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Blockchain technology in maritime supply chains: applications, architecture and challenges

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ABSTRACT

As an essential carrier of cross-border trade, the maritime supply chain has always been plagued by long service cycles, complex structures, and heterogeneous information from multiple sources. In this context, as a distributed database system, the emerging blockchain technology has the characteristics of decentralization, tamper-proofness, and traceability, which can be correctly applied in the maritime industry to promote its transformation and upgrading. However, blockchain application in the maritime supply chain remains notably absent, leaving this critical topic almost unexplored. Thus, we first conduct a comprehensive literature review and an industrial investigation to clarify the current status, problems, and challenges of the blockchain-based maritime supply chain system (BMSCS). We construct a new operation management mode of the maritime supply chain and propose an integrated BMSCS suitable for global economic development. Finally, based on comparison of the current research results, reasonable suggestions for the future operation and development of the BMSCS are put forward to enhance the coordination among members, accelerate the application of blockchain in the maritime industry, and gradually realise the intelligent operation of the maritime supply chain.

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KEYWORDS
Blockchain; maritime supply chain; blockchain-based maritime supply chain system; operations management; implementation challenges

1. Introduction

With the development of international trade and economic globalisation, logistics has become increasingly important in global partnerships (Hackius and Petersen 2020). Given its low-cost and high-efficiency service transportation system, maritime has become the primary mode of transportation in global trade. More than 16 trillion dollars of goods are transported across international borders every year, 90% of which are transported by sea. Nevertheless, the maritime industry still faces a bottleneck that restricts its development. Meanwhile, environmental protection, cost-effectiveness, and the efficient and safe transportation of goods around the world all require higher service standards for maritime (Shin et al. 2018). Although the use of big data, the Internet of Things, and other high-tech technologies have made significant progress in finding innovative solutions for maritime digitisation, the industry still relies on a large number of human resources in terms of maritime management, business process reorganisation, and the verification of global business responsibilities. At the same time, information sharing, coordination and communication, decision-making and time management increase the workload of all parties, leading to human error and overall confusion among all parties with regard to their responsibilities and ultimately significantly delaying shipping efficiency. Therefore, the pain points in the maritime supply chain are mainly the result of trust issues between nodes, product traceability issues, process optimisation, and paperless bills of lading. Facing these problems, global maritime companies strive to find more efficient technical operation procedures. Blockchain technology has also come to the attention of the maritime industry and has been gradually applied to the global maritime supply chain system and provided the possibility for breakthrough development in the maritime field.

In March 2017, shipping giant Maersk announced the completion of the first trial of the blockchain project and successfully used blockchain technology to track cargo transportation. In August of the same year, 14 Japanese maritime companies, including MOL and NYK, announced an alliance to jointly establish a blockchain-based trade data-sharing platform to form a

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BMSCS network with the aim of promoting the innovative development of maritime industry management. In April 2019, the Digital Container Shipping Association (DCSA) was jointly established by the world's four largest container liner companies: Maersk, MSC, Hapag-Lloyd, and ONE. At the same time, policymakers have also taken measures to reduce environmental risks and ensure maritime safety, environmental friendliness, and sustainability (Di Vaio and Varriale 2018; Manupati et al. 2020). In addition to the International Maritime Organization (IMO), some coastal countries have also implemented their own rules to increase transparency, efficiency, and monitor data affecting air and water pollution through blockchain technology (Bai and Sarkis 2020; Castka, Searcy, and Mohr 2020). On 23 September 2019, China's 'Outline for Building a Powerful Transportation Country' proposed the vigorous development of intelligent transportation and for the transportation industry to implement business digitisation. We can use blockchain technology to actively build smart waterways and smart ports and promote the digital transformation and intelligent upgrade of the transportation infrastructure.

High-quality development has become the central theme of maritime in the new era. Against the background of digital transformation, blockchain technology is one of the core technologies that maritime companies must master. Its core value lies in its capability to make the massive data application of maritime companies more orderly, safe, and stable (Yong et al. 2020). The characteristics of blockchain technology, such as complete distribution, decentralization, openness and transparency, security, and stability, also make it more applicable in the field of port maritime. However, the question of how to realise the operation of blockchain in the maritime network is still a difficult problem. This paper focuses on the construction of a blockchain-based maritime supply chain system (BMSCS) and expounds on the following research questions:

RQ1: What are the pain points of emerging blockchain technology in the maritime field?

RQ2: Given the advantages of blockchain technology compared to traditional technology, can the use of blockchain technology build a BMSCS to remove maritime pain points?

RQ3: What challenges will the BMSCS confront in the process of actual operation and management?

Based on these questions, we analyse the possible impact of blockchain technology on the maritime industry, explore the application prospects of blockchain technology in the field of maritime, build a BMSCS based on the identified pain points, improve the global maritime transportation supply chain network, and promote the further development of the traditional maritime industry.

However, there are still gaps in the existing literature on the application of blockchain technology and the promotion of the transformation and upgrading of the maritime supply chain. To the best of our knowledge, this paper is the first theoretical study to discuss the application of blockchain technology in the maritime supply chain. Therefore, the main contributions of this article are as follows: First, we review the development of the maritime supply chain and analyse the development of blockchain in maritime. Second, through research in the maritime field, we identify the pain points of maritime development and the fit point of the combination of maritime and blockchain. Third, because of the development environment and bottlenecks in the maritime field, we creatively propose a BMSCS combining blockchain and the maritime supply chain to remove the pain points in the maritime field and realise the sustainable development of BMSCS operation management. This paper can be used as a practical guideline for the future development of the maritime field, effectively promotes the application research of blockchain technology and the decentralised management of the maritime supply chain and contributes to the research on system design and data management based on blockchain.

The remaining parts of this paper are organised as follows: Section 2 expounds on the theoretical basis of the research, conducts a discussion of the literature, and reviews the technical characteristics of blockchain and its impact on supply chain management. Section 3 elaborates on the application development of blockchain in the maritime field and analyses its development pain points. Section 4 builds the BMSCS and conducts research on its operation management. Section 5 discusses the challenges faced by the implementation of the BMSCS and provides insights for academic and maritime practice. Finally, Section 6 sets forth the research results, discusses the study's significance for scholars and management and makes recommendations for future research.

2. Literature review

Although blockchain technology has not fully spread throughout the maritime industry, it has gained ground in maritime applications. We studied the literature review method of other scholars (Chen et al. 2021; Tranfield, Denyer, and Smart 2003) and reviewed the relevant literature on the application of blockchain in the maritime supply chain.

2.1. Blockchain technology

Since blockchain was proposed in 'Bitcoin: A peer-to-peer electronic cash system' in 2008, its application has gradually evolved from an encrypted digital currency to a platform providing trusted services. From the perspective of data, blockchain is a distributed database. It connects data blocks based on a time sequence to form a chain data structure. From the perspective of accounting, blockchain is a distributed accounting technology or accounting system; that is, a blockchain is a ledger, and the block is each page of a roster. Each node on the block is a bookkeeper. Scholars have also published articles in 'The Economist' emphasising blockchain as a technical means that can build mutual trust without third-party supervision that can be used as the foundation protocol of the second generation 'Value Internet'. In short, blockchain derived from Bitcoin distributed technology is an open ledger system based on the Bitcoin protocol. It is a new application model of computer technology such as distributed data storage, point-to-point transmission, consensus mechanisms, and encryption algorithms (Dolgui et al. 2020).

