J. COMBIN. MATH. COMBIN. COMPUT. 127a (2025) 6357--6373

Journal of Combinatorial Mathematics and Combinatorial Computing
www.combinatorialpress.com/jcmcc

Sustainable industrial digital transformation based on smart blockchain technology

Yishu Liu[1], Xiaowen Lv[2, ✉]

[1] *School of International Business, Xi'an FanYi University, Xi'an, Shaanxi, 710105, China*

[2] *School of Management, Qilu Medical University, Zibo, Shandong, 255213, China*

ABSTRACT
Aiming at the difficulties faced by traditional industries, this paper formulates a smart blockchain solution for sustainable industrial digitalization. Through the theoretical analysis of blockchain technology integration into industry, it provides theoretical support for the application of intelligent blockchain technology in industrial digital transformation. Combining the above three algorithms and the actual situation of industrial digitalization development, an industrial digital transformation scheme integrating intelligent blockchain technology is designed, and a case study of the scheme is conducted. The delay mean value of this paper's scheme is within the allowable range at the maximum throughput, indicating that the scheme can promote the sustainable development of industrial digitalization. In the actual application scenario, the CD-PBFT consensus algorithm performs more prominently, and in addition, it can be seen that the industrial blockchain solution, which can enhance the product recycling rate, well practices the concept of sustainable development.

Keywords: smart blockchain technology, industrial digital transformation, consensus algorithm, hash function

1. Introduction

Digital transformation has become an important trend in the development of global industrial enterprises, and major economies in the world such as the United States, Germany, the United Kingdom, Japan, and the European Union have introduced medium- and long-term digitalization development strategies, and have continued to promote the digital transformation of industrial enterprises in terms of strategic planning, policies and regulations, and institutional settings [1-3]. In the new era, the rapid development and wide application of digital technologies represented by artificial intelligence, big data, etc., have continuously given rise to new modes and new business models, prompting subversive changes in the mode of production, lifestyle and governance of human

✉ Corresponding author.
E-mail address: lvxiaowen@qlmu.edu.cn (X. Lv).
Received 20 February 2024; Revised 15 May 2024; Accepted 20 November 2024; Published Online 15 April 2025.
DOI: 10.61091/jcmcc127a-351

beings, and also bringing new challenges to the production, manufacturing and development of industrial enterprises [4-6].

In order to cope with digital technological change and the challenges it brings in terms of production methods and lifestyles, global industrial enterprises have been transforming and upgrading from the dimensions of corporate strategy, digital technological innovation, digital process optimization of products and services, and digital change in organizational management [7-9]. Overall, there are several main reasons for the digital transformation of industrial enterprises. The first is to improve production efficiency. Through the introduction of advanced automation equipment and manufacturing technology, industrial enterprises can significantly improve production efficiency, reduce production costs and improve enterprise competitiveness. The second is to improve product quality. With the help of advanced big data analysis and other digital technologies, industrial enterprises can significantly improve product quality and product standards to meet market demand for personalized products and services. Furthermore, it is to enhance production flexibility [10-13]. Intelligent machines can be used with systems or stand-alone machines, and quickly respond to changes in market demand, adjust the production plan and product structure, thereby improving the market adaptability of industrial enterprises. Finally, it is to cope with the challenge of rising labor costs. Currently, there is an increasing lack of experienced mechanics and technicians, but the product manufacturing technology is becoming increasingly complex [14-15]. For industrial enterprises, the rational application of artificial intelligence and other technologies can effectively alleviate the shortage of technicians and the problem of rising labor costs. In short, in the context of the development of the digital economy, the development towards intelligent manufacturing and the realization of digital transformation is a necessary way for industrial enterprises to adapt to the development trend of the global economy and enhance industrial competitiveness [16-18].

On the other hand, blockchain, as a distributed encryption and decentralized network consensus mechanism, further realizes the decentralization of value when the Internet realizes the decentralization of information, causes a profound change in the existing production and lifestyle, and provides a new opportunity for the high-quality development of the manufacturing industry [19-20]. The application of blockchain in the manufacturing industry is ultimately to realize the intelligent, personalized and quality transformation of products on the supply side. Under the existing technical conditions and economic and social feasibility, the technical basis for realizing the high-quality development of the manufacturing industry may be different [21-22].

Literature [23] used a questionnaire survey method to examine the obstacles existing in the digital transformation process of aviation enterprises and gave relevant optimization suggestions. Literature [24] introduced an analytical framework for analyzing the digital transformation of industrial enterprises, which is mainly used to analyze the embodiment of three core competencies of industrial enterprises, namely, digital perception, digital capture and digital reconstruction. Literature [25] builds an analytical framework to analyze how the digital transformation of manufacturing enterprises affects the operational efficiency of enterprises in terms of the three dimensions of labor productivity, physical asset efficiency and working capital efficiency, which provides important theoretical guidance for the digital transformation of manufacturing enterprises. Literature [26] discusses the practical path of blockchain technology in Industry 4.0 to improve industrial enterprises, piracy and counterfeiting, intellectual property theft and other related problems, and promote the good development of Industry 4.0. Literature [27] describes the integration of IoT and blockchain technology in the context of Industry 4.0 to promote the development of industrial intelligence and distributed applications in various industries. Literature [28] discusses the development of industrial internet, in which the introduction of blockchain technology has improved the transparency of the manufacturing industry to a certain extent and protected the trust of end-to-end transactions. Literature [29] designed a distributed network architecture with blockchain technology as the core logic to address and improve the self-driving car ecosystem and verified the feasibility through simulation experiments.

In this paper, under the guidance of the principle of smart blockchain technology, the three core algorithms of smart blockchain technology are deeply interpreted, and the fit point of blockchain technology integration with industry is described from three aspects: personalized customization, sharing economy, and digital transformation. Based on the above three core algorithms and corresponding development software, the editable blockchain scheme for industrial digitalization is designed and implemented. The performance of this paper's blockchain scheme is tested in terms of latency and throughput, and then the application effectiveness of this paper's scheme is explored in the scenarios of industrial digitalization transactions and sustainable industrial development.

2. Research on industrial digitization supported by smart blockchain technology

2.1. Smart Blockchain Technology

Smart blockchain technology, with its unique form of distributed ledger, realizes the synchronous storage of data among participating nodes and provides a new paradigm of database technology [30-31]. It relies on a distributed, chained data structure to store information and ensures data security by applying asymmetric cryptography and other digital encryption methods. In addition, it uses consensus mechanisms such as proof-of-work for data generation and updating, and utilizes smart contracts for data management. This technology integrates innovations across multiple domains and marks a new concept of distributed computing, which is known for its immutability, decentralized nature, and traceability. Blockchain technology shows strong potential for securing data, defending against external attacks, and protecting user privacy. The basic framework of the blockchain is shown in Figure 1, in which the blocks within the system are connected into a chain-like structure in chronological order, which is created, verified, and maintained by all participants in the blockchain network, thus constituting a complete blockchain ecosystem.

