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Research Article

Blockchain-driven innovation in fashion supply chain contractual party evaluations as an emerging collaboration model

Minhao Qiao [a], Xuanchang Chen [a], Yangping Zhou [a], P.Y. Mok [a,b,*]

[a] School of Fashion and Textiles, The Hong Kong Polytechnic University, Hong Kong, China
[b] Research Institute for Intelligent Wearable Systems, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

With the advancement of distributed digital technology, the fashion supply chain management system is undergoing unprecedented transformations. Given the expansion and rapid iteration of the fashion industry, traditional supply chain management models struggle to adapt to the volatile market changes. In this context, small and medium-sized enterprises (SMEs), which are integral components of the fashion supply chain, often face significant market pressure, leading to losses and even bankruptcy, which in turn causes delays across the entire supply chain. Thus, there is an urgent need for these businesses to adopt new technologies to reduce risks and achieve profitability. Although there have been attempts to introduce blockchain technology into the fashion supply chain, most of these efforts are still in the preliminary stages, with operations continuing to follow old methods. Therefore, this study aims to introduce an evaluation mechanism into the fashion supply chain, encouraging a collective maintenance of interests among SMEs. The main contribution of this paper includes the introduction of a set of innovative management evaluation mechanisms and collaboration models for SMEs in the fashion supply chain, with the goal of securing their rights to autonomous pricing and promoting healthy competition in the forthcoming Web 3.0 era. We implemented the enterprise-level consortium blockchain framework, Hyperledger Fabric. Through testing, it has been proven that the platform is effective and usable in ensuring data integrity and source transparency.

1. Introduction

The fashion industry has always been an integral part of human society and cultural change. Globally, due to diverse consumer demands, advancements in fashion and textile technology, and the rise of e-commerce, the fashion market has been experiencing robust growth. The annual growth rate (CAGR 2023–2028) of fashion revenue is projected to be 8.67%, with the market size expected to reach $1,062 billion by 2028. This indicates that it has long been one of the most dynamic sectors among consumer goods. As a consumer product, clothing is a typical example of participating in market competition marketing models, with consumer demand driving market development. In the modern fashion market, independent production and sales can no longer meet the rapidly developing market and ever-changing customer needs [1]. To maintain long-term competitive advantage in this highly competitive environment, many leading fashion brands have begun to reevaluate and optimize their supply chain strategies [2]. They recognize that strengthening core businesses and outsourcing non-core businesses through strategic partnerships are key strategies. This not only involves contracting non-critical processes such as design, manufacturing, and the procurement of fabrics and accessories to specialized companies but also emphasizes the importance of establishing stable and mutually beneficial partnerships in this process. This strategy allows brands to focus on their core strengths, such as brand building, marketing, and customer experience, while ensuring that other supply chain processes achieve high-efficiency and high-quality products through collaboration with specialized companies. For instance, outsourcing product design to creative design firms and generative AI [3] can keep brands updated with the latest fashion trends; partnering with excellent manufacturers ensures product quality and production efficiency; and relying on reliable fabric suppliers ensures that the texture and comfort of products meet high standards. Moreover, this collaborative approach not only enhances efficiency and flexibility but also enables brands to respond more quickly to market changes, reduce inventory backlogs, and lower costs. Additionally, it transfers some uncertainties and risks to other suppliers, requiring them to share some of the risks and respon-

* Corresponding author.
E-mail addresses: mok.tracy@gmail.com, tracy.mok@ust.hk (P.Y. Mok).

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sibilities, thus controlling overall costs. Therefore, in today's globalized and consumer-driven fast-changing market, flexible and collaborative supply chain management is crucial for brands to ensure supply chain stability and reliability and achieve sustainable growth.

In recent years, blockchain technology has played a significant role in fashion supply chain management. As consumers increasingly focus on sustainability and ethical standards, they demand more transparency from brands regarding product origins, labor conditions during production, and environmental impact [4]. This trend highlights the importance of supply chain transparency, and blockchain, along with the Internet of Things (IoT) technologies are becoming key tools for enhancing this transparency and ensuring real-time data sharing at every node of the supply chain [5]. The application of these technologies is crucial not only for consumers to make well-informed purchasing decisions but also for improving data quality across the industry. Blockchain ensures the accuracy and reliability of information by making transaction conditions and execution processes transparent, significantly reducing the 'bullwhip effect' in the fashion supply chain, and promoting flexibility in inventory management, thereby reducing overstock. Furthermore, trust issues have long been a major challenge in fashion supply chain management, especially in the context of numerous trading companies operating globally [6]. The introduction of smart contract technology has not only significantly increased the automation of contract execution and reduced disputes, but also provided an effective solution for small and medium-sized enterprises (SMEs) in the supply chain to strengthen partnerships and resolve issues related to benefit distribution. However, current solutions to these challenges are often developed from the perspective of brands or supply chain managers. In today's flourishing fashion market, more attention should be directed towards the SMEs within the supply chain, such as independent design companies, raw material suppliers, manufacturing enterprises, and distribution service providers. Focusing on the interests of these entities can not only enhance the efficiency and responsiveness of the entire supply chain but also help steer the industry in a more sustainable direction. Therefore, adapting operational strategies to fit new fashion supply chain collaboration (FSCC) schemes in the era of Web 3.0 and Industry 4.0 is crucial for promoting the healthy and sustainable development of the entire industry.

In the modern fashion market environment, the primary challenge for SMEs is to improve their competitiveness and profitability [7]. Lacking the substantial financial resources and extensive customer base of large corporations, SMEs must exert greater effort in cost control, particularly when dealing with issues such as inventory buildup, risk management [8], and the bullwhip effect [9]. Moreover, the issue of trust poses a significant challenge that SMEs cannot afford to overlook. Compared with well-established large companies, SMEs often lack the credibility and reputation that come with longevity, putting them at a disadvantage when seeking partners [10]. To address these challenges, this study proposes the development of a blockchain-based management platform designed specifically for SMEs within the global fashion supply chain—referred to as the 'FashionChain'. FashionChain ensures transparent records of all transactions and partnerships, providing a fair and verifiable rating system that allows parties to evaluate each other based on the quality of their services. Key operational data, such as delivery times, order quantities, and transaction amounts, are securely recorded on the blockchain, offering a reliable source of information for all participants and serving as a historical basis for assessing collaboration effectiveness and operational efficiency. By implementing FashionChain, SMEs can not only enhance their credibility within the supply chain and assert greater autonomy over pricing but also leverage shared data to gain insights into market trends and potential collaboration opportunities, thereby optimizing their production capabilities and risk management strategies. The platform aims to provide SMEs with equitable opportunities to compete in the global fashion supply chain, reducing operational costs and risks while fostering innovation and collaborative efficiency across the industry, ultimately driving the fashion sector toward a more sustainable and mutually beneficial future.

The rest of this paper is organized as follows: Section 2 introduces FSCC and operational strategies, the application and management of evaluations, and the latest advancements in blockchain technology. Section 3 details the research methods of this study and the core of the new collaboration solution—information flow transformation. Section 4 presents the design and implementation of the blockchain-based fashion supply chain management platform. Section 5 presents the research results. Furthermore, various tests are conducted on the platform using relevant tools, then the test results are discussed. Finally, Section 6 summarizes the work and outlines potential future research directions.

2. Related work

2.1. Collaboration and operational strategies

FSCC refers to a management approach where all parties within the supply chain (such as raw material suppliers, fashion design companies, manufacturers, distributors, retailers, and logistics service providers) share information, resources, and risks, and sign cooperative agreements to respond to market competition and environmental changes, thereby achieving common profit goals [11]. Common classic collaboration models include vertical collaboration [12] and horizontal collaboration [13]. Vertical collaboration refers to the close cooperation between upstream and downstream enterprises in the supply chain. Through information sharing, joint planning, and collaborative innovation, it optimizes the efficiency and responsiveness of the supply chain from top to bottom. Horizontal collaboration refers to the cooperation between enterprises at the same level within the supply chain. By sharing resources, technologies, and market information, it enhances overall efficiency and competitiveness. The digital transformation of modern information technology has given rise to more derived collaboration models, such as platform collaboration and agile supply chain collaboration [14]. These new models utilize advanced technological means to further enhance the flexibility and responsiveness of the supply chain, enabling all parties to adapt more quickly to market changes and demand fluctuations.