Blockchain technology has the characteristics of decentralization, openness, distributed storage, traceability, and cannot be tampered with. The blockchain network is composed of a single P2P node, and there is no independent third-party control centre. Each node has equal rights and obligations. At the same time, each node in the P2P network has a complete data backup of the blockchain system, and any node data damage will not affect the operation of the entire network. The completely decentralised structure enables data to be recorded in real time and updated in each network node participating in data storage. The fault tolerance of data information is very high, which dramatically improves the security of the database. Open-source blockchain technology makes the entire information system highly transparent (Ding et al. 2020). After the data block is timestamped, the data can be marked to form a data blockchain, thereby recording the complete history of the blockchain data and providing the traceability and positioning function of the blockchain data (Appelhanz et al. 2016; Caldarelli, Rossignoli, and Zardini 2020). The blockchain adopts a chain structure and timestamp. All data has a sequence and time mark. A continuous and complete database is formed through timestamp technology to prevent data tampering and forgery and to further ensure data security (Azzi, Chamoun, and Sokhn 2019; Zhang et al. 2020).

In terms of characteristics, the critical feature of blockchain is that it is distributed, verifiable, and immutable (Babich and Hilary 2020). The distributed architecture means that the blockchain system does not rely on any centralised authority, users have a complete copy of the blockchain, and participants always have access to a comprehensive audit process for tracking activities. Transactions that occur on the chain at the same time cannot be modified or deleted, and the longer the chain, the harder it is to adjust, and the higher the level of trust. Therefore, the security of the blockchain can be maintained (Sidorov et al. 2019). As an emerging technology, blockchain is ideal for investment and financing in the global maritime field and a technical means by which major maritime companies can gain better control of the future development of the international maritime industry.

2.2. Blockchain technology and supply chains

As an innovative application model that integrates multiple technologies, such as databases, cryptography, and network technology, blockchain has become one of the leading forces of change in various fields. A recent industry survey report shows that logistics managers tend to adopt blockchain technology, especially in supply chain management (Kim and Shin 2019; Kumar, Liu, and Shan 2020; Van Hoek 2019b). The unique data structure system of the blockchain can reduce transaction and inventory costs (Martinez et al. 2019; Schmidt and Wagner 2019), eliminate bottlenecks in the supply chain (such as payment or delivery delays), establish a supply chain that can adapt to changes in the global economic environment, track the origin of products safely and reliably (Yoo and Won 2018), and hire cheap labour to reduce transportation demand and deliver the highest quality products to the consumer market. Many studies have reported the significant advantages of blockchain technology in logistics and supply chains (Cole, Stevenson, and Aitken 2019; Hughes et al. 2019; Longo et al. 2019). Such advantages include upgrading and protecting supply chain cybersecurity (Wong et al. 2020a), improving supply chain transparency and traceability (Hastig and Sodhi 2020; Rodríguez-Espíndola et al. 2020; Wu, Fan, and Cao 2021), and implementing digital management and process optimisation (Dubey et al. 2020; Queiroz and Wamba 2019; Rahmanzadeh, Pishvaee, and Rasouli 2020).

Choi (2020) studied supply chain financing problems and developed analytical models for both traditional and blockchain-supported supply chains. Kumar, Mookerjee, and Shubham (2018) also studied the characteristics of problems at the interface between operations management (OM) and information systems (IS) and extended the discussion to provide directions for future research at the OM and IS interface in domains such as fintech and blockchain. Helo and Hao (2019) presented a reference architecture that demonstrates how blockchain can be implemented in the operations and supply chain context.

Wong et al. (2020b) studied the behavioural intention to adopt blockchain for supply chain management. Queiroz et al. (2020) aimed to investigate the blockchain technology (BCT) adoption behaviour and possible barriers in the operations and supply chain management (OSCM) context. Li et al. (2020) proposed a production capability evaluation system by incorporating blockchain technology for supply chain networks to enable open and decentralised data storage and sharing and to provide fair and automatic trading of data. Almost all organisations hope to use blockchain technology to make substantial improvements to the supply chain system to conduct transactions more securely, transparently, efficiently, and in environmentally friendly ways and to enhance the trust and reliability of the entire network (Chang, Iakovou, and Shi 2020; Yadav and Singh 2020).

As the organisational structure of the supply chain has become more complex and stakeholders have become more diverse, many companies lack an overall grasp of supply chain management. Currently, some large organisations rely on centralised supervision or intermediary agencies to establish their subsystems in various regions to maintain the coverage of global business. This low transparency has caused many problems for the supply chain mechanism in terms of security, traceability, authentication, and verification systems, and these problems are more prominent in the maritime field. It is worth noting that the decentralization, immutability, transparency, and trustworthiness of blockchain technology are particularly effective in breaking the bottleneck of the maritime industry.

2.3. The maritime supply chain

The most significant impact of blockchain technology on the maritime supply chain is its traceability. Kamble, Gunasekaran, and Sharma (2020) used blockchain technology to solve the traceability problem of the maritime supply chain. Some scholars have also proven the effectiveness of blockchain deployment in tracing the source of products through a pilot program in the maritime industry (Behnke and Janssen 2020). At the same time, the research of Kshetri (2018) presented early evidence linking the use of blockchain in supply chain activities to increase transparency and accountability. Howson (2020) explored how blockchain technology is leveraged to improve marine conservation and supply chain management globally. It is expected that blockchain will be used to improve trust-related issues in transactions and make maritime more efficient in the new era.

While establishing a transparent maritime network through traceability, we must also pay attention to process optimisation issues. For the maritime supply chain, most risks are caused by delayed payments, inefficient asset management practices, and data threats (Tönnissen and Teuteberg 2020). The deployment of blockchain technology will directly shorten the settlement delivery cycle, merge or cancel unnecessary steps involved in the settlement process (Kamble, Gunasekaran, and Arha 2019), and improve business efficiency by reducing transaction lead times (Ying, Jia, and Du 2018). At the same time, the optimisation of business processes will lead to the broader participation of stakeholders, lower transaction costs, and shorten delivery cycles to improve efficiency (Wang, Han, and Beynon-Davies 2019a).

Blockchain technology is also involved in the digitisation of maritime documents. Maersk and International Business Machines (IBM) are cooperating on the blockchain management of maritime containers. According to a blockchain-based bill of lading created by the two companies, the reduction in administrative costs due to tracking maritime containers and eliminating paper documents was approximately 15% of the value of the shipped goods in early testing. Yoon et al.'s (2020) simulation and numerical analysis results show that the reduced lead time and decreased ocean transport cost under blockchain enable the exporting firm to increase shipment via the ocean. Assets, currency, and contract bills of lading will be presented in digital form in supply chain transactions, which will have a massive impact on business processes (Wang et al. 2019b). Yang (2019) gave maritime shipping blockchain-based digitalisation and pointed out future improvement directions in blockchain technology.

Smart contract. Han et al. (2020) proposed a blockchain-based smart contract and presented a universal framework for a blockchain platform that achieves efficient and effective transactions through multiplayer participation. Saberi et al. (2019) conducted critical research on blockchain technology and smart contracts and elaborated on the potential application prospects in maritime supply chain management. Some scholars have discussed the use of smart contracts and their influence on operational transactions and developed and implemented fully functional virtual public blockchains to store, validate, and maintain transactions (Jabbar and Dani 2020).

