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Research on Risk Prevention and Control and Supply Chain Collaboration Scheme of Digital RMB Based on Blockchain

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SUMMARY: *With the in-depth advancement of the pilot program of Digital RMB (e-CNY) and the increasing complexity of supply chain finance, how to effectively prevent and control financial risks and improve the efficiency of supply chain collaboration has become a key issue. This paper proposes a risk prevention and control and supply chain collaborative innovation solution for digital RMB based on blockchain technology. By constructing a two-layer architecture combining consortium chains and smart contracts, it deeply integrates the legal tender attribute of digital RMB with the technical advantages of blockchain. The core collaborative mechanisms based on blockchain, such as supply chain information evidence storage, programmable payment, and multi-level creditor's rights circulation, were designed. On this basis, smart contracts were utilized to achieve the automatic execution of transaction rules and real-time monitoring of risks. Further, a risk control model and a supply chain collaborative benefit evaluation model based on the improved Byzantine Fault Tolerance (PBFT) algorithm were constructed. And the superiority of the scheme in improving transaction throughput, reducing consensus delay and enhancing system robustness was verified through experiments. The research results show that this scheme can effectively achieve the immutability and full traceability of supply chain transaction data, precisely prevent and control credit risks and operational risks, and through the programmability of digital RMB, realize the efficient coordination of capital flow, information flow and business flow, providing a theoretical basis and practical path for building a safe, efficient and transparent modern supply chain financial ecosystem.*

KEYWORDS: *Digital RMB; Blockchain; Supply chain collaboration; Risk prevention and control; Consensus algorithm*

1 Introduction

With the development of technology, Mustafa et al. [1] have demonstrated that in recent years, blockchain, with its decentralized, secure, transparent and immutable features, has provided potential solutions for digital service failures, fraud detection and secure access to the Industrial Internet of Things (IIoT). Qin [2] pointed out that the digital transformation of the supply chain faces many risks and challenges, such as credit risk, liquidity risk and information asymmetry, etc. However, Li [3] stated that blockchain technology can effectively alleviate these problems by building a decentralized database.

Munir et al. [4] demonstrated that blockchain technology can achieve real-time and transparent sharing of information in the supply chain. Data at each link, from raw material

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procurement to final product delivery, can be tracked and verified. This end-to-end visibility helps to promptly identify and address potential risks. For instance, Vern et al. [5] in the agricultural product supply chain, the traceability framework based on blockchain can provide detailed product information and enhance consumer trust. Meanwhile, Balcioglu et al. [6] also indicate the improvement of supply chain transparency and traceability, which is one of the widely concerned themes of blockchain technology in supply chain management.

Han [7] stated that the encryption and distributed ledger features of blockchain ensure the immutability of data, thereby preventing fraud and data forgery. This is particularly important for supply chain finance (SCF), as SCF has complex business processes and diverse participants, with information asymmetry and credit risks being the main challenges. Guo [8] also stated that blockchain can provide a secure and trustworthy transaction environment for supply chain financial activities such as accounts receivable financing, reducing the risks of fraudulent loans and defaults.

Rauniyar et al. [9] pointed out that by leveraging blockchain technology, enterprises can better identify, assess and mitigate the risks of disruptions in the supply chain. For instance, Wu et al. [10] indicated that the integration of blockchain with the Internet of Things (IoT) and big data analysis can achieve real-time monitoring and intelligent risk early warning, enhancing the resilience of the supply chain. Liu et al. [11] proposed the integration of digital twin technology and blockchain, which can achieve real-time analysis and simulation in the supply chain, enhance decision-making capabilities and operational efficiency, and thereby improve the resilience of the supply chain. Kudrenko [12] pointed out that in the risk management of critical mineral supply chains, the application of blockchain technology helps enhance the resilience of the supply chain.

