Table 1 lists the correlations between the core technical features of blockchain and intelligent manufacturing.

Blockchain can effectively build trust and improve efficiency for intelligent manufacturing, which brings a new value experience (Yang, 2019). This study proposes a model to explain the application of the blockchain technology in the field of intelligent manufacturing from four levels: Industrial big data integration, networked collaborative manufacturing, full life-cycle management, and manufacturing model innovation (Fig. 9). During industrial big data integration, the blockchain technology can safely realize data sharing to provide basic data connectivity for intelligent manufacturing. The blockchain

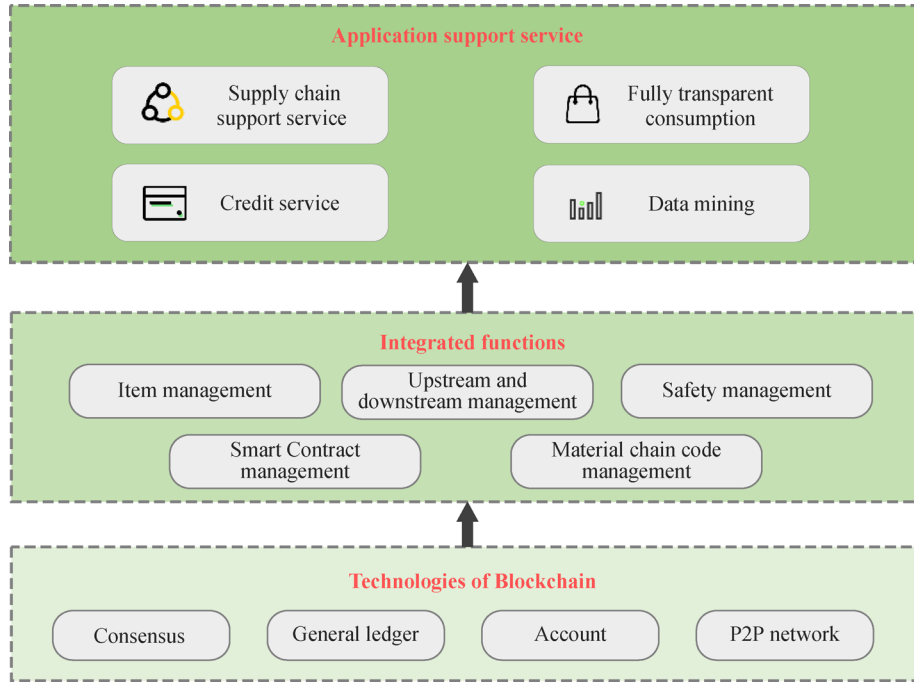


Fig. 8 Applications of blockchain in the field of supply chain.

Table 1 Features of blockchain and their correlation with intelligent manufacturing

Core features of blockchain	Correlation with intelligent manufacturing
Decentralization, openness, and transparency	Resource sharing of networked collaborative manufacturing and distributed manufacturing
Secure encryption and high security	Industrial big data circulation and data sharing
Tamper-proof nature and traceability	Industry traceability and product life-cycle management
Smart Contract with automatic execution	Transfer of manufacturing value and innovation of manufacturing model