The existing literature on the application of blockchain in the maritime supply chain is mainly reflected in four areas: digital management, commodity traceability, process optimisation, and smart contracts. In addition, we explored the comprehensive application of blockchain technology in the maritime supply chain. Verhoeven, Sinn, and Herden (2018) researched examples of blockchain implementation in supply chain management

and discussed 300Cubits, which aims to revolutionise the maritime business by tokenising the contract between customers and container liners. After that, Van Hoek (2019a) extended Verhoeven, Sinn, and Herden (2018) framework and empirical research beyond the use case stage into the pilot stage. Li and Zhou (2020) discussed some case studies of blockchain projects in the maritime industry and illustrated various mechanisms by which blockchain can help achieve maritime supply chain objectives. Pu and Lam (2020) provided a thorough analysis of blockchain applications from the perspectives of different sectors in the maritime industry and developed a novel conceptual framework to provide a holistic view of blockchain adoption in the maritime industry. Czachorowski, Solesvik, and Kondratenko (2019) found that cases of blockchain application in other fields increase the industry's willingness to apply it in the maritime industry.

Although blockchain is suitable for dealing with the various challenges faced by the maritime supply chain system, there is still a gap in the research on the implementation of the combined operation of the maritime supply chain and blockchain. Therefore, integrating the existing literature and providing guiding suggestions for operations management is another emphasis of our research.

3. Blockchain technology in the maritime supply chain: applications and pain point analysis

In recent years, the optimisation of maritime transaction process supervision, trust communication between enterprises, the digital transformation of forms, and environmental sustainability have all posed challenges to the development of the maritime industry. This section will analyse the pain points in the maritime field based on the development of blockchain in the maritime supply chain.

3.1. Pilot initiatives of blockchain in the maritime supply chain

Since 2015, the industry has been testing the application of blockchain in the maritime supply chain (Gausdal, Czachorowski, and Solesvik 2018; Hasan et al. 2019). Some critical maritime companies, such as Maersk, Hyundai Merchant Shipping, and Maritime Silk Road Platform, have collaborated with technology giants to create a blockchain-based system to simplify maritime logistics. Currently, many freight forwarding companies, including Maersk and freight forwarding companies around the world, are jointly developing a fully digital freight platform. The first bill of lading issued electronically through blockchain technology is the smart bill of lading (SBL), which means that all paper bills of lading are digitally transferred to the blockchain to improve global trade and obtain advantages such as speed, security, and transparency. We found that existing maritime projects are scientific pilot experiments based on certain characteristics of the blockchain, which are reflected in logistics traceability, information sharing, electronic bills of lading, and smart contracts. With regard to more specific and comprehensive application models, the industry is still exploring. The specific application of blockchain in the maritime field is shown in Table 1.

Figure 1 shows the functional application of the existing blockchain in the maritime field. Although the ledger is an emerging technology, it has made a huge contribution to cargo transportation, ship design, construction, and tracking the whole life cycle of ships.

Through the practical application of the abovementioned blockchain in the shipping field, we can intuitively find that the industry uses the characteristics of blockchain technology to ensure the openness and transparency of platform information, realise the coordinated operation of nodes, and improve the digital level and operational efficiency of shipping to establish an intelligent, green and ecological integrated shipping blockchain network. However, in many applications, we find that the existing applications are based on a single character instead of fully exploiting the potential of blockchain to truly solve the pain points in the shipping field. Therefore, based on the existing application pilot, we proposed BMSCS to fully tap the potential of blockchain technology in the shipping field.

3.2. Pain points of the maritime supply chain

With the development of international trade and globalisation, logistics is becoming increasingly important worldwide. However, information asymmetry caused by distributed production is a common problem in the maritime supply chain. The chain has low transparency and lacks an effective trust mechanism among the different stakeholders. This has led to the appearance of counterfeit products and product quality scandals, which have harmed the whole maritime supply chain. Although there are many pilot applications of blockchain, the pain points in the maritime field have not been resolved. The most severe issues in the maritime industry focus on the following points:

The trust problem of maritime system nodes. Trust within the main body of the maritime supply chain

Table 1. Applications of blockchain in the maritime field.

Time	Organisation	Events
June 2015	HNA Group	Launch a blockchain-based aviation maritime financial settlement and data service management platform – AirPay Insurance
November 2016	Rotterdam, ABN AMRO Bank, Technische Universiteit Delft	Launch a blockchain logistics contract information sharing application platform
August 2017	PSA, PIL and IBM	Jointly sign a memorandum of understanding to promote supply chain business network innovation based on blockchain technology
August 2017	K-LINE, MOL and NYK	Announce the formation of an alliance to develop a trade data sharing platform using blockchain technology
September 2017	HNA Group	Intelligent container operation management platform project
September 2017	Ernst & Young and Guardtime	Announcing the creation of the world's first maritime insurance blockchain platform
November 2017	Star shipping, Sparx Logistics and Wave	Complete the pilot project of a paperless bill of lading based on blockchain technology
January 2018	Shanghai Customs, COSCO and SIPG	Sign the development of a big data platform for cross-border trade management based on blockchain technology
January 2018	Maersk and IBM	Jointly develop a blockchain-based global trade digital platform
August 2018	Maersk and IBM	Launch the digital industry platform TradeLens with the aim of applying blockchain technology to the global maritime supply chain
September 2018		MarineX, the first maritime blockchain platform in mainland China, announces official establishment
November 2018	DP WORLD, PSA, SIPG, and COSCO	Cosign to create a blockchain alliance for the Global Shipping Business Network (GSBN)
April 2019	Maersk, MSC, Hapag-Lloyd and ONE	Officially announce the establishment of the Digital Container Shipping Association DCSA
June 2019	Samsung SDS and ABN AMRO Bank	Develop a blockchain-based logistics pilot project to track container shipments from South Korea to the Netherlands
April 2020	CargoSmart, COSCO, SIPG and Tesla	Complete the pilot application of digital transformation of the existing cargo release process, which is the first batch of pilot application projects in the maritime industry to realise real-time freight data exchange between ocean carriers and quay operators through blockchain technology
June 2020	China Merchants Port, Alibaba Group and Ant Financial Services Group	Sign the 'Strategic Cooperation Framework Agreement' to open the full link of port business through Ant blockchain technology and to reconstruct the multiparty cooperation system of port trade and logistics
June 2020	China (Shanghai) Pilot Free Trade Zone	Actively deploy and promote the construction of a shared ecosystem of blockchain technology and international shipping
September 2020	Blockshipping	The world's largest shared container platform GSCP