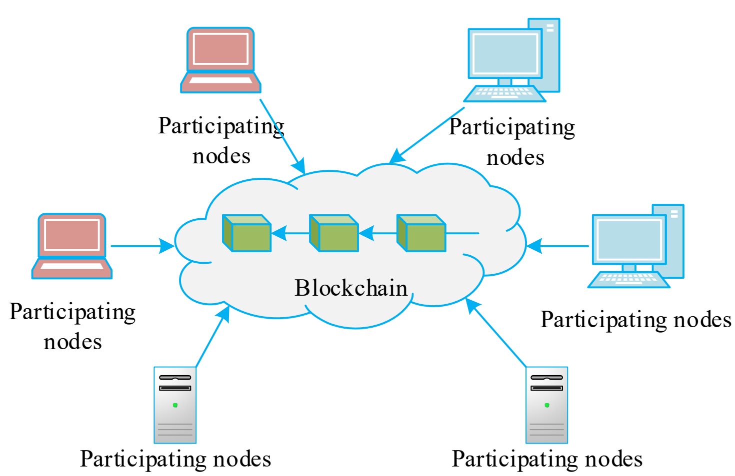


Fig. 1. The basic framework of blockchain

2.2. Core Algorithm of Smart Blockchain Technology

2.2.1. Hash Functions. Hash function, also known as hash function, is an important part of the field of cryptography, which plays a key role in generating hash puzzles and Merkle trees in blocks than DC blocks [32-33]. The basic principle of the hash function is to convert an input string of indeterminate length into a hash code of fixed length. It is an algorithm that is easy to compute but difficult to reverse derive and is commonly used in cryptographic techniques such as encrypting plaintext, generating

Message Authentication Codes (MACs), and digital signatures. The computational form of the hash function can be expressed as:

$$h = H(m) \tag{1}$$

Where m represents a string of arbitrary length, H represents a hash function, and h represents a hash code converted by a hash function.

2.2.2. Encryption algorithms. In the field of digital cryptography, encryption techniques are categorized into two main types: symmetric-key encryption and asymmetric-key encryption, the latter of which is used in blockchain technology. Asymmetric key cryptography involves the use of a pair of keys to securely transmit data, specifically a public key and a private key. In such systems, encrypted data must be decrypted using the corresponding private or public key. While the public key is publicly available, the private key must be kept strictly confidential. During data transmission, the sender encrypts the data it wants to send using the receiver's public key, which can only be decrypted by the receiver who holds the corresponding private key. This design ensures that even if the data is intercepted during transmission, it cannot be decrypted by an unauthorized third party, thus guaranteeing the security of the information. Asymmetric encryption effectively solves the key exchange problem in symmetric encryption and provides a high level of confidentiality. However, its drawbacks are also obvious, including more complex algorithms in the encryption and decryption process, slower processing speed, and security risks in key management.

2.2.3. Consensus Algorithms. One of the highlights of blockchain technology is its ability to ensure the authenticity of data blocks in a decentralized, trust-free environment, eliminating the need to rely on traditional third-party authoritative certification authorities. In such a distributed system, the process of reaching consensus on added data blocks is particularly complex, especially when considering the possible presence of malicious participants intent on disrupting the consensus process. However, this challenge can be overcome by employing specific consensus algorithms to effectively implement trust mechanisms in a decentralized context.

The core of the consensus mechanism lies in how to form a unified decision in a distributed network that both reflects the will of the masses and benefits the majority. Within the blockchain framework, a transaction is confirmed only when the nodes in the network reach a consensus on the legitimacy of that transaction. Ensuring a state of consensus in an untrustworthy environment becomes particularly critical due to the existence of potential attackers who may attempt to confirm illegal transactions for personal gain by controlling network nodes. Based on the different goals and implementation principles of consensus, blockchain technology has developed a variety of consensus algorithms. These algorithms differ according to the type of blockchain, while in this paper the CD-PBFT consensus algorithm is used.

Unlike PBFT, CD-PBFT designs a two-tier architecture based on PBFT, which divides all nodes into upper and lower tiers based on the network state performance.The lower tier nodes of CD-PBFT consensus algorithm can only verify and send data, and the upper tier nodes complete the consensus process [34]. Therefore the latency is lower and more efficient. All the lower layer nodes send the verified data to each node in the upper layer and each node in the upper layer receives the data from all the lower layer nodes and determines whether it is malicious or not by comparing the data from the lower layer nodes.The CD-PBFT consensus algorithm consists of phases of requesting, verifying and forwarding of the data, pre-preparing, preparing, submitting, broadcasting and updating of the node's reputation point value.

2.3. The fit of blockchain technology into industry

2.3.1. Personalization. With the improvement of living standards, people are no longer satisfied with the consumption of mass products, the demand for product customization is increasingly diversified and personalized. Personalized customization is consumer-centered, the consumer's experience throughout the product consumption, design, industrial process, the user's experience needs throughout the product, service, platform and other aspects. In the traditional production model, enterprises use assembly lines to produce homogeneous products based on economies of scale, so people can only consume similar products on the market. Due to the constraints of the communication costs between consumers and enterprises and the production model of enterprises, the cost of producing customized products is often very high, which leads to an increase in the price of products and harms the interests of consumers. The emergence of blockchain can well solve this problem. Through the introduction of blockchain, consumers can make direct contact with industrial enterprises, optimize supply and promote scale customization through on-chain cooperation among different enterprises, so as to better meet the needs of users.

2.3.2. The Sharing Economy. With the development of the Internet, the development mode of sharing economy penetrates into many industries in the real society, and with the help of Internet technology, the development mode of sharing economy breaks through the limitation of space, alleviates the problem of information asymmetry in the economy and society, and profoundly alters the existing mode of production and consumption in the society. The essence of the sharing economy is to minimize transaction costs through changes in institutional arrangements, and its most important feature is the separation of ownership and use of products, which also creates the potential risk of privacy information leakage. Due to the lack of clarity in the data sharing and dissemination mechanisms of various industries, there is a possibility of data loss or tampering in the process of data transmission, and problems in the sharing economy continue to emerge. The technical characteristics of blockchain's "decentralization" and "autonomy" can give rise to a new sharing economy and provide an opportunity for the sharing industry. Through the underlying technology of blockchain, the accuracy and privacy of data can be improved, the massive decentralized resources of the industry can be integrated, and the right of use can be shared. It meets the capital demand and resource demand of both supply and demand respectively, and promotes the intelligent and service-oriented transformation of industrial resource sharing. At the same time, it can enhance the accuracy of matching supply and demand, increase production efficiency, improve resource allocation, and provide new economic growth points for social development while promoting high-quality industrial development.

2.3.3. Digital transformation. Based on the dual background of the booming development of digital technology and the continuous deepening of supply-side structural reform, the integration of digital technology into the real economy has become a consensus. The governance practice of the Xin Guan Pneumonia epidemic further reflects the significance of the integration of industrialization and informatization, and the digital economy has become an important driving force for high-quality economic development. Industry, as the leading industry of the national economy, digital transformation is an urgent need for economic development based on realistic considerations. Based on blockchain technology, integrated changes in product development, production arrangement, logistics management, value-added services, and economic scheduling of industry can be realized.