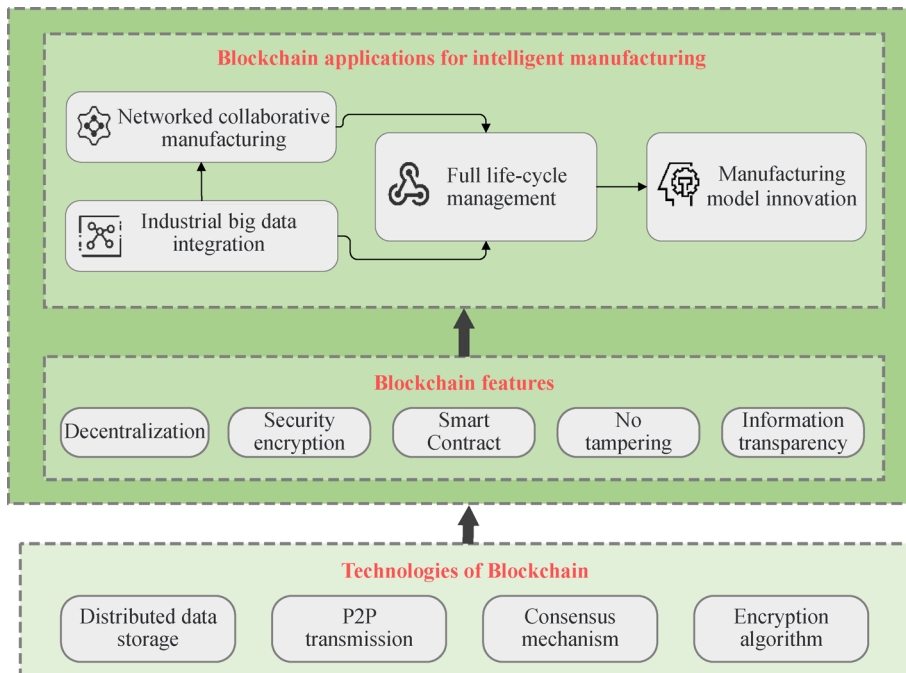


Fig. 9 Applications of blockchain in the field of intelligent manufacturing.

technology uses data integration for networked collaborative manufacturing to effectively organize distributed collaborative production. The data integration and collaborative production for full life-cycle management promote the realization of full-process monitoring, thereby effectively managing the supply chain. The blockchain can achieve transparency of manufacturing resources, thereby providing a good foundation for manufacturing model innovation.

3.1 Industrial big data integration

Blockchain can be used as an adhesive for industrial big data integration. Blockchain realizes the sharing of information among parties after industrial data are linked while ensuring the confidentiality of sensitive information (Korpela et al., 2017). This technology provides an opportunity for the seamless integration of information, logistics and capital flow of upstream and downstream enterprises in the supply chain, and effectively breaks through the data silos of each link of the supply chain, which is of great significance for the establishment of unified industrial big data (Chen et al., 2019; Wan et al., 2019). The core process of intelligent manufacturing is to achieve an intelligent decision making of the core business process of the manufacturing industry by data collection, analysis, and mining. The possibility to obtain massive and effective industrial big data is the premise to realize intelligent manufacturing. Most manufacturing enterprises are not willing to share their manufacturing data in the current environment due to the privacy and sensitivity of industrial data. This situation brings great challenges for the achievement of real industry-oriented intelligent manufacturing. The problem of data areolation occurs even between different parts of the enterprise. Blockchain can be used to share data across various departments of each enterprise and also between enterprises. Moreover, blockchain greatly overcomes the limited sharing of industrial big data to a certain extent by working as an adhesive that enables industrial big data from different data sources to be reciprocally shared, while effectively ensuring data privacy and security.

3.2 Networked collaborative manufacturing

In the future, humans, machines, and things can be fully interconnected through the industrial Internet, owing to the development of intelligent manufacturing (Zhong et al., 2017). The combination of blockchain and industrial Internet can give full play to the role of blockchain, thereby promoting data sharing, optimizing business processes, reducing operating costs, and comprehensively improving the level of networked collaborative manufacturing (Bahga and Madisetti, 2016). Blockchain can enhance the trusted value of the industrial Internet. The industrial application of blockchain involves certain aspects, such as the

interconnection between devices, data sharing and combination, the supply chain and cooperation between enterprises, the coordination of the internal resources of enterprises, and the integration of various factors. For example, the blockchain technology can be used for the management of industrial Internet platforms to form a reliable encrypted database. Moreover, blockchain can increase the value added of industrial data and improve the data security level of the industrial Internet (Liang et al., 2019). In the management of the networked collaborative manufacturing, blockchain can connect sensors, control modules and systems, communication networks, enterprise resource planning and other systems, and continuously supervise each link of production and manufacturing through the unified distributed ledger infrastructure (Zhang et al., 2017). Small enterprises with processing needs can directly find the right manufacturer in the off-season of production by using the blockchain technology to register and share relevant information, such as equipment parts suppliers, to achieve capacity sharing and reasonable allocation (Madhwal and Panfilov, 2017). In relation to the quality management of key products, blockchain can be adopted to record the whole manufacturing of major equipment products to improve quality inspection and maintenance (Helo and Hao, 2019; Longo et al., 2019). Blockchain can comprehensively record the production and circulation process and provide technical support for product supervision (Lin et al., 2018; Sylim et al., 2018). Furthermore, blockchain can provide scalable solutions for the management of a large number of industrial Internet of Things to effectively solve the single point of failure. Finally, blockchain can also help improve the utilization and maintenance efficiency of industrial Internet equipment by establishing a unique and reliable identification mechanism for unified management.