There is a complementary relationship between collaboration models and operational strategies, with each typical operational strategy in the fashion supply chain having its own advantages and shortcomings. For instance, lean production strategies can effectively reduce material costs and waste, improve quality and production efficiency, but they require high initial investment and are highly dependent on the collaboration model of the supply chain (such as enterprises suitable for vertical collaboration), with low-risk diversification. Agile supply chains require investment in information systems, technology, and infrastructure to achieve rapid response and flexible adjustment. However, high costs may increase the financial burden on enterprises, especially SMEs. Additionally, agile supply chains face more variables and uncertainties, including frequent adjustments in material supply, logistics, and production planning. Vertical integration strategies improve control and efficiency by managing multiple supply chain links, but they also require substantial investment and complex management. Despite the advantages and disadvantages of these strategies, selecting an appropriate collaboration model can optimize the overall performance of the supply chain [15].

- Zara [16,17]: Through vertical collaboration and lean production strategies, Zara has successfully built a highly flexible and efficient supply chain system. The vertical collaboration model allows Zara to integrate various supply chain segments tightly and respond to market demands quickly. Lean production strategies, by reducing waste, ensuring quick turnover, and implementing flexible production plans, enable small batch production and efficient operations with strong market adaptability. The combination of these strategies has allowed Zara to maintain a leading position in the highly competitive fashion market.

- H&M [18]: By employing a multi-supplier strategy, an efficient logistics network, demand-driven production models, and sustainable development strategies, H&M has established an efficient, flexible, and sustainable supply chain system. The fast fashion strategy enables H&M to quickly transform the latest fashion trends into products and rapidly bring them to market. These collaboration models and operational strategies help H&M maintain a competitive edge in a fast-changing market environment, continuously meet consumer demands, and fulfill social responsibilities, thereby promoting the long-term healthy development of the company.
- Shein [19]: Adopting an ultra-fast fashion strategy, Shein has achieved rapid design, production, and delivery through an extremely flexible supply chain and data-driven decision-making model. Shein can turn designs from concept to finished products in just a few days, swiftly responding to market trends and consumer demands. This strategy relies on efficient production processes and a global logistics network to ensure optimized inventory management and quick delivery. By utilizing big data and artificial intelligence technologies, Shein accurately predicts consumer preferences, enhances supply chain efficiency, and boosts customer satisfaction, thus quickly rising in the highly competitive fast fashion market.

These case studies usually involve large brand companies with scales in the tens of billions. However, for SMEs in the fashion industry, it is difficult to adopt similar collaboration models and operational strategies due to a lack of substantial production capital [20]. Ho et al. [21] pointed out that collaboration remains the most challenging part of the modern fashion supply chain, with many supply chain collaboration initiatives ultimately ending in failure. The instability and unpredictability of market demand expose fashion product supply chain systems to high risks. Poor supply chain operational strategies have even led to dramatic fluctuations in the price of raw cotton, causing catastrophic consequences and the collapse of many companies.

Jia et al. [22] pointed out that innovation in business models often needs to be combined with new supply chain management collaboration models. Aligning the supply chain decisions of independent entities with their respective independent goals is a major challenge in supply chain management [23]. This challenge becomes even more severe in the presence of information asymmetry. Information asymmetry prevents parties from fully understanding the dynamics of the entire supply chain, hindering optimal decision-making, and further increasing the complexity of management [24]. Currently, there is a lack of a flexible and effective supply chain collaboration model that can help SMEs efficiently acquire information to mitigate risks while also reducing costs.

2.2. Evaluation management

Evaluation is a crucial step in measuring and providing feedback on the quality of goods and services [25]. Evaluation management involves a comprehensive assessment and analysis of performance. For instance, in food safety production, automated detection systems monitor chemical safety health indicators to ensure products meet safety standards. After the sale of goods, e-commerce platforms like Alibaba and Amazon request evaluation information from buyers, including seller service, communication, and product quality. These evaluations, through detection, monitoring, and user feedback, help optimize and enhance service content based on preset indicators.

In fashion supply chain management, evaluation management is widely used for sustainability management and supplier performance evaluation in vertically integrated supply chains. Typically, these systems are controlled and recorded by a central server, ensuring centralized data management and analysis [26]. Through such systems, companies can promptly obtain feedback on supplier performance, product quality, and service levels, and make improvements accordingly [27]. For example, fashion brand companies can use evaluation management systems to assess the delivery punctuality and quality stability of fabric suppliers, thereby deciding whether to continue the collaboration or seek new suppliers. However, for decentralized SMEs in the fashion industry, using such centralized evaluation methods is challenging. This predicament not only affects the transparency of the supply chain but also increases the level of risk faced by SMEs [28]. SMEs often lack the resources and technology to establish and maintain complex evaluation management systems, thus necessitating a flexible, low-cost, and easy-to-implement decentralized evaluation management model to enhance supply chain transparency and reliability and reduce operational risk.

2.3. Blockchain

Blockchain technology was first proposed by Satoshi in 2008 and was applied in Bitcoin transactions. Through distributed ledger and consensus mechanisms, this technology achieves decentralized peer-to-peer transactions, addressing trust and transparency issues in traditional financial systems. With the development of blockchain technology, Ethereum introduced smart contracts, expanding blockchain applications to decentralized applications (DApps). In recent years, there have been significant advancements in blockchain research and applications. Cross-chain technology [29] has achieved interoperability between different blockchain networks, and the inclusion of zero-knowledge proofs [30,31] has enhanced transaction privacy. In the healthcare sector, blockchain technology is used to manage electronic health records (EHR) [32,33], improving data transparency and security. In food safety, large retailers like Walmart have begun using blockchain technology to track the origin and distribution of food [34], allowing consumers to easily trace the production and transportation processes of food, thus ensuring its safety and quality and increasing consumer confidence. Similarly, in the realm of business collaboration, blockchain technology has led to unprecedented breakthroughs [35,36].

In the fashion industry, blockchain technology is applied primarily to enhance transparency, traceability, operational efficiency, and sustainability [37]. Traditional fashion supply chain management often faces issues of information asymmetry and a lack of trust. Blockchain technology, through distributed ledgers and immutable records, provides an effective solution. For example, the LVMH group developed the Aura blockchain platform to verify the authenticity of luxury goods [38]. H&M collaborated with TextileGenesis to ensure that its sustainable fabrics comply with sustainability standards throughout the product lifecycle [39].

Currently, blockchain technology faces the well-known ‘impossible triangle’, which means that decentralization, security, and scalability cannot be optimized simultaneously [40]. The blockchain community has categorized blockchains into three different types to meet varying market demands for security, privacy, efficiency, and control levels.

- Public blockchains [41]: Public blockchains emphasize decentralization and security but face challenges in scalability. For example, Bitcoin provides high security and complete decentralization, but its consensus mechanism (such as Proof of Work) results in slow transaction processing speeds, making large-scale expansion extremely difficult.
- Consortium blockchains [42]: Consortium blockchains attempt to balance decentralization and security while also improving scalability to some extent. Managed by multiple organizations, consortium blockchains maintain data security and transparency while effectively handling transactions. Although they are not as decentralized as public blockchains, their comprehensive performance makes them an ideal choice for multi-party collaborative applications.
- Private blockchains [43]: Private blockchains focus on security and scalability at the expense of decentralization. Controlled by a single

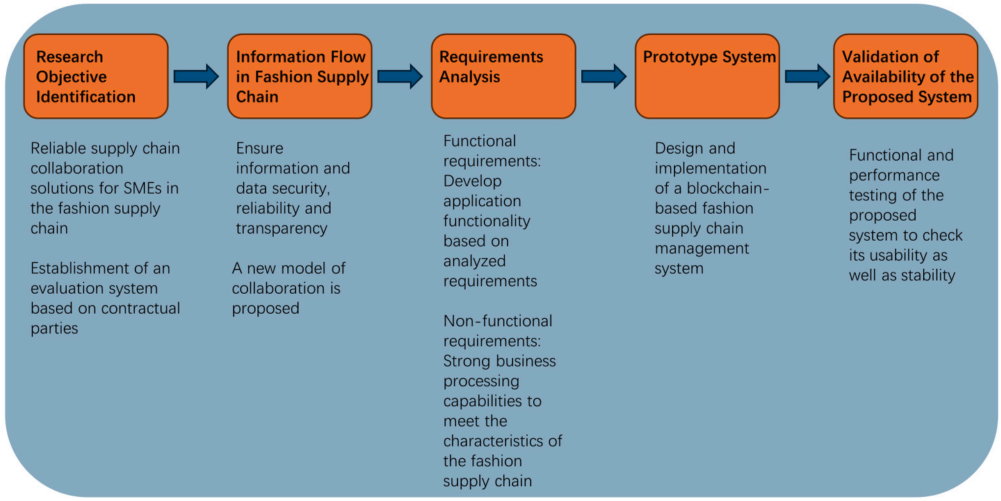

Fig. 1. Research methodology overview.