2.4. Editable blockchain solutions for industrial digitization

This subsection is oriented to the data regulation and governance scenario in the industrial blockchain domain, and proposes an editable blockchain scheme and detailed process using distributed key management in combination with a trusted execution environment. The scheme identifies three types of nodes: regulator, calculator, and verifier, which are responsible for key storage, block packing, consensus verification, and information tracing, respectively. The editing operation is mainly realized through the interaction of the three types of nodes with the blockchain network. On the one hand, this chapter designs blockchain-related modules, including transaction data uploading and editing of error content on the chain. On the other hand, in the process of transaction editing, in order to ensure the computational security of the hashed private key, the CD-PBFT consensus algorithm is utilized for block packing education, and this module can realize the privacy of computation by virtue of the security isolation mechanism of the trusted execution environment technology. Therefore, this solution ensures the efficacy of editable blockchain solution to industrial digitization at the level of realizing blockchain editing function.

2.4.1. Introduction to the Architecture of Industrial Blockchain. The overall architecture of industrial blockchain is shown in Figure 2, which is mainly divided into physical layer, data layer, blockchain layer, interface layer, application layer, and regulatory layer.

1) Physical layer: it includes basic components such as sensors, smart devices, edge devices, servers, and virtual machines. The physical layer is used to collect source data, such as user body temperature in medical systems, temperature and humidity detection data in supply chain systems, and Internet traffic. The physical layer provides basic Internet information services and provides infrastructure for the upper layer architecture.

2) Data layer: data storage generally needs to satisfy the characteristics of verifiability, privacy protection, reliability, and easy query. Among them, verifiability indicates the ability to confirm the source of data, which can be guaranteed by digital signatures. Privacy means that the data cannot be accessed by unrelated personnel, which can be ensured by permission control and data encryption. Reliability means that the asset data is not easy to be lost, so it is stored in IPFS, a distributed file system, and the user's account data, contract address, and other data are stored in MySql for easy querying.

3) Blockchain Layer: It includes core technologies such as consensus mechanism, P2P network, smart contracts, encryption algorithms, etc., which provide security and distributed consistency of the blockchain network. The physical layer of IoT devices determines the reliability of the data source, while the blockchain layer ensures the integrity and accuracy of the information. At the same time, we can also write smart contracts according to the characteristics of different industries, for example, the order intention reaching, order delivery, product traceability, format specification and circulation rules of industrial data in the supply chain can be automatically executed by smart contracts.

4) Interface Layer: The interface layer provides concise API/SDK toolkit and industry standard interfaces and other calling methods for the application layer.

5) Application layer: Users communicate with other nodes by calling RPC interfaces, and access, write and other operations on blockchain ledger data. The application layer extends from production enterprises to consumers, including manufacturers, sellers, and other intermediate links, involving the supply chain and trade chain of multiple subjects to confirm rights, synergies, and management, and to improve the level of industrial digital sustainability.

6) Regulatory layer: The regulatory layer involves top-down monitoring of the overall architecture of industrial blockchain and related certification, authentication and other services.

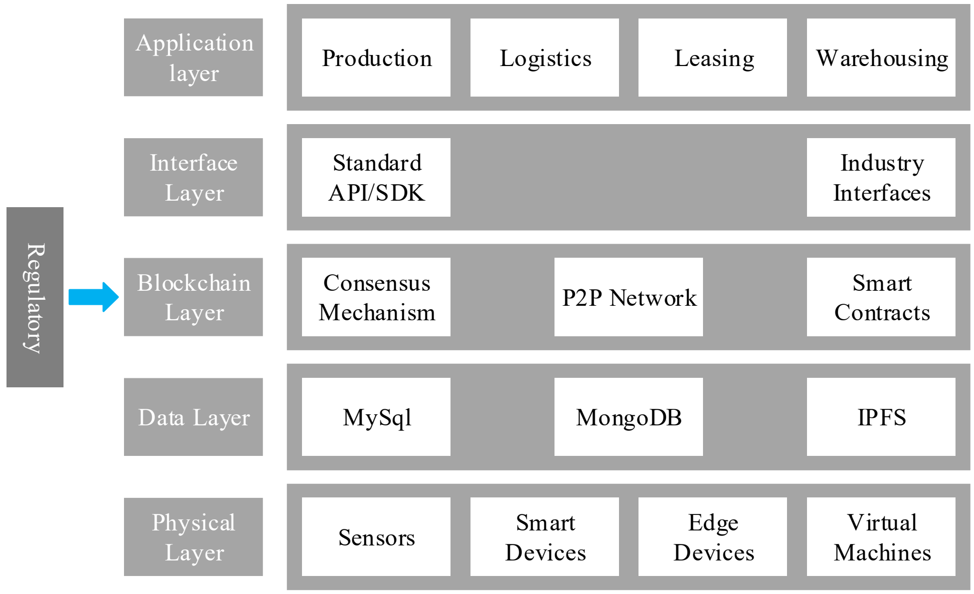


Fig. 2. Industrial blockchain architecture

2.4.2. Overall program design. The editable blockchain process is shown in Fig. 3, and this section mainly designs an editable blockchain scheme. The scheme contains three main bodies, namely, regulator, calculator and verifier, which correspond to the key holding node, calculation node and consensus node in the blockchain network, respectively. The editable blockchain scheme designed in this paper divides the process of revising the blockchain into the following main stages.

1) Setup(): the initialization phase establishes the genesis block and assigns roles to each node. Among them, nodes with Trusted Execution Environment (TEE) module are defined as computing nodes. The key-holding node initializes the hash function and generates the key slice through a distributed hash algorithm based on smart contracts. The remaining nodes are consensus nodes. The nodes initialize the blockchain and start the blockchain after completion of initialization and perform packetized transactions using the CD-PBFT consensus algorithm.

2) ProposalReq(): in the industrial blockchain, any node in the blockchain can issue a revision proposal Req={i, content, timestamp} at any time and broadcast it to the whole network when it monitors the system for errors, expiration and other improper content. Where Req denotes the proposal, i is the height of the block containing the erroneous data, content is the information to be edited, and timestamp denotes the current timestamp. For the case of a deleted transaction, the transaction transaction = 0 is set, i.e., the memo field is empty.

3) VerifyReq(): proposal validation phase, the consensus node verifies the legitimacy of the request and broadcasts the result to the other nodes: whether to accept the request Res=0/1, 1 means accepting the edit, 0 means not accepting the edit. In this process, when 2/3 consensus nodes agree, the request passes, otherwise the request is rejected. Finally the voting result is posted on the blockchain.

4) ChooseCompN(): after a legitimate editing proposal appears, it enters the computational node selection phase. The m computing nodes start performing operations according to the node random selection policy (RSP). The computing node CompN first picks a random number and divides that random number into m parts and sends it to other CompNs. Each compute node combines all the shares it receives into a total random number and computes a hash of that number and the public key, then attaches its own signature to the hash and sends it to the blockchain network. Next, a comparative smart contract is designed to sort these hashes, and then the CompN with the largest hash is determined as the node with editing privileges in this round of views and broadcasted in the blockchain network.