3.3 Full life-cycle management

First, blockchain can make the assets of manufacturing enterprises intelligent; specifically, blockchain can define intelligent assets. Any asset in a manufacturing enterprise can be registered in the blockchain to have an independent value ID. The ownership is attributed to the person who controls the private key and can also sell the asset by transferring it. These assets can participate in the normal production and manufacturing and in the financial transactions as digital assets after the registration of the various equipment and raw materials of the manufacturing enterprises. Second, the blockchain technology plays an important role in the development of the digital twinning technology. A digital twin is a virtual digital model that contains all the information about a physical product (Boschert and Rosen, 2016). The information transmission using blockchain tends to carry all the information of a transaction product, prompting both parties to actively provide all the information involved in the transaction

content, which is the basis for the construction of digital twinning. The features of full record traceability and tamper-proof nature of blockchain ensure great advantages in product traceability and product life-cycle management in the manufacturing industry. The traditional product traceability is maintained and verified by each supplier in the supply chain. However, suppliers may not provide real product traceability data considering their own interests, which is not conducive to product traceability. The false traceability records create obstacles for the tracing of counterfeit and shoddy products and for product recalls. If all trace data were linked, then the data would be completely trustworthy and impossible to be tampered with. The application of blockchain in these contexts will ultimately greatly promote the whole life-cycle management of manufacturing and further promote manufacturing servitization (Brousmiche et al., 2018).

3.4 Manufacturing model innovation

The blockchain technology makes the assets of manufacturing enterprises intelligent; the manufacturing entities can conduct manufacturing value transactions, thus affecting the original manufacturing industry model. For example, the blockchain Smart Contract technology enables users of the industry to form a flexible supply chain through the Smart Contract to automatically discover global business partners, negotiate with them, and obtain business; this situation can help participants in the value chain accelerate the time for new products to enter the market with changing demand and generate trust and fruitful relationships with business partners (Korpela et al., 2017). The manufacturing value chain is a complex, multi-layered combination of various types of organizations that provide design, procurement, manufacturing, delivery, and other types of services across multiple areas. The production of a single part of a product can involve a number of transactions, from the request for quotation to the transfer of purchase orders, as well as the notification of engineering changes. Each type of transaction may require different financial and regulatory intermediaries and contractual and trust relationships between parties. The instant and low-cost guarantee of trust offered by the blockchain technology enables any supplier and manufacturer to immediately gain the useful data and information.

The blockchain technology supports distributed manufacturing and provides participants with an unprecedented opportunity to develop new products and service lines, create new customers, and enter new markets, looking for new ways to use and share assets (Morkunas et al., 2019). First, all parties in a common trading platform obtain real-time visibility in the value chain owing to the improved transparency of the supply chain; the material procurement and interaction among designers, manufacturers, and other service providers are simplified. Supply chain processes, including payments and trade finance, can be simplified

and automated by using Smart Contracts. Second, the immutable records of asset sources, materials, production data, ownership, and other data ensure authenticity and minimize transaction risks by the memory of digital products. Third, transaction parties can be confident that their intellectual property is protected by the secure digital intellectual property. For example, blockchain will allow manufacturers to encrypt proprietary 3D-printed files from one end to the other while creating an immutable transaction history to ensure the production of ceramic components with 3D printers.

4 Challenges and suggestions

4.1 Challenges

Blockchain is undoubtedly an ideal technology with wide application space and prospects in the field of intelligent manufacturing. From the perspective of technology, blockchain still has great natural limitations, referred to as the famous “Impossible Trinity”. This expression demonstrates that a blockchain system cannot simultaneously achieve proper decentralization, good system security, and high transaction processing performance (Qi et al., 2018). The transaction processing performance is often referred to as the number of transactions processed per second (TPS). Figure 10 shows that the blockchain system can currently address only two aspects of the blockchain trinity.