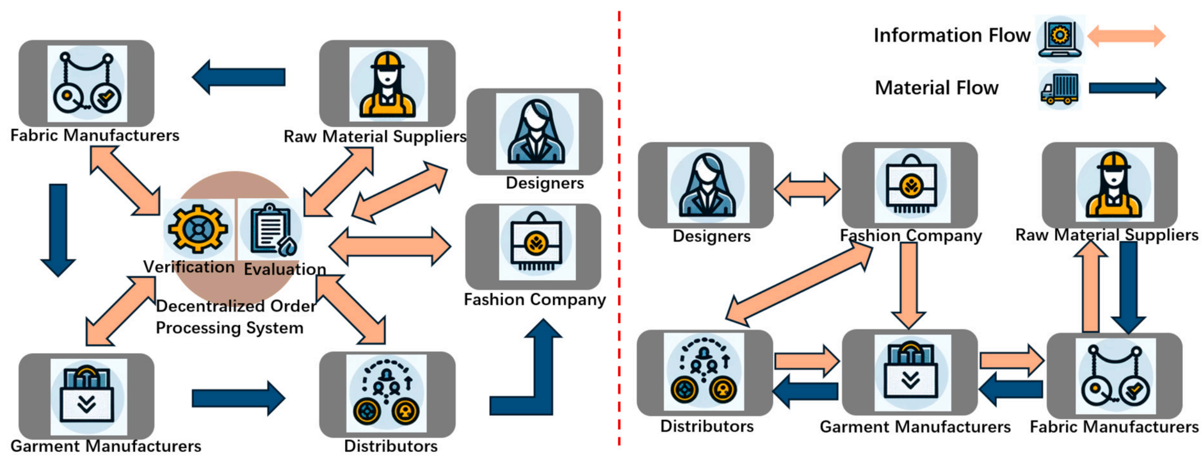

Fig. 2. Information and material flows in the fashion supply chain.

organization, private blockchains can efficiently process large volumes of transactions, ensuring data privacy and security. However, due to the lack of decentralization, they are weak in data transparency and resistance to censorship.

3. Methodology

3.1. Research methodology

Fig. 1 illustrates the research methodology of this study. As discussed in the previous section, we first conducted a comprehensive review of related research, finding that most case studies on collaboration models focus on large fashion brands. SMEs in the fashion supply chain struggle to derive direct improvement suggestions from these studies. These SMEs face unique challenges that large enterprises do not, such as information asymmetry, lack of transparency, and delayed market information. Additionally, due to their smaller scale and limited funds, they find it difficult to adopt the same collaboration strategies as large fashion enterprises. In blockchain-based applications within the fashion supply chain, related studies on improving operational efficiency mainly focus on platform digital transformation and product life-cycle tracking. Therefore, the goal of this study is to address the actual needs of SMEs in the fashion supply chain by utilizing blockchain technology to establish a contract-based evaluation management system, thereby providing them with a reliable supply chain collaboration solution.

After establishing the research objectives, we started our investigation with the information flow in the fashion supply chain. Information flow is the core of supply chain management, encompassing the transmission and processing of all information from raw materials to the final product. By studying information flow, we can better understand how the various stages of the supply chain collaborate, thereby identifying potential bottlenecks and improving efficiency.

3.2. Information flow and collaboration

The collaboration model of the fashion supply chain determines the operation of its information and material flows. Fig. 2 on the right side illustrates the classic collaboration model in the fashion supply chain, where the brand company is the core, centrally leading its collaborating supply chain partners. In this classic collaboration model, bidirectional information flow occurs only between the brand company and the independent design companies and sales departments, whereas for distributors, raw material suppliers, fabric manufacturers, and garment manufacturers, the information is transmitted in a unidirectional chain. After multiple layers of information transmission, the material flow begins to feedback layer by layer. The disadvantages of this model include slow information transmission, which easily leads to the bullwhip effect, contrary to the rapidly changing trends in modern fashion, indirectly causing inventory backlogs and financial breaks.

Fig. 2 on the left side shows the proposed modified collaboration model and information flow process of this study. In the envisioned collaboration model, all information flows are bidirectional and stored in a decentralized manner, and material flows can be changed or interrupted at any time. Thus, all companies can view supply chain information and dynamics in real-time and flexibly arrange their production capacity and expectations based on this information. After each collaboration, both parties to the contract can submit evaluations based on the quality of service provided by the other party. Moreover, other companies in this collaboration model can consider potential partners based on the evaluations of public contracts, paving the way for subsequent communication and production.

Compared to the classic collaboration model, the advantages can be summarized as follows:

Decentralization: Maintained by numerous SMEs, eliminating dependence on a single-brand company. It promotes fairer and more transparent collaboration.

Operational Efficiency: Rapid information updates significantly improve operational efficiency between companies. All supply chain participants can access and share information in real-time, reducing the risks associated with information delays and inaccuracies.

Openness: New companies can join the system at any time after registration and certification, enhancing the flexibility and adaptability of the supply chain. Both emerging companies and small enterprises can equally participate in the supply chain. Additionally, as the number of participating companies increases, it broadens potential collaboration opportunities beneficially.

Evaluation System: As a primary feedback mechanism, it helps monitor and improve service quality while providing foundational data for future potential collaborations. The evaluation data recorded on the blockchain ensure fairness and immutability, enhancing trust among all parties.

4. Prototype system design and implementation

4.1. Functional requirements

4.1.1. Roles in the fashion supply chain

The fashion supply chain involves multiple stages from design, production, and distribution, to retail. It is necessary to develop corresponding application scenarios and service functions based on these roles' characteristics and functions.

- Fashion brand companies: Fashion brand companies collaborate with designers to develop new products, conduct market research to formulate and execute marketing strategies, select and manage suppliers, ensure product quality, and maintain a stable supply chain. They manage sales through multiple channels and provide high-quality customer service, handling customer feedback and complaints to enhance customer satisfaction and loyalty.
- Fashion designers: Fashion designers transform fashion trends and market demands into specific design plans, creating attractive and commercially valuable fashion products. They study market trends and consumer preferences, create design drawings and technical specifications, and select appropriate fabrics, colors, and accessories. Designers work with brand companies and sample-making teams to ensure the feasibility and final effect of the designs.
- Raw material suppliers: Raw material suppliers provide various raw materials needed for fashion production, such as cotton, wool, yarn, and dyes. They are responsible for procuring high-quality raw materials, managing inventory to ensure timely supply, and avoiding production interruptions. Suppliers conduct quality inspections to ensure that materials meet technical specifications and quality standards and deliver raw materials on time.
- Fabric manufacturers: Fabric manufacturers process raw materials into fabrics, via processes such as spinning, weaving, dyeing, and finishing. They develop production plans, implement process controls, and conduct rigorous quality inspections to ensure the quality and consistency of fabrics. Fabric manufacturers also manage inventory to maintain a stable supply chain without overstocking.
- Garment manufacturers: Garment manufacturers turn design drafts into final products, including cutting, sewing, processing, and assembly. They develop production plans based on order requirements, execute cutting and sewing processes, implement comprehensive quality management systems, and conduct quality inspections to ensure timely delivery and meet customer delivery requirements.
- Distributors: Distributors transfer garments from manufacturers to retailers or directly to consumers, helping fashion brand companies manage product storage, transportation, and distribution. Based on market demand and competition, they provide reasonable pricing suggestions to fashion brand companies to ensure product competitiveness. By analyzing sales data and market demand, they optimize inventory levels, avoid overstocking or shortages, and improve supply chain efficiency.

4.1.2. Scenarios and service functions

1. Company Information Company information not only helps build trust among enterprises at various stages but also enhances the transparency and efficiency of the supply chain. By sharing company information, each role within the supply chain can better understand the qualifications, capacity, and operational status of its partners, enabling more informed decisions, optimized partnerships, and reduced risks associated with information asymmetry.