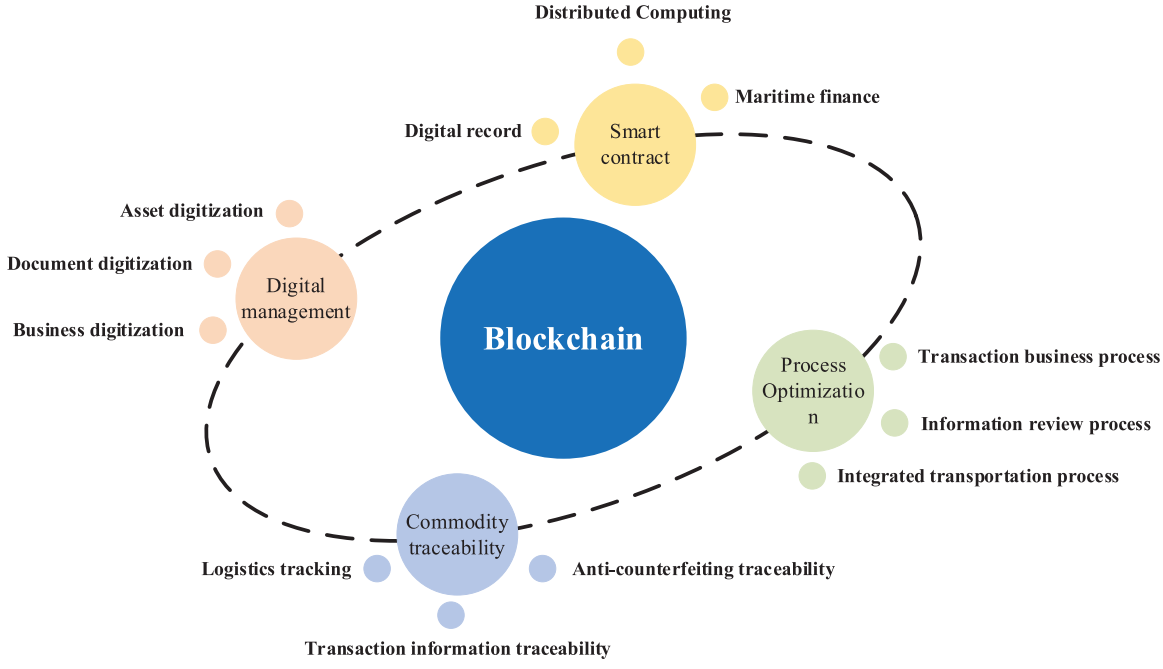

Figure 1. Blockchain technology for maritime supply chain functions.

network cannot be passed on, and the credit of the core enterprise can only be passed on to first-tier suppliers. Meanwhile, since the trade background is difficult to verify, it is prone to the risk of fraud such as warehouse receipts and bill fraud. There are also information islands, and trade information relies on paper documents to

transmit, which increases the financing costs of maritime companies and affects the operating costs of financial institutions (Dutta et al. 2020).

Logistics tracking and commodity traceability. With the deepening of economic globalisation and the advent of the upgrading of consumer concepts, consumers have increasingly higher requirements for the quality and sources of goods, the traceability of cross-border logistics, and service quality. Due to the centralisation of the traditional maritime network commodity traceability system, there are many problems such as data distortion (Choi 2019), information tampering, and data islands. There are difficulties with the traceability of commodity information. Even if logistics supply chain companies are willing to exchange and share data through interface docking, there will be problems of low trust and high cost, low transaction efficiency, and insufficient safety factors.

Process optimisation and paperless bills of lading. Maritime services involve complex partners and many transportation documents. Among them, there are as many as ten types of documents generated by transportation services such as bills of lading, commercial invoices, and insurance certificates. Moreover, the digital conversion and delivery of documents may lead to inefficiencies in the entire maritime supply chain and transaction delays, which will increase the transaction cost of each participant. At the same time, traditional paper documents (labour, paper, printing) will produce waste in terms of cost management for the existing paper-based office. Second, from the issuance of a document to the return of the final document to the biller, the average transmission time is more than two weeks, resulting in a serious information lag, which seriously affects the delivery and settlement of goods. In recent years, some enterprises have realised the digitisation of records through the transformation of logistics and supply chain information systems. However, due to the centralised system architecture of the internet, the security and immutability of electronic documents cannot be guaranteed; thus, the popularity is low, and most of them still use paper documents.

Coordination and alliance of maritime networks. Whether the data and information transmission among maritime enterprises can be coordinated and consistent, information processing and responses are quick, and the processing system of each link in the supply chain is complete remain unclear. These are all factors affecting maritime efficiency. The existing supply chain business model includes multiagent procurement information, transaction information, and logistics information. To build a traditional integrated information system, the business personnel of all parties must invest substantially to develop and maintain it. The fundamental reason for such problems lies in the opacity of the information, cumbersome business processes, and the fact that the one-way data transmission mode of point-to-point transmission can easily cause information islands and transaction disputes. For the maritime supply chain, the question of how to build a digital supply chain and cooperate with global maritime network enterprise alliances has become the primary issue in this field.

In addition, there are problems in terms of electronic deposits and judicial supervision, logistics and supply chain credit investigation, and digital asset transactions. On the one hand, this is due to the large difference between the practitioners in each link of the logistics and supply chain. On the other hand, the service levels of companies in the logistics and maritime supply chain are uneven. Moreover, there are no unified, cross-organizationally recognised evaluation standards in the maritime field. Evaluation information and rating rules are incomplete, and the service relationship is unstable, which leads to the existing credit issue and inaccurate credit data. The specific business process and pain points in the maritime field are shown in Figure 2.

As a decentralised, shared, encrypted repository, blockchain is not affected by database changes or damage. It can provide a basis for collaborative commerce and simplify the decision-making process at each stage, which enables simultaneous audits between partners and makes real-time optimisation possible, thereby increasing the trust of the entire supply chain. Therefore, blockchain technology is a potentially disruptive technology for the design, organisation, operation, and general management of the maritime supply chain. Identifying how to take advantage of blockchain technology to address the industry's pain points in the maritime supply chain and build a blockchain-based network system is critical to maritime operations management.

4. The conceptual architecture and function of the BMSCS

Blockchain provides new opportunities and challenges for enterprises to improve productivity, rethink coordination in the supply chain, and accelerate economic development (Choi et al. 2020), and it plays an increasingly important role in promoting innovative changes in maritime supply chains.

4.1. Conceptual architecture of the BMSCS

Given the pain points and bottlenecks in the maritime field, the paper creatively proposes a BMSCS. The distributed characteristics of the blockchain contribute to building a maritime network system, and it can promote

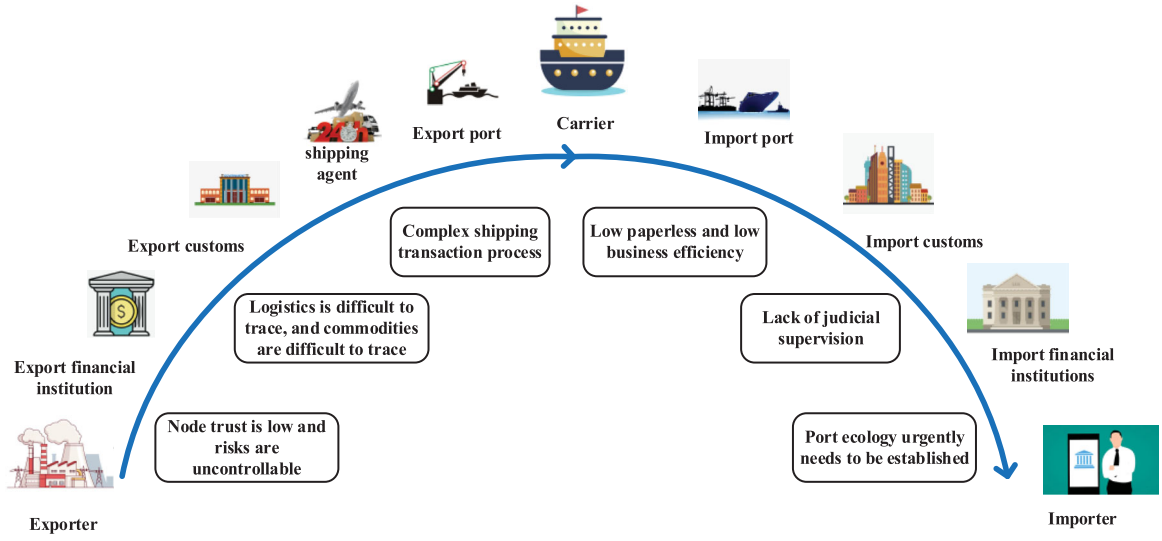

Figure 2. Pain points of the maritime supply chain.