5) RedactBC(): in the revision phase, the selected computational node initializes the TEE first if it is the first revision. A public-private key pair is generated in the TEE and the public key is made public in the blockchain network as a unique identity for the TEE. The private key is stored securely in the TEE and cannot be accessed by the host or any other party in the system. A certification report for that TEE is then generated π and stored on the blockchain. This report proves the identity of the TEE, that the application has not been tampered with, and that it is running on a genuine platform.
6) VerifyRedaction(): in the verification phase, the computing node sends the revised and completed new block to the blockchain, and at the same time deploys a voting smart contract in the blockchain network. The consensus node verifies the new block and the corresponding TEE authentication report π and then votes, and the new block is put into the block pool only when 2/3 consensus nodes agree, otherwise the new block is discarded. The block validation here is firstly content validation, i.e., whether the new block is correctly revised as per the request of the editorial proposal. Secondly the validity of CD-PBFT consensus algorithm is verified. Finally the validity of the transaction is verified according to the standard blockchain validation method, and all three are satisfied before it can be uploaded to the chain.
7) UpdateBC(): In the ledger update phase, all nodes synchronize the master node and replace the original block with the new block in the block pool to ensure the distributed consistency of the blockchain system.

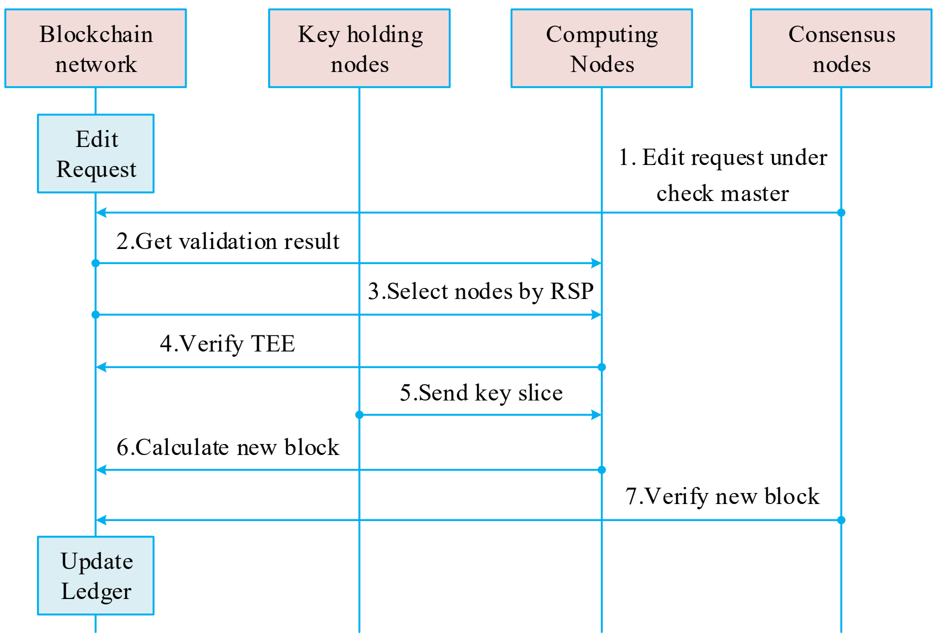


Fig. 3. Editable blockchain process

3. Case Study of Industrial Digitization Incorporating Blockchain Technology

3.1. Blockchain program testing

3.1.1. Description of testing. The throughput and average latency of a blockchain network are measured in a performance test of a blockchain solution for industrial digital transformation. Throughput indicates the number of requests that the blockchain network can process per second. The average latency indicates the time taken to process the requests. The operations involving the blockchain platform in the proposed system mainly contain creation, deletion, modification, and lookup of data in the blockchain ledger. Lookups and modifications are the most frequently performed operations, so the performance of lookup and modification operations of the blockchain solution for industrial digital transformation is tested.

3.1.2. Analysis of test results. The test computer and the blockchain platform are on the same LAN. The blockchain benchmark performance testing tool Caliper is deployed in the test computer to test the throughput and average latency of the blockchain solution for industrial digitization. The performance of the blockchain network in handling lookup requests is shown in Figure 4. When the submission speed of the lookup request is lower than 400 times/sec, the throughput of the blockchain network in processing the modification request is basically equal to the request submission speed, and the average latency is less than or equal to 0.125 S. When the submission speed of the lookup request is greater than 380 times/sec, the blockchain network in processing the lookup request is greater than the request submission speed, and the average latency is reduced substantially. Therefore, the maximum throughput of the blockchain network for processing lookup requests is about 380 times/second. When the submission rate of lookup requests is greater than 380 times/second, the latency of the scheme reaches the minimum value (0.02).

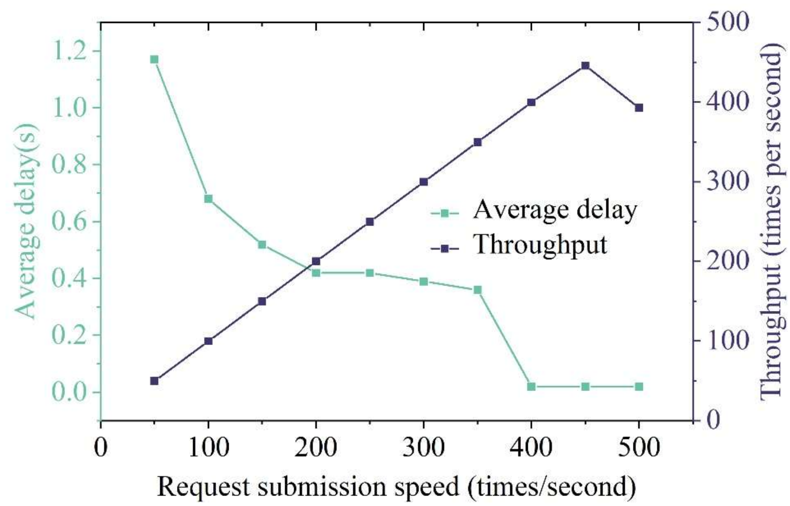


Fig. 4. Performance of the blockchain network in handling lookup requests

The performance of the blockchain network in processing modification requests is shown in Figure 5. When the submission speed of modification requests is lower than 130 times/sec, the throughput of the blockchain network for processing modification requests is basically equal to the request submission speed, and the average delay is about 2.423 s. When the submission speed of modification requests is greater than 130 times/sec, the blockchain network processes modification requests at a speed lower than the request submission speed, and the average delay is reduced substantially. When the request submission speed is much smaller than the throughput of the blockchain network, a large number of modification requests are submitted successfully. As a result, the maximum throughput of the blockchain network for processing modification requests is about 119 requests/second. When the submission rate of modification requests is greater than 110 times/second, the success rate of modification requests increases substantially.