New enterprise registration: New enterprises joining the supply chain platform need to register and provide detailed company information, including company name, address, contact details, and qualification certificates. This ensures the legality and qualifications of the new member companies.

Enterprise qualification query: Enterprises within the supply chain can query the qualification information of their partners at any time, such as business licenses, certification certificates, and credit ratings. This helps in selecting suitable partners and reducing collaboration risk.

Real-time dynamic query: Enterprises can query real-time dynamic information about their partners, including capacity schedules, production progress, and inventory status. This enhances the transparency and response speed of the supply chain, ensuring smooth production planning and collaboration.

2. Product Information Product information helps enterprises at various stages better coordinate and cooperate, improving production efficiency and reducing errors and waste. By sharing product information, each role within the supply chain can understand product specifications, quality standards, production progress, and inventory status, optimizing production planning and supply chain operations, and increasing customer satisfaction.

Product information entry: At different stages of product development and production, enterprises need to enter detailed product information, including product specifications, materials, production processes, and quality standards.

Product information query: Enterprises within the supply chain can query detailed product information at any time, including production progress, inventory status, and quality inspection reports.

Product traceability: By recording and tracking the flow of products within the supply chain, enterprises can achieve product traceability and understand the specifics of each stage. This enhances product transparency and traceability, ensures product quality, and boosts consumer trust.

3. Evaluation Information Evaluating the performance of each supply chain stage and partner improves supply chain transparency and cooperation efficiency, helping enterprises optimize decisions and improve service quality. Sharing evaluation information allows each role within the supply chain to understand the reliability and performance of their partners, select suitable partners, reduce risks, and enhance the overall competitiveness of the supply chain.

Evaluation information entry: After each collaboration or order completion, roles within the supply chain need to enter evaluation information about their partners, including scores and comments on quality, delivery, and response speed. This records collaboration experiences and provides reference data to help enterprises make more informed decisions.

Evaluation information query: Enterprises can query the historical evaluation information of their partners at any time to understand their performance and reliability. This helps in selecting suitable partners and optimizing supply chain collaboration.

Evaluation analysis and reporting: By analyzing evaluation information, detailed performance reports can be generated, which can help enterprises identify strengths and weaknesses within the supply chain. This improves service quality and enhances overall supply chain efficiency.

4.2. Non-functional requirements

In the fashion supply chain management platform, non-functional requirements ensure that the system not only performs its intended functions but also operates efficiently, reliably, and securely in real-world environments. These requirements cover several key aspects, including performance, reliability, security, maintainability, and deployability. Performance and reliability need to be validated through testing, whereas security and ease of maintenance and deployment must be addressed during the system design phase.

1. Performance Requirements

High concurrency handling: The platform should handle at least 200 concurrent transaction requests per second during peak usage periods, ensuring that all participants' transactions and queries are processed promptly. This is especially important during seasonal fashion changes when garment manufacturers and distributors need to simultaneously access the platform for a large number of order signings and deliveries.

Large-scale transaction processing: The platform should process at least a million supply chain information transactions daily, ensuring that every piece of information from design to delivery to feedback is accurately recorded and tracked. Sufficient processing capacity should be reserved to support future system integration, feature expansion, and an increase in users.

Fast response time: When submitting queries or transaction requests, the system should respond within seconds, ensuring that related enterprises can quickly obtain the necessary information, adjust production and sales strategies promptly, and guarantee a user-friendly experience.

2. Reliability Requirements

High availability: The fashion supply chain management platform should achieve 99.9% availability, ensuring that it is inaccessible for only a minimal time throughout the year. This is crucial for maintaining the continuity of order processing, production scheduling, and delivery management, thereby reducing the risk of breaches due to system failures.

Stability: The platform should remain stable over long-term operations, with no memory leaks or program crashes, preventing widespread outages that could cripple the entire fashion supply chain.

3. Security Requirements

Decentralized data storage: Using blockchain's distributed ledger technology, data should be stored across multiple nodes to prevent single points of failure and data tampering, enhancing data credibility and transparency.

Smart contracts: Smart contracts should be used to automatically execute transactions and contract terms, ensuring the transparency and automation of contract execution, reducing human intervention and errors.

Access control: The system should have strict permission management and access control, ensuring that only authorized users can access and manipulate sensitive data, preventing unauthorized design changes and order modifications.

Emergency recovery capability: The platform should have robust disaster recovery capabilities to quickly restore data in the case of system failure or data loss, ensuring business continuity.

4. Maintainability and Deployability Requirements

Compatibility: The platform should be compatible with low-end hardware facilities, capable of running efficiently in different hardware environments, and meeting the needs of enterprises of various sizes within the supply chain, thereby helping reduce hardware costs and maintenance expenses.

Modular design: The system should adopt a modular design, making maintenance and upgrades easier. Each module should be independently deployable, reducing the complexity of system updates and maintenance.

4.3. System architecture

Fig. 3 shows the platform architecture of the blockchain-based fashion supply chain platform. Based on the key points raised in the previous section's non-functional requirements, we adopted Hyperledger Fabric as the underlying blockchain framework and ChainSQL as the auxiliary storage database, each with its own complete blockchain. Additionally, to ensure good compatibility and ease of deployment, we used Docker images and orchestrated the startup of all the components and related services with Docker Compose.

1. Hyperledger Fabric

Hyperledger Fabric, as a consortium blockchain, not only possesses common blockchain capabilities but also features modular architecture, identity management, smart contracts, and extensive API support. These characteristics make Hyperledger Fabric an ideal blockchain framework to meet the complex needs of enterprise applications, providing efficient, secure, and customized blockchain solutions.

Modular Architecture: Allows users to select and customize different pluggable components according to their needs.

Identity management: Based on public key infrastructure (PKI), the identity management system uses certificate authorities (CAs) to authenticate each node in the network, ensuring that only certified enterprises can join the network and conduct transactions.

Chaincode: Chaincode executes automatically on the Hyperledger network, ensuring the reliability and automation of transactions.

API and SDK: Provides extensive API and SDK support, allowing developers to interact with Hyperledger, deploy smart contracts, query data, and manage the network.

High performance: Supports processing hundreds or even thousands of transactions per second, making it suitable for enterprise application scenarios that require high throughput.

2. ChainSQL

ChainSQL is an open-source distributed database with efficient text and image processing capabilities. It adopts the same identity management mechanism as Hyperledger, ensuring ease of development alongside Hyperledger. Additionally, the following features are useful for the proposed platform.

Data reliability: When data are written to a single node, the network's data reliability reaches 100%, and any illegal data tampering on a single node will not be synchronized to other nodes.

Custom table operations: Allows custom table operations; after synchronization, data consistency across nodes reaches 100%, and in the case of simultaneous reading and writing by multiple nodes, the data consistency is not less than 99%.

General blockchain language support: Supports general blockchain programming languages like Solidity, allowing direct operations on data tables through provided APIs.