Zhang et al. [13] indicated that as a form of central bank digital currency, the underlying technology of the digital RMB can be combined with blockchain, bringing new opportunities to supply chain finance and collaboration. For instance, in accounts receivable financing, financial institutions and small and medium-sized enterprises (SMEs) are confronted with credit risks and information asymmetry risks. Introducing central bank digital currencies into accounts receivable financing can leverage blockchain technology to address these issues. The integration of digital currency technology, blockchain technology with regulatory authorities and financial institutions can form a secure and efficient supply chain financial service platform.

Shamsan [14] stated that the shared ledger mechanism of blockchain can ensure that all participants reach a consensus on transaction records, thereby enhancing trust among supply chain participants. This trust is the foundation for achieving effective collaboration. Research of Wu [15] indicates that enterprise blockchain capabilities (BCC) have a positive impact on inter-enterprise collaboration, supply chain resilience, and innovation. Xia et al. [16] also indicated that in multi-party involved supply chains, blockchain technology can significantly enhance collaboration efficiency, especially in industries such as food, agriculture, and medicine that have high requirements for traceability and transparency.

Chauhan et al. [17] indicated that blockchain technology can not only enhance the resilience of supply chains but also promote the achievement of the Sustainable Development Goals (SDGs) of supply chains. Xiang [18] stated that by optimizing information sharing and decision-making processes, blockchain can help reduce operating costs, minimize resource waste, and enhance the overall efficiency of the supply chain. Furthermore, Faisal et al. [19] indicated that blockchain can also promote the competitive and cooperative relationship among supply chain participants, that is, to cooperate in competition and jointly promote the adoption of blockchain, thereby achieving the sustainability of the supply chain.

Based on the above research content, this paper studies the risk prevention and control and supply chain collaboration scheme of digital RMB based on blockchain. By analyzing the risk spectrum of traditional supply chain finance and the independent application of digital RMB, a collaborative architecture based on consortium chain and supporting digital RMB smart contracts is designed. The risk quantification model and collaborative benefit evaluation model under this architecture are constructed, and the technical feasibility and performance advantages of the scheme are verified through experiments. Provide innovative ideas for enhancing the overall competitiveness of the industrial chain of the digital RMB.

2 Theoretical Basis

This chapter aims to lay the theoretical foundation for the research. It first delves deeply into the core features of the digital RMB and its inherent risks, and then systematically sorts out the application models and existing challenges of blockchain technology in the field of supply chain finance, providing a theoretical basis for the subsequent construction of integrated solutions.

2.1 Digital RMB

The Digital RMB (e-CNY) is a legal tender in digital form issued by the People's Bank of China, operated by designated operating institutions. It is based on a broad account system and supports the loose coupling function of bank accounts [20]. It is equivalent to physical RMB and has the following core features:

(1) Statutory solvency and centralized management

① Connotation: e-CNY is the legal tender of China, backed by the national credit. No unit or individual may refuse to accept it. Its issuance and circulation management follow the centralized management model of the central bank, ensuring the transmission efficiency of monetary policy and the stability of the financial system.

② The difference from cryptocurrencies: This feature makes it fundamentally different from decentralized cryptocurrencies such as Bitcoin. e-CNY is not a decentralized investment product but a centralized payment tool. Its value is stable and there is no risk of price fluctuations.

③ Value in the plan: It provides the possibility for the integration of centralized regulation and decentralized technology (blockchain). As a core node or ultimate arbiter, the central bank can ensure the compliance and stability of the entire system.

(2) Controllable anonymity (small amounts anonymous, large amounts traceable)

① Connotation: e-CNY follows the principle of voluntary participation at the front end and real-name registration at the back end. In daily small payments, protect user privacy like cash. However, when it comes to legal requirements such as anti-money laundering, anti-terrorist financing, and anti-tax evasion, authorized institutions can trace the flow of funds through the background system.

② Value in the solution: It provides a perfect solution for balancing business privacy and regulatory requirements in supply chain finance. On-chain transactions can maintain a certain degree of anonymity to protect business secrets, and regulatory authorities can conduct thorough investigations in accordance with the law when necessary, effectively preventing and controlling compliance risks.