the solution of node trust in the maritime system, digital services, electronic manifests, logistics tracking and commodity traceability, process optimisation, maritime collaboration and alliances, and maritime finance. The BMSCS is based on the unique distributed data structure of the blockchain. It takes cargo owners, ports, maritime companies, customs, regulatory authorities, financial institutions, and freight forwarders as nodes to build a point-to-point maritime transmission network. Establish a collaborative, intelligent, digital, platform, green and ecological integrated BMSCS network through blockchain technology to realise customised, visualised, safe, reliable, competent, and efficient maritime supply chain system management. The system architecture is shown in Figure 3.

The construction of the BMSCS utilises the characteristic decentralization, openness, independence, and security of blockchain technology. A maritime blockchain network is built among various nodes such as ports, customs, and shipyards to realise intelligent transactions, resource scheduling, maritime service, supervision and auditing, and data sharing. Given the pain points in the maritime field, we coordinate the main nodes of the supply chain to build an open blockchain network that is open and transparent and fully protects the privacy of all parties. We create a model to truly realise the integration of the four streams of business flow, information flow, capital flow, and logistics in the maritime supply chain system and ultimately improve the operational management efficiency of maritime enterprises.

In terms of commodity traceability (logistics tracking), the transaction data in the BMSCS are recorded on the chain in chronological order and stored separately. However, each newly generated block carries all the data of the previous block and uses cryptographic methods to prevent data tampering or forgery on the chain. Each node can obtain all transaction information through a public key so that every transaction can be traced.

In terms of digital management, the BMSCS improves efficiency by increasing the level of digitisation. The application of blockchain can completely change the basic technology of maritime and logistics supply chain systems and promote the transformation of BMSCS. The traditional paper contract will be converted into a smart contract to realise the function of digital and automatic reading, which provides a wave of cooperation across the entire maritime industry ecosystem. Distributed ledger technology (DLT) can be used to collect data and improve transportation operations through process acceleration, which ensures that data are transmitted to all interested parties consistently and accurately and will eliminate the need to fill out various paper forms and logs and to make operations safer and more environmentally friendly (Xu et al. 2021). However, the implementation of maritime digitalisation involves the coordination of the government supervision system, especially customs clearance and management, which also requires the support of the government system.

In terms of process optimisation, the maritime industry must optimise its business processes, upgrade core technology, and improve the ability to create added value in the context of blockchain technology. The optimisation of the maritime supply chain business process integrates and coordinates the core business processes of waterway cargo transportation, agency business, comprehensive transportation, and other links in the maritime logistics service process in a certain way through modern management, blockchain, and information technology

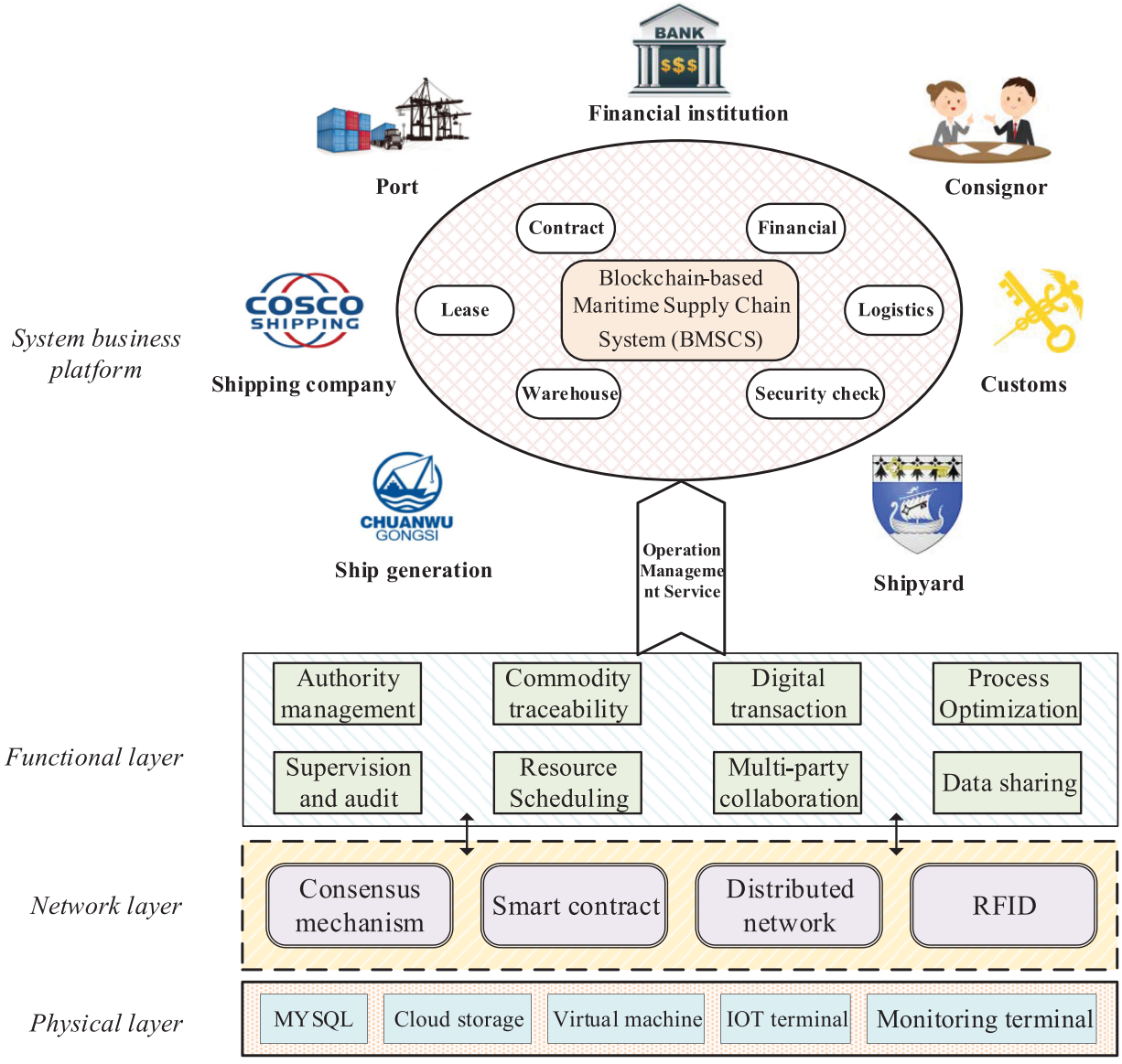

Figure 3. Blockchain-based maritime supply chain system (BMSCS).

and builds ports, maritime companies, third-party logistics companies, and related nodes into a closely connected network chain structure with specific functions to improve business processes.