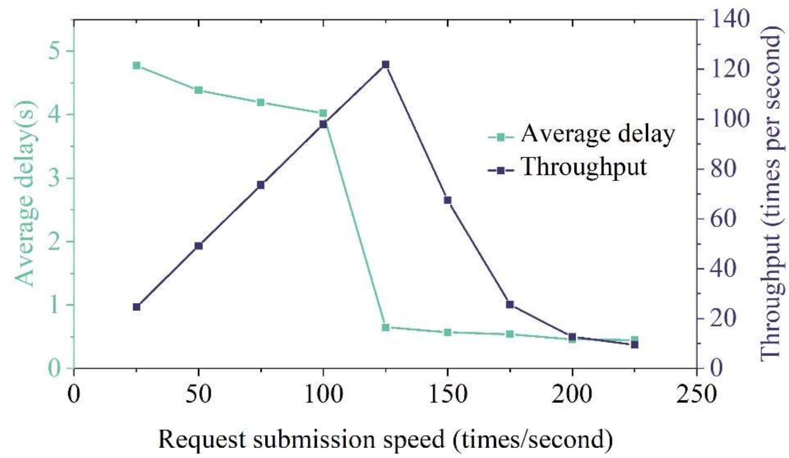


Fig. 5. The performance of the blockchain network in handling modification requests

According to the test, it can be seen that the maximum throughput of lookup requests is greater than that of modification requests in the blockchain scheme for industrial digitization, which is due to the fact that the execution steps of modification requests are more than those of lookup requests. The use of smart contract technology to record the operations of managers improves the security and reliability of industrial digitalization management, and the scheme can meet the needs of sustainable development of industrial digitalization.

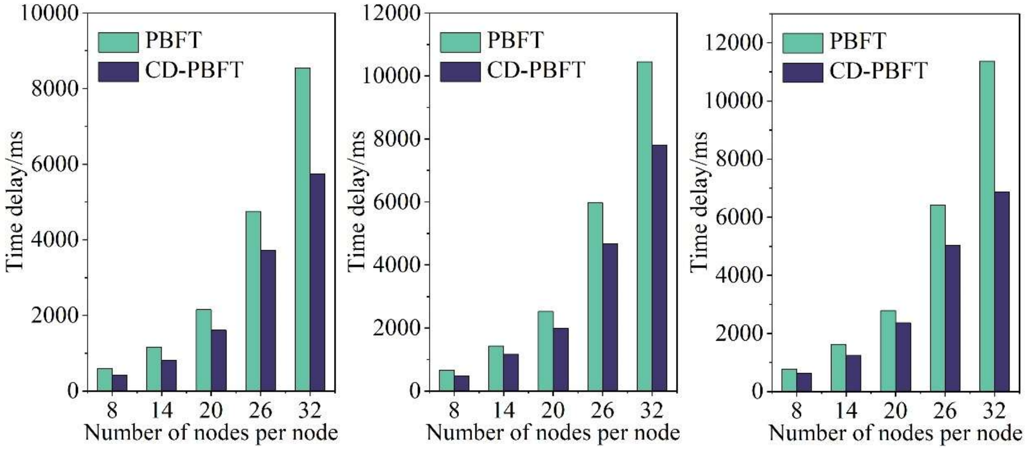
3.2. Analysis of program application examples

The performance of blockchain solutions for industrial digital transformation was tested above, and this subsection will explore the practical application effect of blockchain technology in industrial digital transformation from two aspects: industrial digital transactions and industrial sustainable development. The detailed analysis process is shown below:

3.2.1. Analysis of industrial digitization transactions:

1) Transaction Delay. In industrial digital transaction scenarios, transaction latency refers to the time interval required from the time the client sends a transaction request to the master node to the time the client confirms the completion of consensus. In this experiment, different limits of 800, 1600 and 2400 packed transactions are set simultaneously in order to observe the impact of the number of packed transactions on the consensus performance. With the increase of the number of packed transactions in industrial blocks, the latency increases gradually. With the increase of the number of packaged transactions in industrial blocks, the time delay gradually increases, but under the same conditions, the time delay of this paper's method is always lower than that of PBFT.

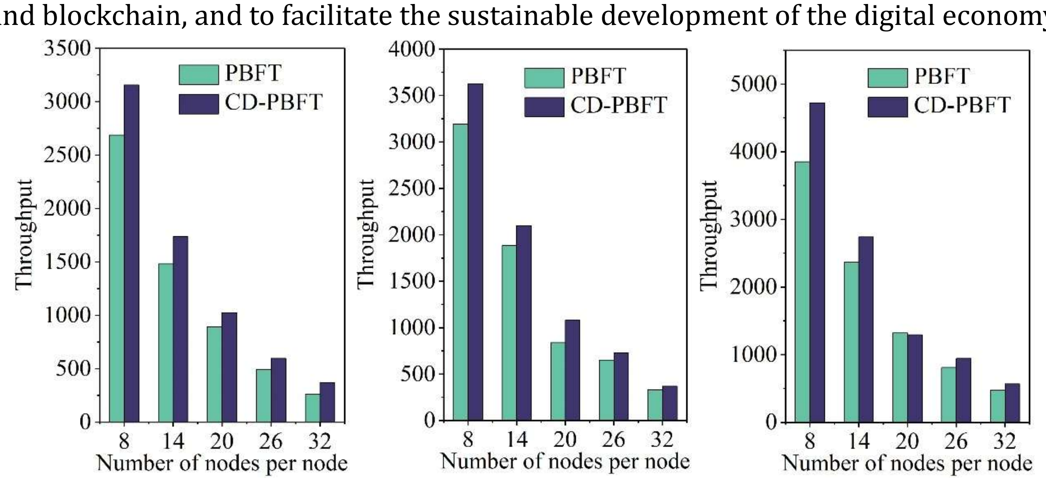
The comparison of user transaction latency is shown in Fig. 6, (a)~(c) are 800, 1600, and 2400, respectively. in terms of the maximum value, the transaction latency of CD-PBFT consensus algorithm reaches the highest value of 6838ms under the condition of the number of nodes is 32 and the number of block packaged transactions is 2400, while that of PBFT consensus algorithm in the same condition reaches 11679ms. compared with the PBFT, the packetized transaction latency of CD-PBFT is reduced by 37.9%. Under the condition that the number of nodes is 8 and the number of block packing transactions is 800, the transaction latency of CD-PBFT reaches the lowest value of 459ms, while the transaction latency of PBFT under the same condition is 676ms, compared with PBFT, the transaction latency of CD-PBFT's packing transactions is reduced by 30.37%. In terms of average value, the average packaged transaction latency of the consensus algorithm in this paper is reduced by 35.6% compared to PBFT. In addition, with the increase of the number of packaged transactions and the number of nodes, the latency of CD-PBFT grows slower than that of PBFT, which indicates that in industrial digitalization scenarios, the transaction latency of CD-PBFT is better than that of PBFT, which is more favorable to industrial digital transformation.