The following three famous blockchain platforms are taken as examples to illustrate the “Impossible Trinity” problem of the blockchain:

(1) The consensus mechanism based on POW in the Bitcoin system. In terms of transaction processing performance, the TPS of Bitcoin is only about a few transactions per second, thereby making it totally unsuitable for routine and high-frequency small transfers. This low transaction performance has generated different opinions in the Bitcoin community about the future of Bitcoin (Vujičić et al., 2018). Bitcoin is by far the best, without any doubt, in terms of security. On the one hand, the whole network computing power is constantly promoted with the upgrading of the Application-Specific Integrated Circuit mining machine. On the other hand, the new mining machine is continuously improved to enhance the whole network computing power. The POW consensus mechanism represented by Bitcoin can theoretically guarantee security and decentralization on the basis of a large amount of computational power. However, this mechanism has several disadvantages, such as difficulty in improving the scalability, slow speed, and high cost.

(2) The Ethereum platform is also a consensus mechanism based on POW (Wood, 2014). This platform has lower computing monopoly than Bitcoin, but a better performance in terms of decentralization because it can

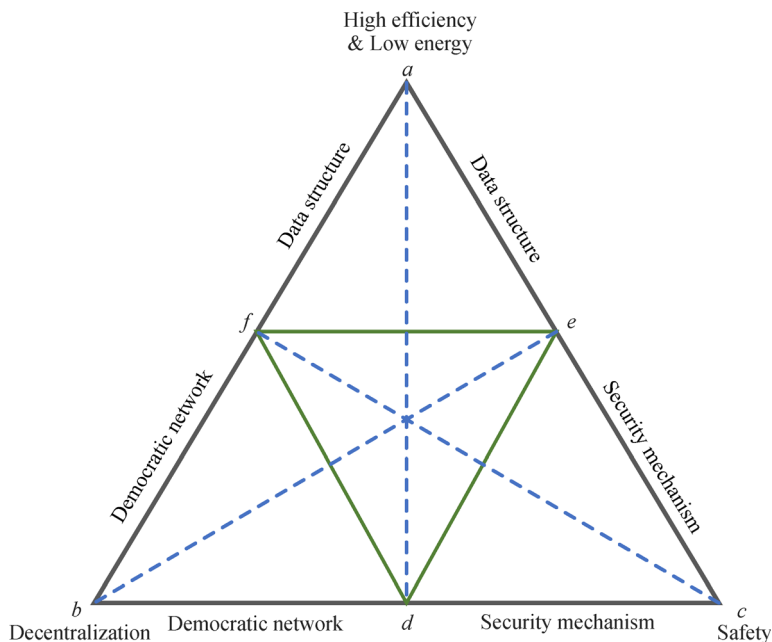


Fig. 10 Compatibility of blockchain systems.

still mine with graphics cards. In the future, Ethereum will completely shift to POS consensus to solve the problem of low computing monopoly (Vujičić et al., 2018). The TPS of Ethereum is approximately 7 to 15 (i.e., slightly higher than that of Bitcoin). However, the application scenarios of Ethereum are more complex and prone to congestion than Bitcoin because it is a Smart Contract platform. Accordingly, the performance issues of Ethereum have received great attention, which is the reason why the much anticipated Enterprise Operation System (EOS) emerged. Finally, Ethereum is second only to Bitcoin in terms of security.

(3) When EOS appeared, its biggest selling point was a high TPS and a strong transaction performance. The true performance of EOS is not as high as officially claimed, but is approximately 3000 to 4000 (i.e., far higher than Bitcoin and Ethereum). However, the EOS has made great sacrifices in terms of decentralization to achieve such a high TPS. In comparison with the tens of thousands of nodes in the networks of Bitcoin and Ethereum, only 21 nodes are present in EOS, and its decentralization is the lowest among the three public chains. The low number of nodes entails also security problems because hackers can easily attack 21 nodes than the thousands of nodes of Bitcoin or Ethereum. Hence, EOS has the lowest performance in terms of security among the three platforms.

The comparison of the safety, extensibility, and decentralization of the discussed mainstream blockchain platforms is given in Table 2.