In terms of collaboration and alliances, the data are jointly maintained by the members of the alliance and are open only to the members of the organisation. Participants have the right to determine or select the database to read directly. The application of the BMSCS begins with the source of the goods and establishes a safe and integrated service platform for maritime companies, ports, and customs. Each piece of transaction information can be traced to the source through the chain structure. Essential data, such as bills of lading, manifest booking, receipts, and other documents, must be encrypted. During the transaction, both parties require a joint visa to truly realise the entire process of records, multiparty certification, and joint supervision, which enhances the trust of the parties in the transaction and the trust of the entire maritime system. The trust mechanism of the blockchain will also establish a new order of ecological alliances in the maritime supply chain field, with consensus on rules, security and co-governance, and value sharing. The information coordination, generation, verification, and recording of blocks among nodes in the BMSCS are shown in Figure 4:

The information of each node in the maritime system is kept consistent based on the unique consensus mechanism of the blockchain, which is conducive to the construction of the maritime operation management system and improves the efficiency of the maritime service mechanism, the security of the transaction, and the

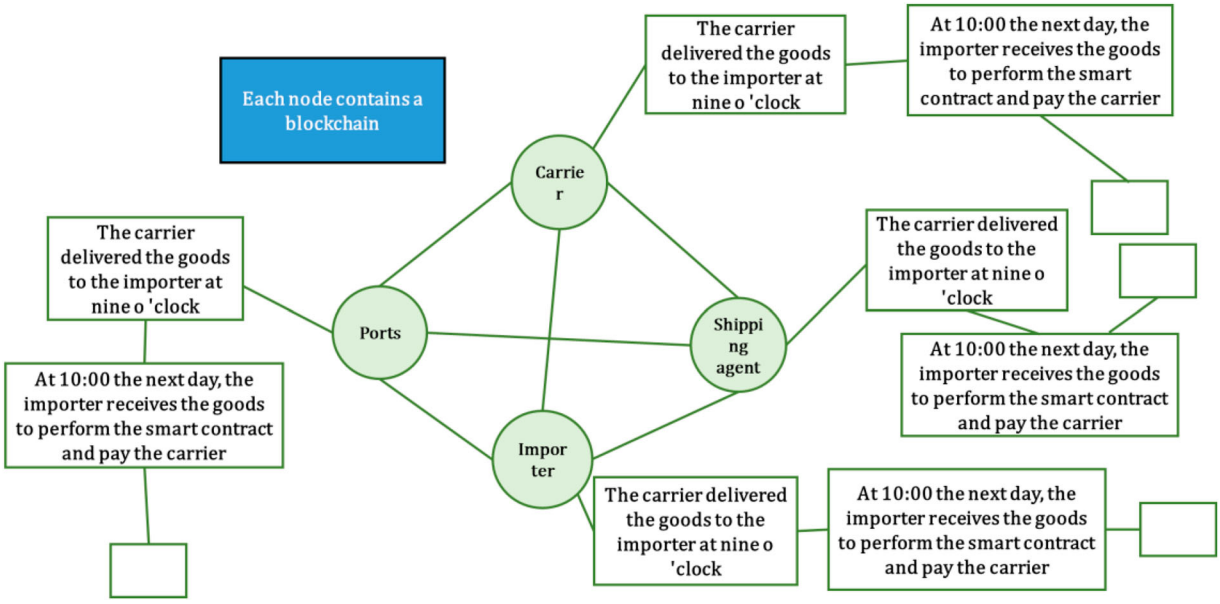

Figure 4. Block generation, verification, and recording of the BMSCS.

real-time performance of services. At the same time, the intervention of blockchain technology can also ensure the openness, transparency, and equality of platform information and solve the problem of mutual trust among maritime supply chain enterprises and between enterprises and the platform at the technical level, reduce communication costs, and efficiently deliver value. In short, the application of blockchain technology is expected to reconstruct all aspects of maritime companies and realise the organic integration of the maritime field and information technology, the real economy and the digital economy, and the traditional services and high-tech, which improves the stability of the BMSCS and promotes the development of the maritime industry.

4.2. Major functions of the BMSCS

The transparency of maritime supply chain trading platforms, the collaboration of industry operations, the standardisation of network connections, and the digitisation of business processes are some of the major functions that can be transformed with blockchain technology.

4.2.1. Trading platform transparency

We propose building an available information platform; creating an information network covering maritime, production, circulation, storage, and transportation; and realising the general development of maritime transaction platforms. The value of blockchain technology will be reflected in three main areas: smart contracts, supply chain financing, and increased supply chain visibility and traceability. The service platform combined with blockchain and artificial intelligence can raise the traceability, transparency, and sustainability of the maritime supply chain. The network integration of all participants improves the overall service delivery, optimises the workflow, enhances efficiency, and accelerates the flow of goods, which benefits everyone in the maritime network. The smart contract mechanism provided by blockchain technology allows the cost of transaction mediation to be reduced. The obstacles to the publicisation of maritime operating and trading platforms are the awareness and understanding of technology (Mathivathanan et al. 2021), organisational culture, cost and efficiency, market supervision, and the security and privacy issues caused by new technologies. Therefore, blockchain technology still must be explored in a broader scope.

Enterprises should actively promote the process of maritime information management to connect the resource planning system among the nodes of the maritime network and achieve information sharing, exchange, and flow between internal business processes and partners to make it an organic whole.

4.2.2. Industry operation coordination

We anticipate the need to strengthen infrastructure construction and provide a complete maritime blockchain industry security system. A sound infrastructure and collection and distribution system are the premises of collaborative operation and management. Figure 5 shows the operation and management process of the BMSCS.

Good transportation infrastructure and convenient transportation conditions, as well as extensive resource