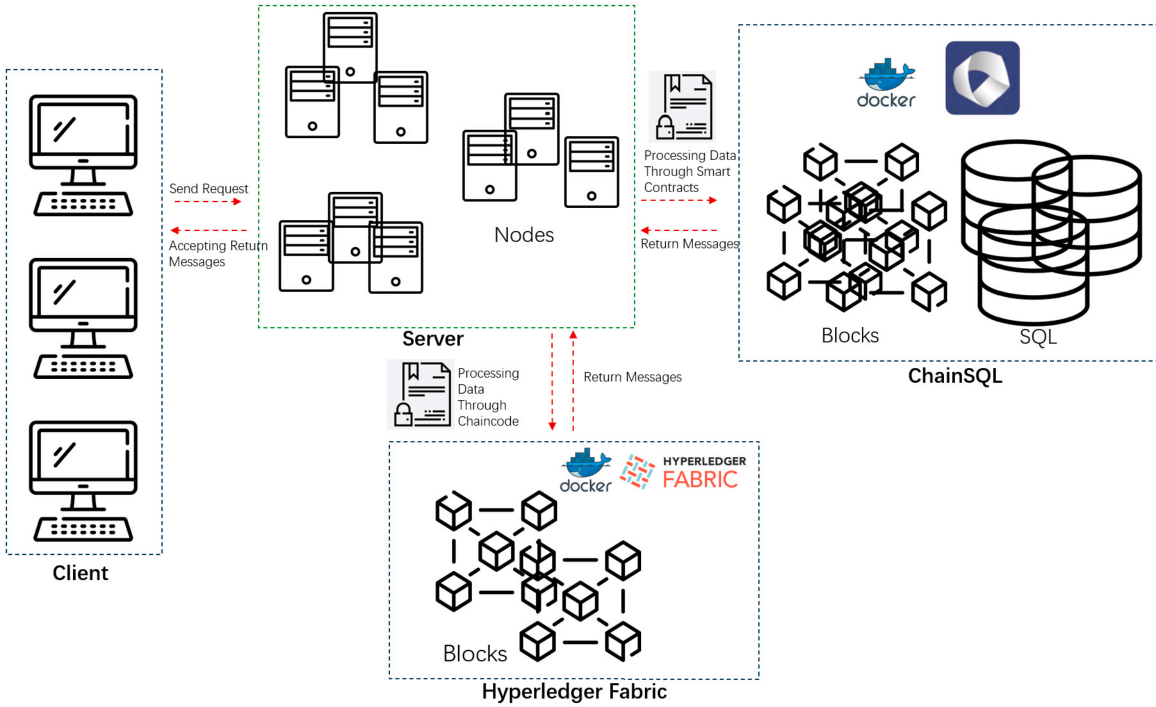

Fig. 3. System architecture.

Log-level data recovery: Current data operations are separated from logs; when data is damaged or lost, data can be recovered using logs, ensuring high data recovery capability and minimizing interruptions.

3. Containerization Technology

Containerization technology, as a lightweight and efficient virtualization method, packages applications and their dependencies together into an independent unit called a 'container'. The core advantage of this technology is that it provides a consistent runtime environment, ensuring that applications exhibit the same behavior regardless of where they are deployed. Each container runs in an isolated environment, separated from other parts of the system, which reduces conflicts between applications and enhances overall system security.

4. Doker and Doker Compose

Docker is a widely used open-source containerization platform that allows applications to run in containers, which is critical for deploying blockchain supply chain management systems. This approach not only simplifies the deployment process but also improves the portability and reliability of the system. When building a blockchain supply chain management system, Docker Compose, a powerful tool, can effectively define and run multi-container Docker applications. It conveniently manages and coordinates the operation of various service containers, such as databases and application servers, as well as other critical components, significantly reducing the maintenance workload. By using Docker and Docker Compose, the proposed platform is not only easy to deploy and maintain but also easier to promote in different environments, providing a solid foundation for implementing a blockchain supply chain management system.

Fig. 4 illustrates the design of the database tables. We categorize and process the information data according to the functional service requirements specified in Section 4.1. For example, when storing product information, images are first passed to ChainSQL through smart contracts. ChainSQL calculates a hash value using a hash function, along with a product code and the information of the block in which it resides, and returns this value to Hyperledger. These data are then passed to Hyperledger via chaincode. ChainSQL retrieves the accepted data from Hyperledger using Hyperledger's REST API and stores them in the database through smart contracts. Whenever information is called, it is retrieved directly from ChainSQL, and the performance overhead of ChainSQL is negligible compared to Hyperledger. Additionally, the features of ChainSQL are far more extensive than the built-in CouchDB functionality of Hyperledger. Although this increases the complexity of design and programming, it brings higher flexibility and functionality, allowing the system to better meet diverse security needs.

5. Results and discussion

5.1. Platform function overview

5.1.1. Order services

As shown in Fig. 5, the order service displays the order contract information, which consists of an 8-digit order ID and the contract name. The contract ID is a unique identifier used to query order contract information. The order service also provides the registration IDs and company names of both parties signing the contract on the platform. Different roles in the supply chain have distinct registration codes and numbers, such as 'GarmentM' for garment manufacturers and 'Retail' for distributors, with a unique 5-digit identification number assigned to each. Product information comprises product images and product numbers. Products can be any item within the fashion supply chain, such as design drawings, cotton, silk, etc. After product images are uploaded to ChainSQL, ChainSQL returns a hash value, which is assigned a unique code known as the product code. The service terms information includes various requirements for the contract subject, such as material requirements, process requirements, quality standards, total product price, latest delivery time, and breach compensation. Finally, blockchain-related information, including hash values, timestamps, and block numbers, ensures security.

5.1.2. Evaluation services

Fig. 6 shows the platform's evaluation services for both contract parties. Besides the relevant order contract information, it also includes logistics information records, evaluation content, and blockchain information. The logistics information records provide the original agreed-upon date and the actual recorded delivery date. The evaluation content

Field	Data Type	Description
Contract_ID	INT	Primary Key, Unique identifier for each contract
Contract_Name	VARCHAR(255)	Name of the contract
Party_A_ID	INT	Unique identifier for Party A
Party_A_Company_Name	VARCHAR(255)	Company name of Party A
Party_B_ID	INT	Unique identifier for Party B
Party_B_Company_Name	VARCHAR(255)	Company name of Party B
Product_ID	INT	Unique identifier for the product
Product_Details	VARCHAR(255)	Detailed description of the product
Service_Detailed_Description	VARCHAR(255)	Detailed description of the service
Price	DECIMAL(10,2)	Price of the contract
Delivery_Deadline	VARCHAR(255)	Deadline for the delivery
Payment_Conditions	VARCHAR(255)	Conditions for payment
Liabilities_for_Breach	VARCHAR(255)	Liabilities in case of breach
Creation_Time	TIMESTAMP	Time when the contract was created
Signing_Time	TIMESTAMP	Time when the contract was signed
Operator	VARCHAR(255)	Name or ID of the operator handling the contract
Status	ENUM('Signed', 'Completed', 'Breach')	Current status of the contract

Field	Data Type	Description
Hash_Value	VARCHAR(255)	Hash value of the data for blockchain integrity
Timestamp	TIMESTAMP	Timestamp of the record in the blockchain
Block_Number	INT	Block number in the blockchain where the record is stored

Field	Data Type	Description
Company_Name	VARCHAR(255)	Name of the company
Location	VARCHAR(255)	Location of the company
Contact_Info	VARCHAR(255)	Contact information of the company
Business_Scope	VARCHAR(255)	Scope of business operations
Current_Capacity	VARCHAR(255)	Current production capacity
Order_Delivery_Date	VARCHAR(255)	Delivery date of ongoing orders
Order_Quantity	INT	Quantity of ongoing orders
Preorder_Date	VARCHAR(255)	Date of preorders
Preorder_Quantity	INT	Quantity of preorders
Company_Reviews	VARCHAR(255)	Reviews received by the company
Last_Update_Time	VARCHAR(255)	Last update time

Field	Data Type	Description
Contract_ID	INT	Unique identifier for each contract
Product_Quality	DECIMAL(2,1)	Rating for product quality (1.0-5.0)
Contract_Compliance	DECIMAL(2,1)	Rating for contract compliance (1.0-5.0)
Response_Time	DECIMAL(2,1)	Rating for response time (1.0-5.0)
Problem_Solving_Efficiency	DECIMAL(2,1)	Rating for problem-solving efficiency (1.0-5.0)
Cooperation_Attitude	DECIMAL(2,1)	Rating for cooperation attitude (1.0-5.0)
After_Sales_Service_Quality	DECIMAL(2,1)	Rating for after-sales service quality (1.0-5.0)
Technical_Support	DECIMAL(2,1)	Rating for technical support (1.0-5.0)
Satisfaction_Survey	DECIMAL(2,1)	Overall service satisfaction rating (1.0-5.0)
Repeat_Cooperation_Willingness	DECIMAL(2,1)	Willingness for repeat cooperation (1.0-5.0)
Comments	VARCHAR(255)	Text comments
Comment_Time	VARCHAR(255)	Time when the comment was made

Fig. 4. Database tables designed for supply chain services.