In addition to the mentioned “Impossible Trinity” limitation of the blockchain technology, the blockchain

Table 2 Comparison of different blockchain platforms

Protocol	Safety	Extensibility	Decentralization
Bitcoin	?	×	?
Ethereum	?	×	?
EOS	×	√	×

scenarios involved in the field of intelligent manufacturing are relatively complicated and, therefore, difficult to apply. This situation is mainly reflected in industrial problems, such as the lack of top-level design, imperfect network infrastructure, inconsistent application standards of the blockchain technology, concern about industrial data security and privacy, and lack of talents in industrial blockchain. These issues are briefly discussed below.

(1) Lack of top-level design and standard system construction of the industrial blockchain. At present, governments around the world have issued policies to encourage the layout and development of blockchain; however, policies specifically aiming at the application and development of blockchain in intelligent manufacturing are lacking. No clear direction or objective is available in industrial application development, and specific implementation and promotion measures are currently lacking. To date, the application of blockchain in the field of intelligent manufacturing in China is still in the stage of theoretical exploration, and specific programmatic and technical development objectives are lacking. Certain aspects, such as industrial blockchain foundation, privacy and identity authentication, industrial blockchain security, and industrial blockchain Smart Contract, still need further

planning and development, even though China has recently formulated and released the Blockchain-Reference Architecture. At present, some organizations and local governments have begun to explore the application standards of blockchain in the manufacturing supply chain, although they are still in the experimental stage.

(2) Insufficient research on basic theories and core technologies of industrial blockchain. Blockchain, a high-end technology that has been rapidly valued, has only been around for the past 10 years. A number of core technologies and the “Impossible Trinity” of blockchain have not been strictly theoretically and mathematically proved. Some key technologies, such as TPS, have not been broken through, thereby resulting in a technical bottleneck in blockchain industrial application. Research on relevant basic theories and key technologies are urgently needed in the application of multiple scenarios, such as the integration of blockchain and the industrial Internet platform, and the specific implementation of blockchain to the supply chain in the field of intelligent manufacturing. At present, blockchain will have a broad application prospect in distributed manufacturing resource sharing, new-generation supply chain and logistics optimization, autonomous management of the industrial Internet of Things, industrial product tracking and traceability, and other segmentation fields, although there is still a lack of relevant basic research.

(3) Industrial blockchain application models need broken through. At present, the application development of blockchain in the field of intelligent manufacturing is still in the early stage of exploration. Few mature industrial blockchain applications have been implemented worldwide. The application of blockchain in the field of intelligent manufacturing is confronted with several difficulties due to the huge amount of data and inconsistent data standards in the intelligent manufacturing industry. No mature large-scale application is present in core intelligent manufacturing fields, such as intelligent supply chain, industrial big data sharing, and networked collaborative manufacturing, except the existing relevant market-oriented industrial blockchain applications in manufacturing product traceability. Standardizing and scaling up the application of industrial blockchain are difficult due to the large number of industries involved in intelligent manufacturing and the great differences among industrial attributes and business characteristics of different industries. Therefore, the lack of an industrial blockchain application model and business model innovation will greatly restrict the application process and depth of blockchain in the field of intelligent manufacturing, thus further affecting their integrated development.

(4) Lack of an industrial blockchain talent cultivation system as well as professional talents. Industrial blockchain is a multidisciplinary and interdisciplinary technology that concerns disciplines such as cryptography, mathematics, management, computer science, and

mechanical manufacturing, with great difficulties and high thresholds for learning. At present, many domestic blockchain trainings and the popularization of the government-administration-led blockchain technology are descriptions of the external characteristics and industrial application prospects of the blockchain technology, while which do not address the core principles and technologies of blockchain. Accordingly, high-end talents with a professional blockchain background are difficult to cultivate. Although the education departments in China have actively deployed blockchain-related education and teaching plans, only a few teachers in domestic colleges and universities can be highly competent in imparting blockchain knowledge, thereby bringing great difficulties to the establishment of related disciplines and the cultivation of professional talents. Therefore, the lack of cultivation and output of professional talents directly limits the in-depth application and model innovation of blockchain in the field of intelligent manufacturing.