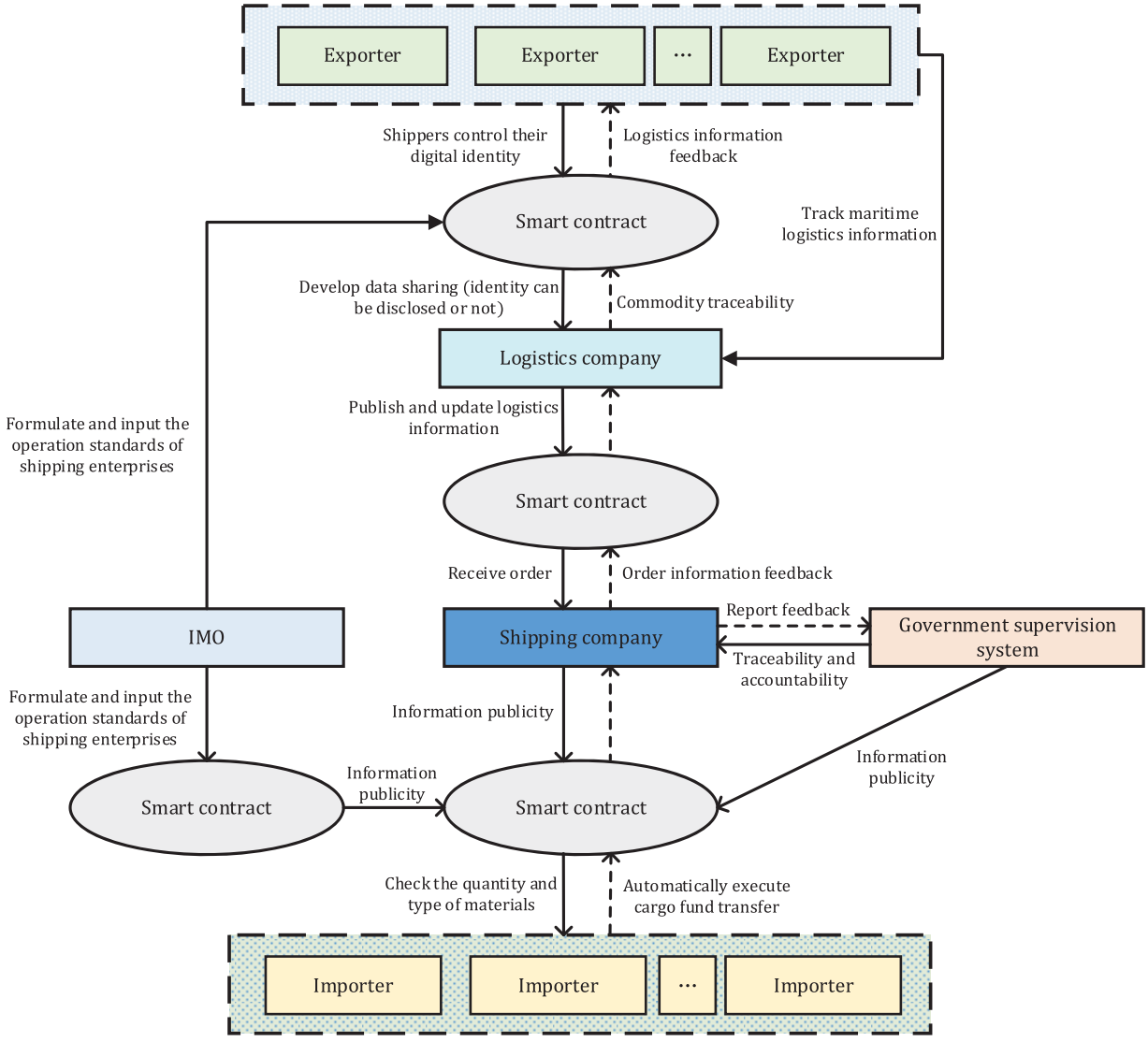

Figure 5. Operation and management process of the BMSCS.

agglomeration and radiation capabilities, have an overall impact on the reasonable layout, smooth connections, and efficient operation of the port itself and the entire maritime network. The system should be centred on the operation alliance platform based on blockchain technology, connect upstream and downstream business systems through interfaces, and strive to build comprehensive transportation and BMSCS with waterways, highways, and ports as the main body, a clear structure, efficient connection, advanced equipment, and excellent services. While utilising the shared infrastructure and improving the collection and distribution security system among ports, the operating costs of the quays will be reduced, and the connection among the quays can also be strengthened, which is conducive to the optimisation of resource allocation.

With the growing maturity of blockchain technology, the tracking and visualisation of nodes will be realised in the operation and management of the BMSCS, the penetration supervision technology of the alliance chain will be improved, the system structure and standards of chain governance will be strengthened, and the modular security cryptography protocol will be implemented. With the support of the policy, the application prospect of blockchain in the field of maritime supply chain collaboration is bright and full of opportunities.

4.2.3. Network connection standardisation

Coordinating the development of the maritime blockchain network, will strengthen cooperation among maritime nodes, improve the level of informatization, and realise the standardisation of maritime network connections. The operation and development of the maritime network involve multiple departments and multiple entities. The development of a network connection can be constrained by policy issues such as taxation, financing,

traffic management, and administrative management. Although a complex maritime network is difficult to describe, blockchain technology is a way to solve the transparency problem of multilevel maritime supply networks. It provides opportunities for the standardisation of network connections and promotes the construction of trust, openness, visibility, and integrity in the maritime field.

A fascinating aspect of blockchain is that it can establish a reliable and secure system to ensure the transparency and immutability of data through the entire maritime supply chain system. For most companies, blockchain is still a complex technology or concept, especially considering that blockchain is a fundamental technology. The existing system must be entirely replaced, which may take many years to realise its full potential and gradually penetrate the construction of economic and social infrastructure.

4.2.4. Business process digitisation

Blockchain is an ideal technology for different aspects of large-scale networks and is regarded as a feasible solution to reduce the complexity of global maritime supply chains. International trade is the most complex transaction. It involves many entities, and most transaction cooperation processes are also based on paper documents, which waste many resources, cause transaction delays and hinder the effective flow of goods. Converting traditional paper contracts into smart contracts and realising the functions of digitisation and automatic reading provides a wave for cooperation within the whole shipping ecosystem. Since distributed ledger technology will prevent the possibility of illegal actions and the forgery of documents, it can be used for proper monitoring, recording, and measurement to ensure environmental sustainability. The blockchain-based operating platform can realise the digital transformation of paper documents and establish a stable and shared network to promote the management of blockchain data and data monitoring and minimise risks.

The government, industry, and individuals are paying attention to the development of the platform. For the maritime industry, the BMSCS is worth deploying. Nevertheless, the potential risks and challenges related to BMSCS cannot be ignored. In addition to the inherent dangers of the platform structure, low operations, broken capital chains, or loss of trust between consumers and society may also lead to platform bankruptcy (Wamba and Queiroz 2020). However, the internal interaction mechanism between platform operations and related risks remains unclear. Some scholars are also looking for the answers to the research question, 'How should a blockchain enabled supply chain be designed?' (Wang, Chen, and Zghari-Sales 2020). It is still necessary to analyse the challenges in the implementation of a BMSCS.

5. Implementation challenges of BMSCS

The BMSCS constructed based on blockchain technology will face technical, application, regulatory, and security challenges in specific implementation and application.

5.1. Technical challenges

With the expansion of the blockchain value chain, a maritime system with modern service advantages will be built. Its competitive platform will be upgraded from simple maritime price competition to complete maritime system competition. Facing the pressure of cost reduction and service improvement, the maritime industry presents technical challenges to the blockchain.

The technical barriers of the BMSCS are mainly reflected in three ways: scalability, transaction uncertainty, and high sustainability costs. The first is scalability. The nodes in the chain must process all transactions that occur in the system. When a transaction is expanded in the global scope, this technology will be energy intensive, and the calculations in the block will consume considerable processor power. Moreover, the distributed ledger technology mainly depends on the size of the blocks used to transmit information, the transmission speed of the network, the underlying work proof protocol, and the verification of information on each node. Therefore, the BMSCS is limited in scalability. Second, the uncertainty of transactions will be another challenge for the BMSCS when executing transactions through the network. Once approved, transactions that occur in the blockchain system can hardly be modified, and deals are irreversible. Therefore, when the system has the possibility of blacklisting the transaction, this uncertainty makes the consignor face the risk of losing the transaction value. The energy consumption caused by the continuous operation of the blockchain may far outweigh its ultimate benefit to solve the shortcomings of the maritime supply chain. When the scale of the maritime blockchain network expands and the transaction costs are expensive after adding new blocks, it must take into account the large number of computing resources required.

Another problem of the blockchain is the loss of keys. If any user loses the set of public or private keys, the user data block will not be retrieved. Although they may physically exist in the BMSCS network, they cannot be further extracted or mined. Therefore, unlike traditional

application software and operating systems, blockchains face severe technical challenges.