(a) batch=800 (b) batch=1600 (c) batch=2400

Fig. 6. User transaction delay comparison

2) Throughput. Throughput refers to the number of transactions completed in a given time unit in an industrial digital transaction scenario. The experimental setup for measuring throughput is consistent with the time delay. The throughput gradually increases as the number of transactions packed in the block increases. As the number of nodes increases, the throughput gradually decreases. However, under the same conditions, the throughput of CD-PBFT is always higher than that of PBFT.The comparison of PBFT and CD-PBFT throughputs is shown in Fig. 7. The throughput of CD-PBFT consensus algorithm reaches the highest value of 4716 under the condition of 8 nodes and 2400 block packing transactions, while the throughput of PBFT consensus algorithm under the same condition is only 3905. Compared with PBFT, the throughput of CD-PBFT is improved by 20.77%. Under the condition of 32 nodes and 800 block packing transactions, the throughput of CD-PBFT reaches the lowest value of 337, while the throughput of PBFT under the same condition is only 257. Compared with PBFT, the throughput improvement rate of CD-PBFT is 31.28%. In terms of average value, the average throughput of CD-PBFT consensus algorithm is improved by 26.03% compared to PBFT. In addition, with the increase of the number of packaged transactions and the number of nodes, the throughput of CD-PBFT decreases at a lower rate than that of PBFT, which indicates that in industrial digitalization scenarios, the throughput of CD-PBFT is better than that of PBFT, and the CD-PBFT consensus algorithm in this paper is expected to promote the in-depth fusion of the industrial Internet of Things and blockchain, and to facilitate the sustainable development of the digital economy.



(a) batch=800 (b) batch=1600 (c) batch=2400

Fig. 7. Throughput comparison

3.2.2. Analysis of applications in sustainable industrial development:

1) Stepwise utilization. Stepwise utilization refers to the process of extracting high-value compounds from resources before gradually extracting low-value compounds in order to maximize the use of resources. In the field of industrial products, stepwise utilization refers to the process of reusing products that have been scrapped by first using them in fields such as energy storage, and then gradually extracting valuable materials from them by separating the product components in order to reuse the product materials. The gradual utilization of products that have been scrapped and the realization of their residual value not only promotes the development of a recyclable economy, but also reduces the production and recycling costs of commodities, eases the current pressure on recycling due to the excessive number of products scrapped and promotes the development of the commodity industry.

2) Resource recovery model based on blockchain technology. Using blockchain technology, it is important to determine the appropriate level of product traceability information. In this case, the adoption of blockchain technology has a positive impact on consumers with a preference for traceability information. It is assumed that the increase in demand for new products under the influence of blockchain technology is kt, where t represents the level of traceability information delivery by blockchain technology, referred to as the traceability level, and k represents the sensitivity of consumers to the traceability level. Therefore, this paper obtains that the relationship between product price and quantity is:

$$q_n^{'} = \alpha - bp_n + kt \tag{2}$$

Where, α is the market size, p_n is the price of new products, k is the sensitivity of consumers to traceability information, t is the efficiency of traceability information delivery based on blockchain technology, and b is the price sensitivity factor.

(1) Product manufacturer recall model using blockchain technology (MW). In the product manufacturer recycling model, the product manufacturer collects used products directly from consumers. The profit function of the product manufacturer is written as:

$$\max \pi_m = \left(w_n - c_n\right) q_n^{'} + \left(\lambda p_s - p_r - \varphi c_r\right) q_r - \rho F - \frac{\mu t^2}{2} \tag{3}$$

The profit function of a merchandise retailer is written as:

$$\max \pi_r = \left(p_n - w_n\right) q_n^{'} \tag{4}$$

where $\frac{\mu t^2}{2}$ to describe the relationship between the level of traceability and its associated costs, the cost of collection of end-of-life products is ρF, φ is the optimization factor for the cost of recycling, ρ is the optimization factor for the cost of collection, w_n denotes the wholesale price of the new product, c_n is the cost of producing the new product, p_s is the revenue per unit gained from laddering the end-of-life products, p_r is the price of the old product paid to the consumer at the time of recycling, F is the cost of collecting the old product, and q_r is the quantity recycled.

(2) Merchandise retailer recycling model (RW) using blockchain technology. In the Merchandise Retailer Recycling (RW) model, a merchandise retailer collects end-of-life products directly from consumers. Then, λ part of the parts of the end-of-life product is used for laddering and the rest of the unusable parts are resold to the product manufacturer. The profit function of the product manufacturer is written as:

$$\max \pi_m = \left(w_n - c_n\right) q_n^{'} - w_r \left(1 - \lambda\right) q_r \tag{5}$$

The profit function of a merchandise retailer is written as:

$$\max \pi_r = \left(p_n - w_n\right)q_n^{'} + \left(p_s\lambda - w_r\left(1-\lambda\right) - p_r - \varphi c_r\right)q_r - \rho F - \frac{\mu t^2}{2} \tag{6}$$

(3) Third-party recycling model using blockchain technology (TW). In the third-party recycling model, a third-party recycler collects end-of-life products directly from consumers and resells them to a product manufacturer, who uses λ part of the end-of-life product's parts for laddering.

The profit function of the product manufacturer is written as:

$$\max \pi_m = \left(w_n - c_n\right)q_n^{'} - w_r\left(w_r + c_r\right)q_r + p_s\lambda q_r - \frac{\mu t^2}{2} \tag{7}$$

The profit function of a merchandise retailer is written as:

$$\max \pi_r = \left(p_n - w_n\right)q_n^{'} \tag{8}$$

The profit function of the third-party recycler is written as:

$$\max \pi_t = \left(w_r - p_r\right)q_r - \rho F \tag{9}$$

3) Numerical simulation. In order to more intuitively compare the optimal decision and optimal profit under the three models, the parameters are assigned values according to the actual situation. We will determine the ladder utilization $\lambda = 0.66, \alpha = 40$, $p_s = 15$, $c_n = 40$, $b = 1.1$, $F = 4$, assuming $\rho = 1.6$, $\varphi = 1.5$.

(1) Effect of ladder utilization rate on recycling prices. The effect of ladder utilization rate on recycling price is shown in Figure 8, when the ladder utilization rate increases, the recycling price will increase. When the ladder utilization rate is relatively low, the supply chain is not willing to take the responsibility of recycling, this is because the recycling supply chain members have to bear the cost of recycling and collection, and they are not willing to pay high recycling prices to consumers when they cannot enjoy the profits from ladder utilization. In addition, in most cases, consumers can get a higher recycling price if the product manufacturer recycles their end-of-life products. At this point consumers prefer to have the product manufacturer do the recycling. As the ladder utilization rate increases, the recycling price paid by the product manufacturer will also be higher. Therefore, consumers should pay close attention to the use of their new energy vehicle products and choose to recycle them when the ladder utilization rate is high in order to obtain a higher recycling price. At the same time, members of the recycling supply chain should also take into account the impact of the ladder utilization rate, and choose the right member to take on the recycling responsibility under the appropriate ladder utilization rate, in order to reduce the recycling cost and obtain a higher recycling price. Consumers and recycling supply chain members alike should pay close attention to the impact of ladder utilization rates and choose the right companies to recycle at the right time in order to obtain higher recycling prices and lower recycling costs, which will help accelerate industrial digital sustainability. For example, Tesla has used blockchain technology to establish a closed-loop tracking of its product lifecycle, effectively connecting all the links from production to recycling and reuse, making its products traceable and conducive to sales and recycling.