4.2 Suggestions

The in-depth integration of blockchain into intelligent manufacturing is a strategic choice, which would bring disruptive changes to the development of the global information technology and manufacturing industry. As stressed by the Chinese government, “blockchain should be regarded as an important breakthrough of the independent innovation of core technologies, and it is necessary to accelerate the innovation and development of blockchain technology”. The report of the 19th National Congress of the Communist Party of China pointed out that we must “cultivate new growth areas and form new driving forces”. According to the national informatization plan of the 13th Five-year Plan, the blockchain technology innovation, technology experiment, and application should be strengthened. Based on the strategic arrangements, the overall deployment requires efforts to improve the independent innovation capability of core technologies. This necessity provides an important historical opportunity for intelligent manufacturing in China to achieve a high-quality development with the integration of blockchain technology.

In accordance with a recent report by the technology research firm ReportLinker, the US manufacturing market for blockchain technology applications is expected to significantly grow from 2020 to 2025. This study found that the market for blockchain technology in the manufacturing sector is expected to reach \$30 million by 2020, with an annual compound growth rate of 80% by 2025 (Alexandre, 2018). The German ZPC, the first blockchain industrial application project in the world, focuses on the application of blockchain in the industrial manufacturing industry and has attracted attention from all walks of life. ZPC is jointly developed by Commerzbank and the RWTH Aachen University and is based on the

Blockchain 4.0 technology. This project solves the limitations of the previous blockchain design and emerged among many other blockchain projects. According to the Nikkei Asian review, a total of 100 manufacturers in Japan, including Mitsubishi Electric and Yaskawa Electric, will join forces to share information, reduce operating costs, and improve efficiency by using blockchain. Thus, the attention paid to the blockchain technology by top global manufacturing enterprises indicates that its application in the field of intelligent manufacturing is full of prospects.

The Chinese manufacturing industry ranks first in the world with a whole range of sectors and systems and plays an important role in supporting national economic and social development. The Blockchain-Whitepaper of China in 2018, released by the Ministry of Industry and Information Technology of the People's Republic of China, indicates that China has prioritized the integration between blockchain and intelligent manufacturing. The Whitepaper pointed out that the blockchain technology is expected to become one of the underlying technologies of the fourth industrial revolution. The organic integration between the industrial blockchain and the industrial cloud will greatly promote the operation efficiency of the real economy and prompt the transformation and upgrading of the manufacturing industry. Relevant development suggestions are proposed on the basis of the industrial background described above and on the dilemma of blockchain application in intelligent manufacturing, as follows:

(1) Basic and key technology research on blockchain should be strengthened, especially around the technology bottleneck of the “Impossible Trinity”. The quantity of core technology is an important index to measure the high-quality development of the intelligent manufacturing industry. How to solve the technical constraints and improve the development of intelligent manufacturing? First, the international cutting-edge technology should be the main aim, and independent and cooperative innovations must be combined. One must strive for the realization of “single-point” breakthroughs in key intelligent manufacturing technologies and gradually transit to multi-point, or even full-line effective breakthroughs in key links of multiple fields. Research in key areas of intelligent manufacturing should be performed to form an international leading edge and avoid getting stuck in key core technologies. Second, the market demand of intelligent manufacturing should be combined, and the key scientific and technological breakthroughs at multiple levels (e.g., at the national, industrial, and enterprise levels) should be actively achieved. The role of new scientific and technological achievements should be given full play. The transformation and application of the intelligent manufacturing industry should be expedited, and its international competitiveness should be enhanced. Third, the development of key technical standards for intelligent manufacturing should be expedited. International standardization should be promoted, and Chinese standards in

“going global” should be improved. One must participate in the formulation of global rules on the basis of technological breakthroughs. In parallel, the leading role of international standards should be given full play, and domestic intelligent manufacturing technology innovation must be guided. The upgrading of the core competitiveness of the industry must be expedited.

(2) A top-level design of industrial blockchain should be properly realized, and the construction of a standard system should be expedited. First, the overall plan and schedule for the application and development of industrial blockchain in the field of intelligent manufacturing should be strategically proposed at the national level. The development of the blockchain industry should be placed in a prominent position in social and economic development. Second, policies to support the development of targeted industries must be issued, and the research and development of key technologies should be supported on the basis of the application and developmental status of the blockchain technology in the intelligent manufacturing industry in China. Third, a roadmap for the development of industrial blockchain technology and application standards should be formulated. Standard application guidelines for industry segments should also be formulated. The compatibility between the blockchain technology and the application standards must be gradually improved. The development of industry certification standards should be explored according to the industrial scale and application capacity. Certification services relying on third-party institutions should be provided to regulate the competitive market in the industry. Standardized applications in segmented areas should also be expedited.