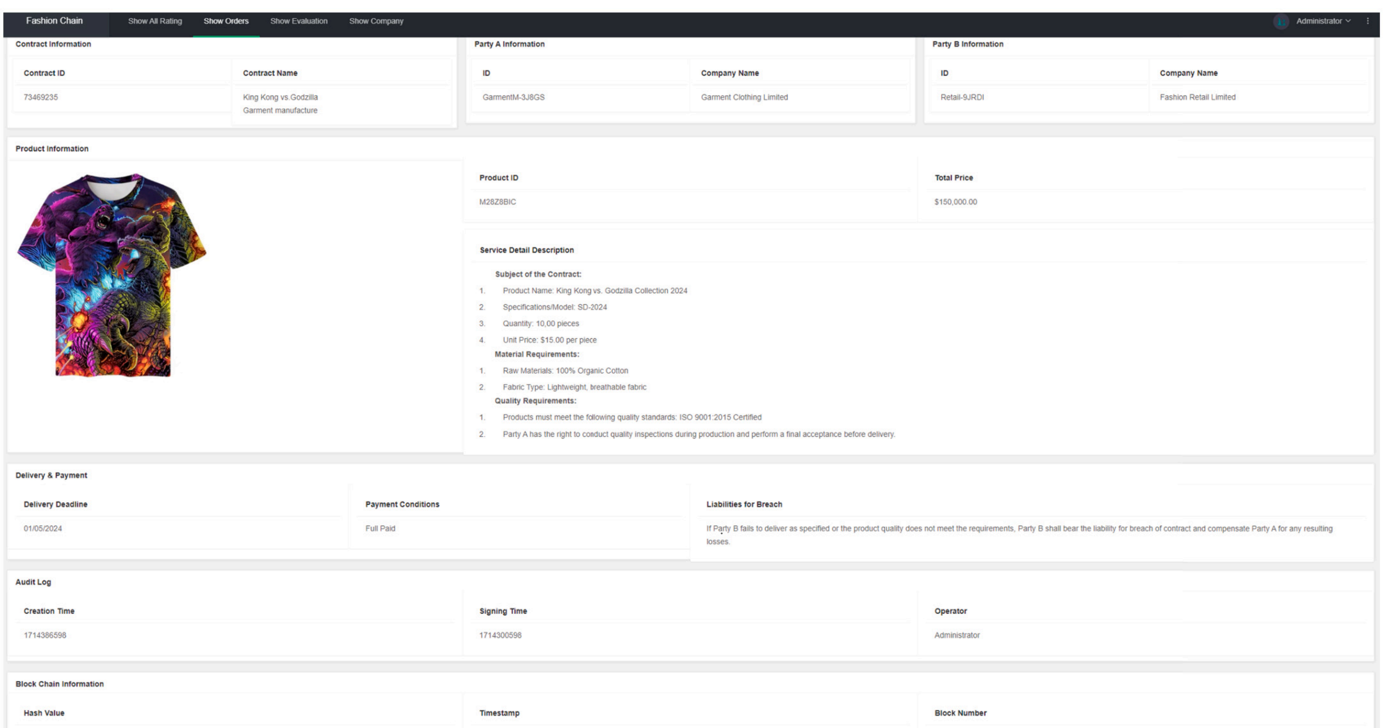

Fig. 5. Interface: Contract service.

is divided into standardized evaluation and textual content. Textual content can be scored based on personalized and actual situations, providing guidance for future partners seeking cooperation. Since standardized evaluations may not be comprehensive, textual guidance is also included.

We also offer a service to query all evaluations of a single enterprise. As shown in Fig. 7, this interface displays all the evaluation content from companies cooperating with Enterprise A, providing an intuitive score histogram. Sorted by order completion time, it visually reflects the changes in cooperation evaluations, aiding in bidirectional

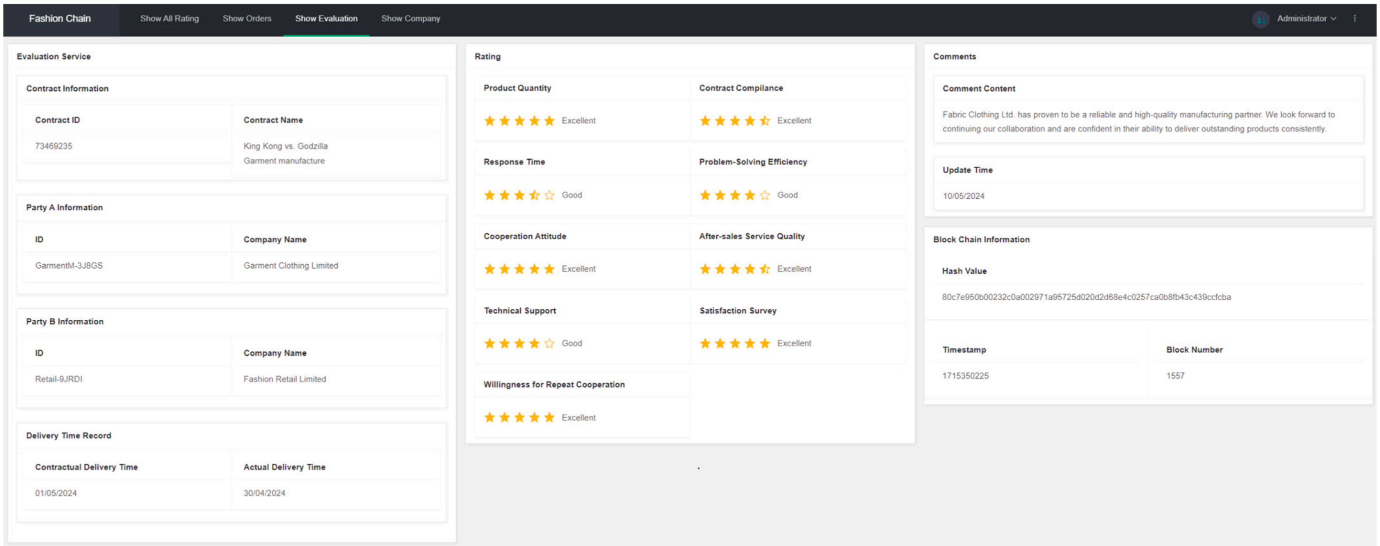

Fig. 6. Interface: Evaluation service.

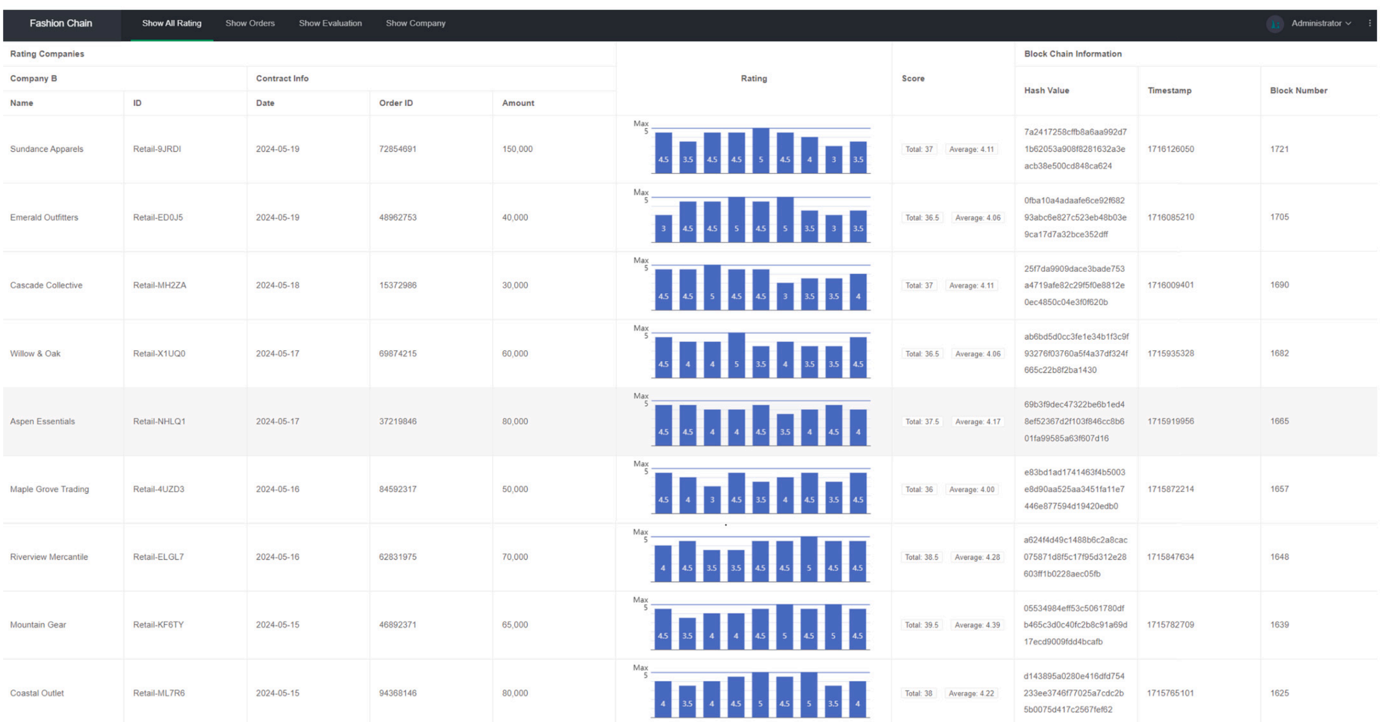

Fig. 7. Interface: Evaluation overview.

feedback for potential cooperative enterprises and the enterprises themselves.