(3) Dual offline payment

① Connotation: When both the payer and the payer are offline (such as without network signal), value transfer is completed through methods like "tap-to-tap". After one or both parties are connected to the network, the transaction data will be synchronized to the central bank's system for clearing and settlement.

② Value in the solution: It greatly enhances the robustness of the payment system, making it particularly suitable for supply chain scenarios with unstable network environments such as logistics, warehousing, and production lines, ensuring the continuity and reliability of payment behaviors.

(4) Programmability and smart contracts

① Connotation: This is the most revolutionary feature of e-CNY. It allows programmable scripts to be embedded in the currency or smart contracts to be called through external systems, enabling the currency to automatically perform operations such as payment and settlement when specific conditions are met.

② Value in the plan: It is the key to achieving automatic coordination between the capital flow and information flow in the supply chain. Smart contracts can automatically trigger the transfer of e-CNY based on business events confirmed on the chain, greatly enhancing efficiency and reducing operational risks and moral hazards.

2.2 The Application Value of Blockchain in Supply Chain Finance

As a distributed ledger technology, the core value of blockchain lies in establishing trust through technical means in scenarios involving multiple parties, which is highly consistent with the characteristics of supply chain finance, such as multiple subjects, cross-links, and high trust costs[21].

(1) Build a trustworthy data evidence preservation and traceability system

① Mechanism: Throughout the entire supply chain process from orders, logistics, warehouse receipts to invoices, all key data are digitally signed by the relevant parties and stored on the chain. Due to the immutability and traceability of the data, a unified and reliable single source of fact has been formed.

② Solved problems: Effectively cracked the problem of information silos, eliminated information asymmetry among all participants, and provided a real and reliable data foundation for the risk control of financial institutions.

(2) Achieve digitalization of assets and efficient circulation

① Mechanism: Convert the creditor's rights assets such as accounts receivable and warehouse receipts issued by core enterprises into digital certificates (Tokens) on the chain. These digital certificates can be split, merged, and circulated and financed along the supply chain to suppliers at all levels upstream.

② The problem solved: It has achieved the splitting, circulation and financing of core enterprise credit, enabling small and medium-sized enterprises at the end of the supply chain to also obtain low-cost financing, fundamentally alleviating the problems of difficult and expensive financing. The schematic diagram of achieving core enterprise credit penetration through blockchain is shown in Figure 1.

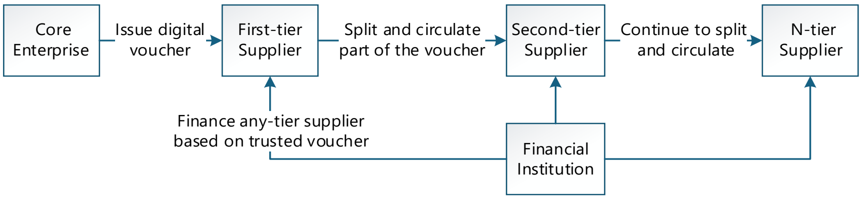

Figure 1: Schematic diagram of core enterprise credit penetration achieved by blockchain

(3) Achieve process automation through smart contracts

① Mechanism: Incorporate business rules into smart contracts. When the preset conditions are met (such as receipt confirmation, expiration date), the contract automatically performs operations such as payment and settlement.

② Solved problems: It has greatly reduced manual review, reconciliation, approval and other links, lowered operational risks and moral hazards, and at the same time shortened the traditional process that takes several days or even weeks to the minute level, significantly improving the capital turnover efficiency of the entire supply chain.

3 Design of a Supply Chain Collaboration Solution for Digital RMB Based on Blockchain

This chapter aims to build a supply chain collaboration solution that deeply integrates blockchain technology with the digital RMB. This solution is dedicated to breaking down information silos, achieving efficient integration and trusted collaboration of capital flow, information flow and business flow, and on this basis, building a comprehensive risk prevention and control system.