(3) Application innovation of industrial blockchain business model is encouraged and must be supported. To this respect, industrial policies related to the application of industrial blockchain must be issued, and manufacturing enterprises are encouraged to use blockchain platforms to innovate their business models. The coordinated development of industrial application innovation must be strengthened, and the role of application demonstrations must be given full play, aiming at common blockchain application technologies and solutions in the field of intelligent manufacturing. The differentiated development of blockchain must be promoted in various segments of intelligent manufacturing and different regions. The gathering of featured applications of industrial blockchain should be vigorously promoted. Clusters of featured applications should be created in various regions by closely combining the local foundation and development level of intelligent manufacturing. The optimization and integration of resources in the blockchain industry should be strengthened. Leading demonstration enterprises should promote the integration and innovation of blockchain in different fields, such as industrial big data sharing, supply chain coordination, and logistics optimization. Close cooperation and collaborative innovation are encouraged

among enterprises upstream and downstream of the industrial chain. The technological “isolated islands” must be broken, and the division of labor and collaborative development among the main parts of the industrial blockchain must be improved.

(4) A talent training system should be rapidly established to remove the existing bottlenecks on talent cultivation. A number of specialized and high-quality courses related to blockchain and intelligent manufacturing should be added in colleges and universities. Interdisciplinary talents majored in both blockchain and intelligent manufacturing should be trained. A group of technical professionals focusing on the development, improvement, and application of the industrial blockchain technology is also needed. Cooperation between education providers and enterprises should be improved. The government should encourage enterprises to perform the study of and training on relevant professional knowledge and set up relevant training courses for enterprises. A variety of incentive measures should be adopted to optimize the scientific research environment. A high-level technical innovation team directed by lead talents should be organized to promote the innovative application and development of blockchain in the field of intelligent manufacturing.

(5) New technologies, such as 5G, have brought good developmental opportunities for network transmission, network performance, and data transmission of industrial blockchain. The dividends brought by these new technologies should be fully seized, the technology integration and innovation should be strengthened, and the application level of industrial blockchain should be improved. The application of industrial blockchain based on 5G will effectively solve the deficiencies of traditional communication network protocols and infrastructure to ensure the fast transmission speed of industrial data under the chains in the 5G environment. The Smart Contract technology of industrial blocks can also fully activate idle resources of industrial users, which is conducive to the extensive construction of industrial 5G-related infrastructure and the rapid development of the 5G technology in the field of intelligent manufacturing. The blockchain technology is not a panacea. In the future, the blockchain technology can fully express its application value in the field of intelligent manufacturing only by integrating with 5G, Internet of Things, big data, artificial intelligence, and other new-generation information technologies.

5 Conclusions

The core features of blockchain technology, including decentralization, openness, transparency, high security, and tamper-proof modification, bring great convenience for large-scale data sharing and social collaboration. In the field of intelligent manufacturing, the blockchain technology has a broad application prospect. This study

first summarizes the basic structure and main characteristics of blockchain to analyze its application prospect in the field of intelligent manufacturing. Then, we elaborate on the theoretical basis of blockchain application in the field of intelligent manufacturing from four levels: Industrial big data integration, networked collaborative manufacturing, full life-cycle management, and manufacturing model innovation. Next, the current difficulties of the blockchain application in the field of intelligent manufacturing are summarized, including: (1) lack of top-level design and standard system construction, (2) insufficient research on basic theories and core technologies, (3) business application models requiring breakthroughs, and (4) the imperfect talent training system. Finally, we proposed several suggestions: (1) realizing the top-level design of industrial blockchain; (2) strengthening basic research on key technologies of industrial blockchain; (3) encouraging application innovations of industrial blockchain business model; (4) accelerating the establishment of a talent training system; and (5) promoting the application of new technologies, such as 5G. These challenges and corresponding suggestions are helpful in guiding the development of the blockchain technology in the field of intelligent manufacturing.

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