5.1.3. *Enterprise information services*

As shown in Fig. 8, the enterprise information overview is updated in real-time, including geographic location, contact information, business scope, capacity, etc. It displays information on successfully completed and ongoing orders. The advantage of this service is that it updates the blockchain with the latest data whenever there is a change in any on-chain information, marking the update time. Lastly, we provide an evaluation information radar based on the evaluation information. This radar collects all historical evaluation records on the blockchain, deriving a weighted average value. This value is compared with the current company data, providing a more intuitive data comparison for the inquirer.

5.2. *Tests*

5.2.1. *Test software*

Existing testing tools are typically designed to test the performance of Hyperledger alone. However, due to the special design of our system architecture, these tools are not suitable for our platform. Therefore, we developed a hardware information monitor, as shown in Fig. 9. This monitor is composed of Prometheus, NodeExporter, and Grafana, and is used to monitor and visualize hardware activity performance. Additionally, we use JMeter to measure and evaluate the platform's performance, ensuring its reliability and efficiency under various load conditions. Ta-

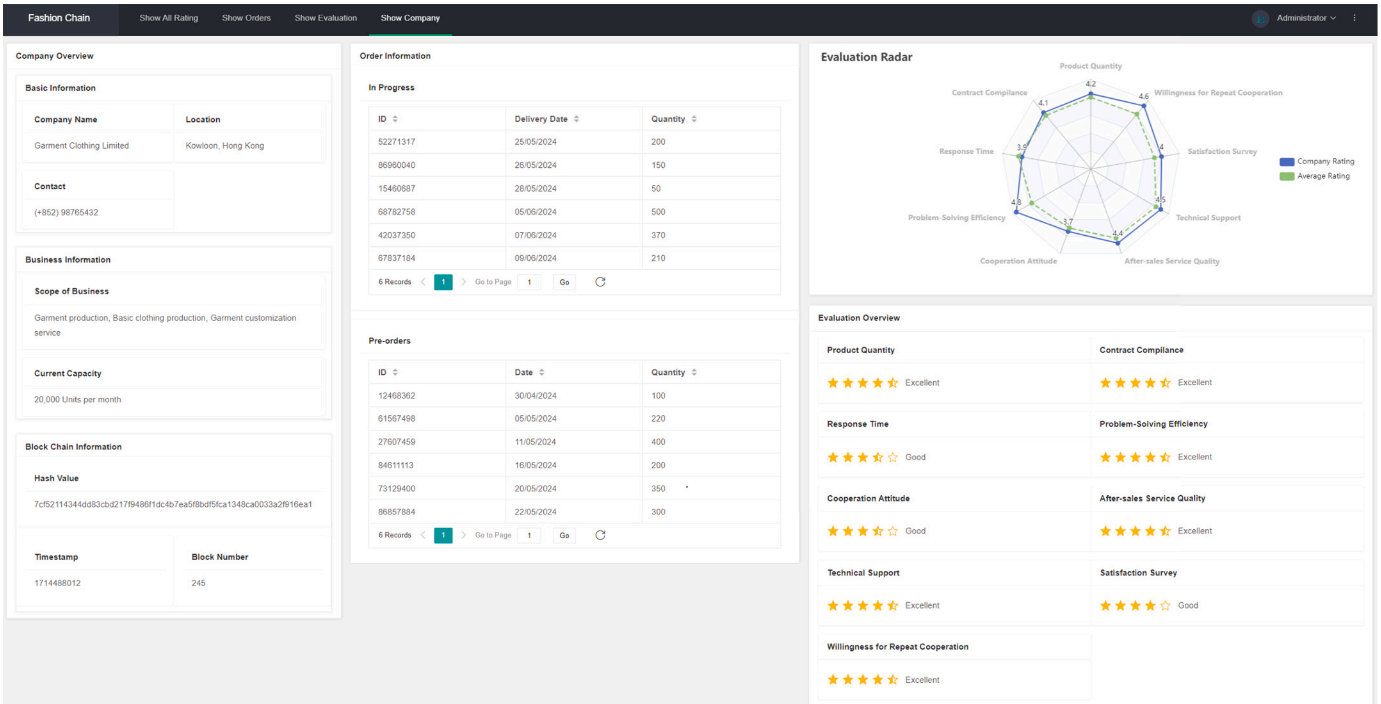

Fig. 8. Interface: Enterprise information.

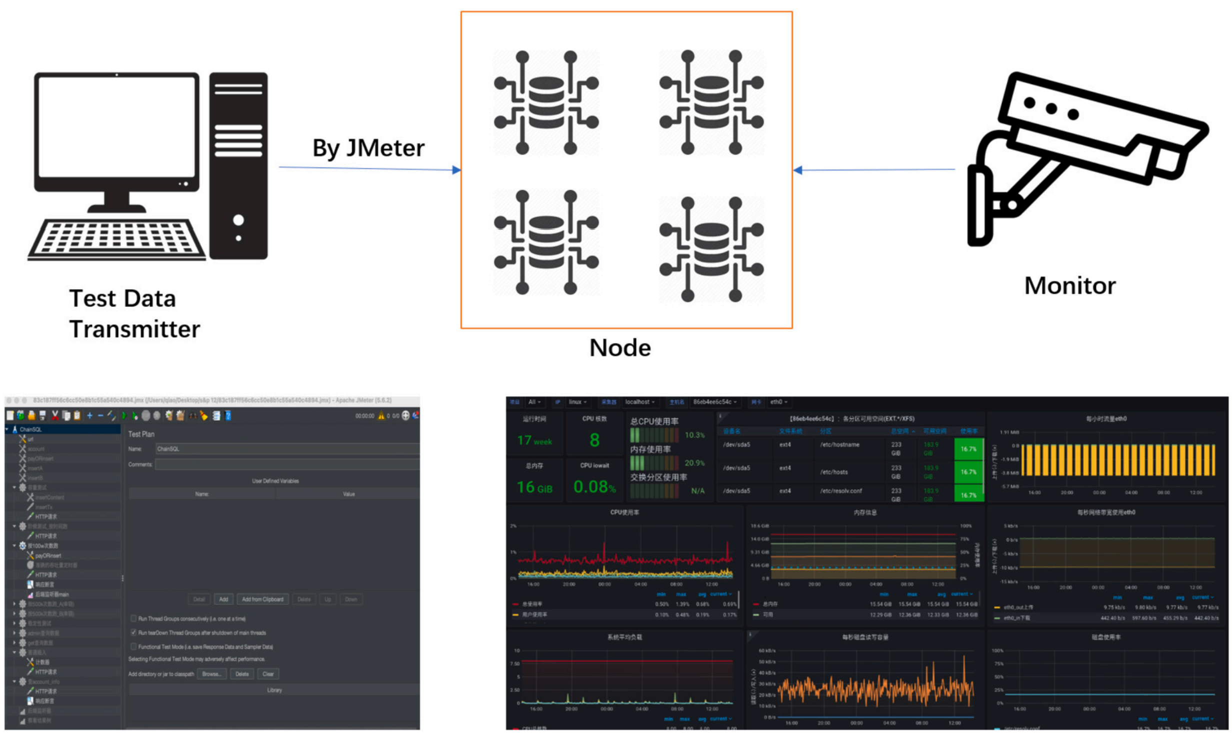

Fig. 9. Interface: Enterprise information.

ble 1 summarizes the different testing and monitoring tools used in the project.