5.2. Application challenges

In the era of a knowledge economy characterised by highly developed information technology, the modernisation of information systems in the maritime industry has become an essential means of market competition and core competitiveness. To improve the utilisation rate of maritime resources and the competitiveness of enterprises, maritime companies must establish an integrated and globally shared information network. However, except for digital currency, there are still few practical applications of blockchain in the maritime supply chain system, and most of the practical applications are also verification and exploratory projects. It is therefore difficult to form a sustainable business model. At the same time, if the aim of the blockchain is to operate in the global maritime supply chain network, it must comply with different laws and regulations. In this environment, it is an extremely complex task to realise the perfect combination of the blockchain and maritime supply chain.

Although blockchain technology has the digital properties of tamper-proof transactions, occasional errors, conflicts of interest, corruption, and malicious attacks may still occur. The resulting delay is also a huge obstacle to the construction of a global maritime blockchain information system.

5.3. Legal and regulatory challenges

In the face of huge demand, the maritime system has always been tested by the world, and the emergence of blockchain technology also enables the maritime supply chain system to achieve more complex reforms. As disruptive information technology, blockchain operations in various fields around the world are facing a lack of regulatory standards, insufficient regulatory technology, and a lack of regulatory experience.

Since the government and market supervision have not formed a complete system, there are still unscrupulous practitioners in the maritime field who cheat investment through fake blockchain projects. For example, when blockchain technology first appeared and was put into use, it was used by some freight men to sell illegal or disputed goods due to the lack of unified regulatory standards. Some illegal fundraisers interfere with the public perception in the name of 'digital currency' and 'tokens'. In addition, the government cannot provide significant support for the industrial application of blockchain technology until effective regulatory measures are in place. Foreign governments cannot even implement any monetary policies that restrict blockchain, nor can they charge any taxes on the revenue, sales, or value-added services of transactions.

The distributed nature of the BMSCS may be a major limitation to the overall control and governance of the organisation. The automatic execution of smart contracts and the difficult-to-tamper-with characteristics of the blockchain have introduced difficulties to legal validity, data privacy, and content supervision. If an obvious security breach occurs, there is no central authority to contact, and it lacks the recognition of laws, regulations, and users. Coupled with the immaturity of the technology, it is another big test for the already complicated maritime system.

5.4. Information security and privacy protection

With the continuous opening and development of the maritime industry, the shipper will put forward increasingly personalised requirements to the carrier. Behind meeting the diversification of transactions, maritime companies should also ensure the security of system transactions and user information. The BMSCS improves the credibility of the network through open-source code. However, the open-source code also means that it is easier for attackers to attack the system by locking loopholes in the code, adding incorrect timestamps, forging proof of rights, stealing account numbers, and other means to gain profits. Such attacks may cause blockchain network delays and congestion, change the efficiency of user nodes in the receipt of information, and distort ledger views. Existing proof-of-work algorithms have difficulties handling such attacks. Although the blockchain uses public-key encryption for transaction authentication and execution, if one party loses or unintentionally releases a private key, the system does not provide additional security mechanisms. At the same time, smart contracts in the maritime system have the advantages of low operating costs and low risk of human intervention. However, problems in the design of smart contracts can generate great losses.

Finally, the blockchain places trust and authority in a decentralised network, representing a complete transformation of traditional supply chain organisation and management. Cultural resistance and existing business processes will also become a stumbling block in the transformation of maritime blockchains. The complexity of blockchain technology itself also makes it a challenge for individual users to understand, accept, and participate with confidence.

The above restrictions outline some specific technical challenges and unintended consequences, which

will significantly limit the development and commercial application of blockchain technology in the maritime field.

6. Conclusions

The increasing frequency of global trade exchanges promotes economic integration while also promoting the vigorous development of the international maritime industry and new technologies. Our research has developed a blockchain-based maritime supply chain system to discuss the application and challenges of blockchain technology in the maritime field. Overall, it provides guidance for the deployment of blockchain technology to strengthen the coordination capabilities and improve the service level of the maritime supply chain.

6.1. Theoretical implications

As an emerging disruptive technology, blockchain has incomparable merits including decentralization, openness, independence, and security. Although many recent studies have analysed the practical applications and challenges of blockchain technology in the supply chain field, the literature on extending the blockchain to the maritime field is still limited, and the research on the pain points in the maritime field is even rarer. We have carried out a bold attempt to study the application of blockchain technology in the maritime supply chain and supplemented the existing literature on maritime and blockchain. Specifically, our research proposes a blockchain-based maritime supply chain system to make full use of the advantages of blockchain technology to solve the long-standing pain points in the maritime field. At the same time, we also analyse the specific challenges of implementation for such a system.

The system architecture proposed in this research can accelerate the innovative development of blockchain technology in the operation and management of maritime companies, improve the functions of blockchain technology in terms of flexibility, concurrency, and security, and realise the implementation of blockchain projects in multiple fields. It not only fills the blank for the transport of academic research but also comprehensively promotes the leapfrog development of the maritime supply chain network. Therefore, this study also opens up a new path for the research on maritime supply chains.

6.2. Suggestions for industrial applications

Based on the potential advantages and challenges of a BMSCS, we can find that the deployment of a BMSCS is worth a try. The correct implementation of the blockchain can help companies obtain strategic advantages over competitors, eliminate third-party participation, greatly shorten transaction time, and reduce costs. However, as an industry manager, it is necessary to conduct a detailed assessment of the implementation of the blockchain in the industry to provide it with a specific development plan. Scientific planning can effectively ensure the stable and sustainable development of port enterprises, reduce, and control the cost of strategic investment, save resources, and eliminate waste. In terms of the future development and positioning of the maritime port, systematic consideration should be given to the coastline required by the port, the planning of the entire port area and the rear land area should be coordinated, and the system should be implemented in strict accordance with the plan. Meanwhile, strict resource protection measures should be taken for the development of the maritime supply chain to promote its coordinated operation. It is also necessary to pay attention to the application of blockchain technology, which should be kept low-cost, simple, easy to implement and deployed. Because the exploration of blockchain technology is still in its infancy, large-scale investment is prone to situations where the input exceeds the output, which will trigger a crisis of capital chain rupture. Therefore, for industry managers or the government, investment in blockchain technology should be approached with caution.

6.3. Recommendations for future research

Our research aims to explore how to take advantage of blockchain technology to address the industry's pain points in the maritime supply chain and to build a blockchain-based network system. Although the research has achieved significant results by developing a BMSCS, there are some limitations for possible future research directions regarding blockchain technology. First, we quantify the impact of blockchain technology in the maritime supply chain and use models to analyse the impact of quantified variables on the industry. Second, in response to the challenges raised by our research, eliminating the problem of smart contract design loopholes at the technical level is another research direction. At present, blockchain technology lacks uniform standards on a global scale. While deeply exploring the application of blockchain technology, it is necessary to actively formulate a wide range of operating standards and technical agreements.

In the digital age, how to make full use of the internet, big data, artificial intelligence, blockchain and other new-generation information technologies to improve the operations management and international competitiveness of global maritime companies are worth considering

in the future. The establishment of a modern management system for the maritime supply chain will promote the modernisation of the maritime governance system and governance capabilities and enhance the integration of new technologies with the real economy and industries while also helping to promote the development of the global economy.

Disclosure statement

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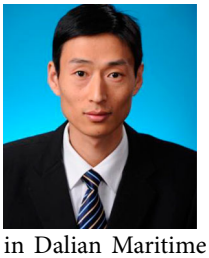

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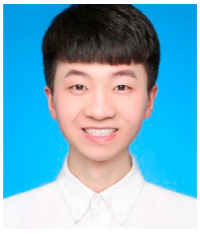

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