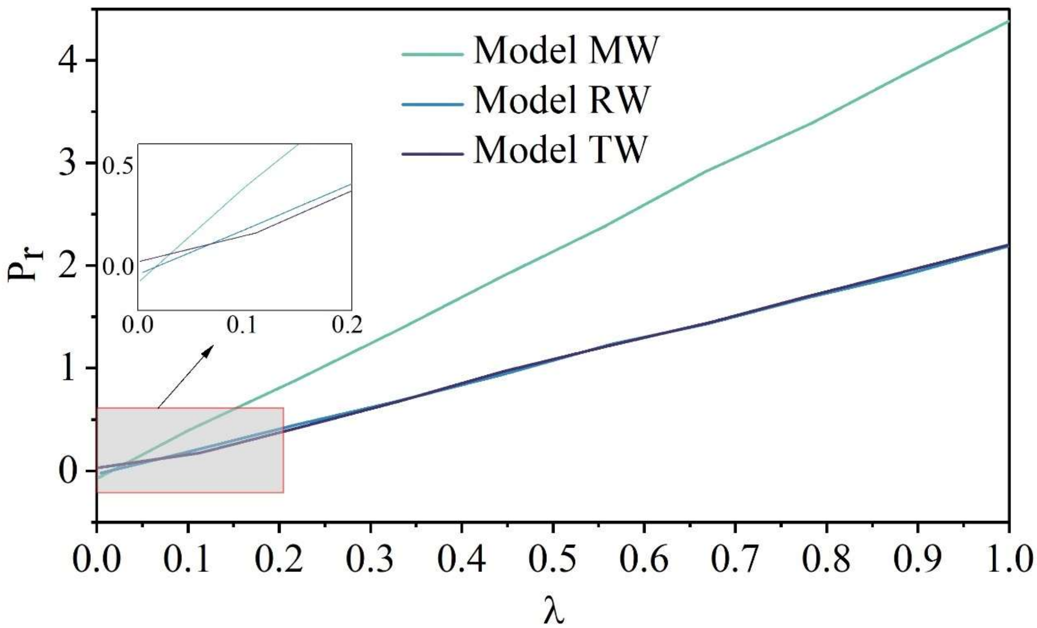


Fig. 8. Effect of echelon utilization rate on recovery price

(2) Effect of ladder utilization rate on product manufacturers' profits. The impact of ladder utilization rate on product manufacturer's profit is shown in Figure 9, where product manufacturer's profit increases with the increase of ladder utilization rate. Specifically, for the benefit of product manufacturers, in the case of a relatively low ladder utilization rate, third-party recyclers can assume the responsibility of recycling, and at the same time utilize blockchain technology to track the entire recycling process, ensuring that recyclers have a clear understanding of the product's history of use, improving the efficiency of recycling and reducing the cost of recycling, as well as enhancing the transparency and fairness of recycling, thus safeguarding the rights of the consumer and the degree of trust. And in the case of high ladder utilization, product manufacturers should be allowed to carry out recycling and ladder utilization. Reasonable ladder utilization can form an effective recycling model and further increase profits. By adopting blockchain technology, the entire life cycle of a product can be tracked to optimize recycling costs and recycling efficiency, thus helping supply chain members to improve profits and efficiency. In short, no matter who is responsible for recycling, they should improve the ladder utilization rate as much as possible and adopt blockchain technology to optimize the entire processing, improve consumer trust and supply chain profits, further promote the development of product recycling and reuse, so that it helps to accelerate the level of digital sustainability of the industry to a new level. The adoption of blockchain technology can improve the trust and collaboration efficiency of recycling supply chain members, facilitate the autonomous completion of recycling tasks, reduce recycling costs and improve recycling efficiency in order to better promote the sustainable development of industrial digital transformation. For example, a communications company has cooperated with BYD to carry out the application of IoT technology and blockchain technology in the field of product recycling, realizing the traceability and efficiency of the product recycling process.

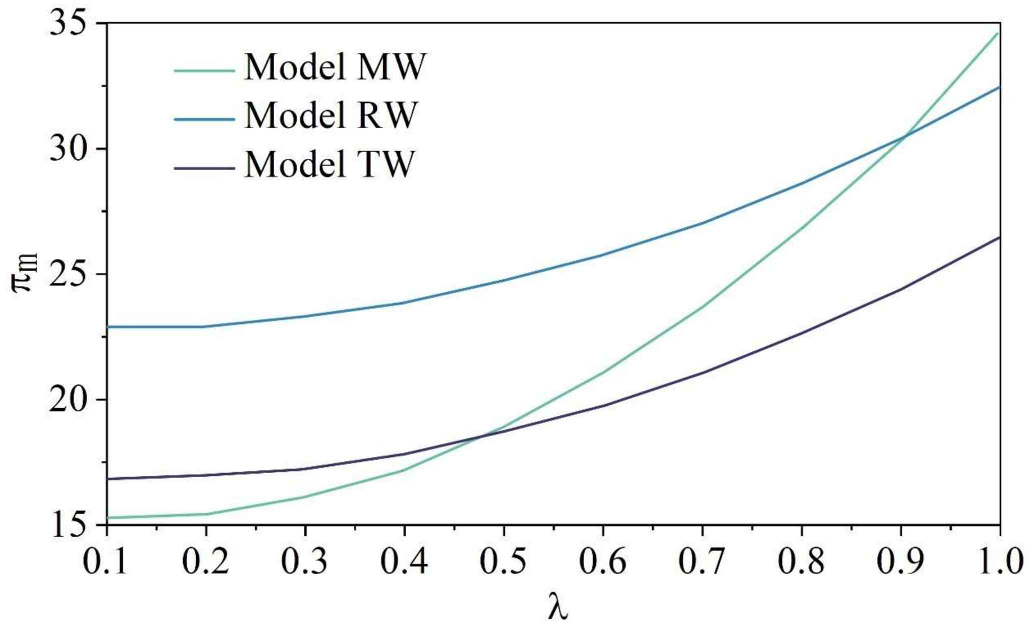


Fig. 9. The impact of cascade utilization on the profit of battery manufacturers

4. Conclusion

This paper is both a challenge and an opportunity for industrial digital transformation in the context of the rapid development of blockchain technology. In order to face the current dilemma, the research on industrial digital transformation supported by intelligent blockchain technology is proposed and case studies are conducted. The research results of this paper are as follows:

1) When the modification request scheme is less than 130 times/second, resulting in the throughput of processing modification requests is basically equal to the request submission speed, and the average value of delay is 2.423 s. When the maximum throughput of the blockchain network processing modification requests is at 119 times/second, the average value of delay will be reduced significantly, and the success rate of the user's modification request rises dramatically, and the scheme in this paper is capable of industrial digitalization sustainable development task.

2) In the industrial digital transaction scenario, compared with the PBFT consensus algorithm, the industrial blockchain scheme based on the CD-PBFT consensus algorithm performs better. In terms of industrial sustainable development, the industrial blockchain scheme can improve the trust and collaboration efficiency of recycling supply chain members, and better promote the sustainable development of industrial digital transformation.

References

[1] Ebert, C., & Duarte, C. H. C. (2018). Digital transformation. IEEE Softw., 35(4), 16-21.

[2] Liu, P., & Lu, C. (2021). Strategic analysis and development plan design on digital transformation in the energy industry: A global perspective. International Journal of Energy Research, 45(14), 19657-19670.