- Prometheus is a widely popular open-source monitoring and alerting toolkit specifically designed for real-time recording of service status and performance metrics. By periodically pulling data from predefined targets (such as HTTP endpoints), Prometheus efficiently collects information.
- NodeExporter focuses on collecting hardware and Linux operating system metrics from the host (e.g., servers). It provides various important metrics, including CPU, memory, disk usage, and network conditions, as well as system load information. As an HTTP service, NodeExporter can send these collected data to Prometheus, facilitating data collection and in-depth analysis.
- Grafana is an open-source data visualization and analysis platform that is widely used for displaying monitoring metrics. It seam-

Table 1
Testing and monitoring tools.

Software tool	Version	Environment dependencies	Detailed description
JMeter	5.6.2	Java 11	An open-source load and performance testing tool primarily for Web applications.
Prometheus	2.28.1	Linux, Go language Environment	An open-source system monitoring and alerting toolkit used for reliable data logging and real-time alerts.
NodeExporter	1.2.2	Linux	A tool for monitoring Linux and UNIX systems, integrated with Prometheus.
Grafana	8.0.6	Linux, 2 GB RAM, 1 GB Disk Space	An open-source platform for analytics and monitoring, used for visualizing time-series data.
Chrome	109.0.5414.72	/	This method is used to browse monitoring data.

Table 2
System performance indicators.

Performance indicator	Explanation	Ideal level in stress testing
CPU utilization	Ratio of time CPU spends on tasks to total time.	Below 70-80% to leave room for sudden load spikes.
Memory utilization	Ratio of used memory to total memory.	Below 70% to prevent system overload.
System average load	The average load on the system, reflecting tasks waiting to be processed by the CPU.	Close to the number of CPU cores; reaching 100% may indicate overload.
Disk read/write rate (IOPS)	Rate at which data are read from or written to the disk, usually measured in MB/s or GB/s.	According to the SSD performance, the lab device's (Under PCIE 3.0) random 4K write speed is approximately 87 MB/s as tested with the CrystalDiskInfo software.
Disk write throughput per second	The amount of data written to the disk per second indicates the write speed of the disk.	Below 85% of the threshold value can be considered as not affecting other transactions.

lessly integrates multiple data sources, provides various charts, graphs, and dashboards, and makes complex datasets easy to understand and analyze. This helps developers and system administrators quickly identify issues and optimize system performance.

5.2.2. Hardware and system performance indicators

In this experiment, we used the following hardware configuration: three i7-7700 machines as nodes and one i7-13700 machine as the orderer node. All machines are equipped with the Ubuntu 20.04 LTS operating system, 16 GB of RAM, and 256 GB solid-state drives. The key metrics of the system are listed in Table 2.

5.2.3. Test results and discussion

1. **Stress Testing**: Stress testing is a performance testing method used to evaluate the reliability of a system, component, or application under extreme workloads. This type of testing is carried out primarily to examine the behavior of a system under the most adverse conditions or under extreme workloads.
   In this experiment, 100 accounts continuously sent transaction requests from a Mac terminal using JMeter. Each account sent 1000 transaction requests. Using a scripted subscription approach, the number of transactions in the blockchain and the interval between successfully packaged blocks were checked to determine the transactions per second (TPS) and average response time. The JMeter load generator sent 100 thousand transaction requests to the test node's insert interface, and all the transactions were successfully incorporated into blocks, resulting in a 100% success rate for transactions and a consensus rate of 722.34/s. When the node started receiving transactions, the CPU usage rate reached a maximum of 22.49%. As the transaction sending concluded, the CPU usage returned to normal. The memory usage rate was 20.52%, and after the experiment, memory was released to the system's idle level, indicating no memory leakage. The system's load rate was 74%, maintaining a normal level during stress testing, and the disk usage rate was 32%. With a disk write rate of 120 MB/s, and using SSDs, there were no performance bottlenecks.
2. **Stability Testing**: Stability testing is a software testing method aimed at ensuring that software can operate stably under continuous running or normal workloads. This type of testing focuses on the behavior of the system during long periods of operation, detecting potential issues such as memory leaks, performance degradation, failures, or other stability problems.

Table 3
Experimental data of inserting image data.

File size	Concurrent number	Success rate	Average response time
200kb	80–90	100%	1.82 s
500kb	40–50	100%	3.57 s

   JMeter is used to send transaction requests from the Mac side, simulating the scenario where 5 accounts send 6 transaction requests per second. This corresponds to processing 30 transactions per second. We will continuously monitor the system's performance under this workload to ensure that the system can operate steadily.
   The test proceeded smoothly and passed the stability assessment. After 24 hours of testing, there were no significant changes in the system's parameters, leading us to conclude that the system operates stably under these conditions.
3. **Continuous image file writing test**: The objective of this experiment is to assess the system's performance when handling images provided by roles in the fashion supply chain.
   JMeter is used to send transaction requests from the Mac side. Between 30 and 50 accounts automatically launch concurrent requests to server nodes via scripts, and each attempts to insert both 200 kb and 500 kb image files via a base64 encoded string. This approach simulates the insertion of large files in our system. The author recorded and observed the results to draw conclusions. The results in Table 3 indicate that the system exhibits favorable performance when handling concurrent insertions of large files. However, it is worth noting that the response speed is noticeably reduced during the simultaneous storage of large files. Despite this slowdown, the system maintains a reasonable level of functionality and continues to demonstrate its ability to handle substantial data loads.

5.3. Cost analysis

The system uses a virtual container orchestration deployment strategy, which excels in the current technological landscape by offering extremely low maintenance, infrastructure, and operational costs. This approach is particularly well-suited for organizations and enterprises with limited resources.

- Maintenance Costs: In terms of system maintenance, the use of virtual containers greatly simplifies environment management and deployment processes. Through the unified deployment of smart contracts, the system can automatically update all member nodes within the consortium blockchain, ensuring consistent operations across the network. This automation significantly reduces the manual effort required for updates and configurations while also avoiding compatibility issues caused by environmental differences, thereby lowering operational risks and costs. Furthermore, the lightweight and highly portable nature of virtual containers ensures stable system performance across various working environments, further reducing the resources needed for maintenance.

- Infrastructure Costs: The system is highly resource-efficient, with minimal hardware and network bandwidth requirements, as demonstrated in simulation tests. It can run smoothly even on standard personal computers, meaning enterprises do not need to invest in expensive hardware to deploy and operate the system. When using cloud servers and cloud deployment, the cost of rental services is even greater.
- Operational Costs: On the operational side, the system integrates advanced visualization monitoring tools, allowing SME administrators to monitor service status in real-time via the web interface. The intuitive interface of these visualization tools enables users to identify and resolve potential issues easily, reducing the workload of operational staff. Additionally, the system provides detailed log-level data analysis services through ChainSQL.

6. Conclusions and future work

This study reviewed the current collaboration strategies in the fashion supply chain and the status of related blockchain applications. Based on the idea of transforming the information flow in the fashion supply chain, a collaboration model suitable for SMEs was proposed. After analyzing functional requirements such as roles and application scenarios in the fashion supply chain, as well as a series of non-functional requirements such as performance and maintainability, we developed a blockchain-based contract party evaluation management system. This system demonstrated excellent stability and usability after simulated testing. In this system, we record enterprise information, product order information, and evaluation information into smart contracts and store them on the blockchain. This ensures the transparency of this information and encourages enterprises to improve continuously based on evaluations. Establishing such a fair platform is beneficial for an increasing number of SMEs to actively join and participate in a competitive supply chain environment. Additionally, this study can stimulate other scholars' interest in new forms of supply chain structures.

Future research could consider recording and analyzing historical transaction data through blockchain, introducing demand forecasting services to help enterprises more accurately predict market demand, optimize production and inventory management, and reduce surpluses and shortages. Integrating customer relationship management systems with the proposed platform could track and analyze customer behavior, feeding data back into the supply chain to enhance consumer satisfaction. Moreover, companies may be reluctant to fully disclose their supply chain details and transaction information. Further exploration is needed on how to protect commercial secrets while ensuring data transparency by adopting privacy protection technologies.

CRediT authorship contribution statement

Minhao Qiao: Data curation, Investigation, Methodology, Writing – original draft, Formal analysis. **Xuanchang Chen:** Resources, Software, Validation. **Yangping Zhou:** Investigation, Visualization. **P.Y. Mok:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing.

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Declaration of competing interest

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

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