[3] De Bem Machado, A., Secinaro, S., Calandra, D., & Lanzalonga, F. (2022). Knowledge management and digital transformation for Industry 4.0: a structured literature review. Knowledge Management Research & Practice, 20(2), 320-338.

[4] Ellström, D., Holtström, J., Berg, E., & Josefsson, C. (2021). Dynamic capabilities for digital transformation. Journal of Strategy and Management, 15(2), 272-286.

[5] Linderoth, H. C., Elbanna, A. R., & Jacobsson, M. (2018, December). Barriers for Digital Transformation:

The Role of Industry. In ACIS (p. 84).

[6] Rocha, C., Quandt, C., Deschamps, F., Philbin, S., & Cruzara, G. (2021). Collaborations for digital transformation: Case studies of industry 4.0 in Brazil. IEEE Transactions on Engineering Management, 70(7), 2404-2418.

[7] Gölzer, P., & Fritzsche, A. (2017). Data-driven operations management: organisational implications of the digital transformation in industrial practice. Production Planning & Control, 28(16), 1332-1343.

[8] Borangiu, T., Trentesaux, D., Thomas, A., Leitão, P., & Barata, J. (2019). Digital transformation of manufacturing through cloud services and resource virtualization. Computers in Industry, 108, 150-162.

[9] Krasovskaya, O. A., Vyaznikov, V. E., & Mamaeva, A. I. (2021, November). Application of BIM technologies as it projects for digital transformation in industry. In International Scientific and Practical Conference Digital and Information Technologies in Economics and Management (pp. 104-116). Cham: Springer International Publishing.

[10] Alrabadi, T., Talib, Z., & Abdullah, N. (2023). The role of quality 4.0 in supporting digital transformation: Evidence from telecommunication industry. International Journal of Data and Network Science, 7(2), 717-728.

[11] Ku, C. C., Chien, C. F., & Ma, K. T. (2020). Digital transformation to empower smart production for Industry 3.5 and an empirical study for textile dyeing. Computers & Industrial Engineering, 142, 106297.

[12] Sanchis, R., García-Perales, Ó., Fraile, F., & Poler, R. (2019). Low-code as enabler of digital transformation in manufacturing industry. Applied Sciences, 10(1), 12.

[13] Abdallah, Y. O., Shehab, E., & Al-Ashaab, A. (2021). Understanding digital transformation in the manufacturing industry: a systematic literature review and future trends. Product: Management and Development, 19(1), 0-0.

[14] Lopez-Vega, H., & Moodysson, J. (2023). Digital transformation of the automotive industry: an integrating framework to analyse technological novelty and breadth. Industry and innovation, 30(1), 67-102.

[15] Gray, J., & Rumpe, B. (2017). Models for the digital transformation. Software & Systems Modeling, 16, 307-308.

[16] Kozhevina, O. V., Salienko, N. V., Starozhuk, E. A., Klueva, V. A., & Pavlova, I. V. (2020). Digital transformation of the industrial sector: Challenges and prospects. Scientific and Technical Revolution: Yesterday, Today and Tomorrow, 530-539.

[17] Bashynska, I., Mukhamejanuly, S., Malynovska, Y., Bortnikova, M., Saiensus, M., & Malynovskyy, Y. (2023). Assessing the Outcomes of Digital Transformation Smartization Projects in Industrial Enterprises: A Model for Enabling Sustainability. Sustainability, 15(19), 14075.

[18] Ustundag, A., & Cevikcan, E. (2017). Industry 4.0: managing the digital transformation. Springer.

[19] Treiblmaier, H., & Beck, R. (Eds.). (2019). Business transformation through blockchain (Vol. 1). Cham, Switzerland: Palgrave Macmillan.

[20] Aoun, A., Ilinca, A., Ghandour, M., & Ibrahim, H. (2021). A review of Industry 4.0 characteristics and challenges, with potential improvements using blockchain technology. Computers & Industrial Engineering, 162, 107746.

[21] Javaid, M., Haleem, A., Singh, R. P., Khan, S., & Suman, R. (2021). Blockchain technology applications for Industry 4.0: A literature-based review. Blockchain: Research and Applications, 2(4), 100027.

[22] Bodkhe, U., Tanwar, S., Parekh, K., Khanpara, P., Tyagi, S., Kumar, N., & Alazab, M. (2020). Blockchain for industry 4.0: A comprehensive review. Ieee Access, 8, 79764-79800.

[23] Heiets, I., La, J., Zhou, W., Xu, S., Wang, X., & Xu, Y. (2022). Digital transformation of airline industry. Research in Transportation Economics, 92, 101186.

[24] Ghosh, S., Hughes, M., Hodgkinson, I., & Hughes, P. (2022). Digital transformation of industrial businesses: A dynamic capability approach. Technovation, 113, 102414.

[25] Tian, M., Chen, Y., Tian, G., Huang, W., & Hu, C. (2023). The role of digital transformation practices in the operations improvement in manufacturing firms: A practice-based view. International Journal of Production Economics, 262, 108929.

[26] Mushtaq, A., & Haq, I. U. (2019, February). Implications of blockchain in industry 4. o. In 2019 International Conference on Engineering and Emerging Technologies (ICEET) (pp. 1-5). IEEE.

[27] Chen, Y., Lu, Y., Bulysheva, L., & Kataev, M. Y. (2022). Applications of blockchain in industry 4.0: A review. Information Systems Frontiers, 1-15.

[28] Khan, A. G., Zahid, A. H., Hussain, M., Farooq, M., Riaz, U., & Alam, T. M. (2019, November). A journey of WEB and Blockchain towards the Industry 4.0: An Overview. In 2019 International Conference on Innovative Computing (ICIC) (pp. 1-7). IEEE.

[29] Sharma, P. K., Kumar, N., & Park, J. H. (2018). Blockchain-based distributed framework for automotive industry in a smart city. IEEE Transactions on Industrial Informatics, 15(7), 4197-4205.

[30] Ruthbah Tahsin,Sakib Bin Alomgir Rantu,Mahjabin Rahman,Sheak Salman & Md. Rezaul Karim. (2025). Towards the adoption of AI, IoT, and Blockchain technologies in Bangladesh's maritime industry: Challenges and insights. Results in Engineering103825-103825.

[31] Heejoo Kim,Zhe Xiao,Xiaocai Zhang,Xiuju Fu & Zheng Qin. (2024). Rethinking Blockchain Technologies for the Maritime Industry: An Overview of the Current Landscape. Future Internet(12),454-454.

[32] Yijun Yang,Huan Wan,Xiaohu Yan,Ming Zhao,Jianhua Zeng & Bin Li. (2025). Parallel cryptographic hash function based on cellular automata and random diffusion model.Applied Soft Computing112546-112546.

[33] Abdullah Sevin & Ünal Çavuşoğlu. (2024). Design and Performance Analysis of a SPECK-Based Lightweight Hash Function. Electronics(23),4767-4767.

[34] Zhe Li,Jinsong Wang & Yi Li. (2024). An improved PBFT consensus algorithm based on reputation and gaming. The Journal of Supercomputing(1),323-323.