3.1 System Architecture

This plan adopts a hierarchical and modular design concept to build a collaborative ecosystem with consortium chains as the foundation of trust, smart contracts as the core driver, and digital RMB as the value carrier. Its overall architecture is shown in Figure 2.

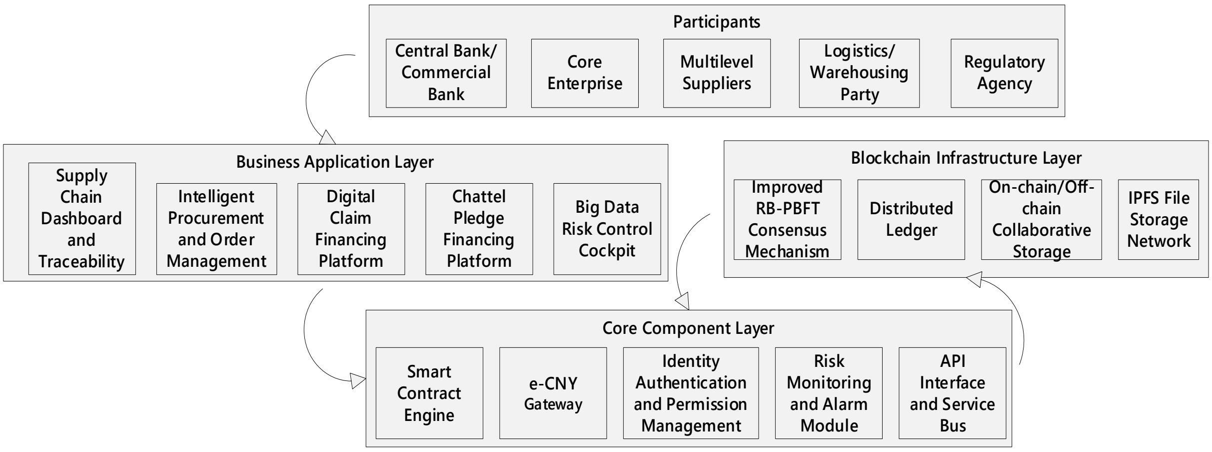

Figure 2: shows the overall architecture diagram of the digital RMB supply chain collaboration solution based on blockchain

This architecture is divided into four levels from top to bottom.

(1) Blockchain infrastructure layer

The blockchain infrastructure layer serves as the trust foundation of the entire system and adopts a permissioned consortium chain as the underlying framework.

Improved RB-PBFT consensus mechanism: By adopting the Reputation Authorized Byzantine Fault Tolerance (RB-PBFT) algorithm, it dynamically elects high-performance and high-reputation nodes to form a consensus committee. This ensures the security of Byzantine fault tolerance while significantly enhancing transaction processing efficiency (TPS) and reducing latency.

Distributed ledger: It stores the transaction logs (Tx Hash) of all transactions, smart contract codes, status change records, and hash fingerprints of key business data. The ledger data is synchronized among all nodes in the network to ensure consistency and immutability.

On-chain/off-chain collaborative storage: To address the performance bottleneck of blockchain storage, only the hash values of critical data are stored on the chain, while the original large files are stored in the Interplanetary File System (IPFS). The content identifier (CID) returned by it is anchored to the on-chain hash, which not only ensures the integrity of the data but also avoids the expansion of on-chain storage.

(2) Core component layer

The core component layer is the key part of the system, encapsulating the core business logic and technical capabilities.

Smart contract engine: It is the core of automatically executed business rules and contains a series of pre-deployed contract templates: ① Payment contract: Automatically triggers digital RMB payment based on business events confirmed on the chain; ② Financing contracts: Manage financing applications, disbursements, repayments and settlements based on digital accounts receivable certificates; ③ Reconciliation contract: Regularly and automatically execute multi-party reconciliation and generate uncontested reconciliation results.

Digital RMB Gateway: It serves as a crucial security bridge connecting the consortium chain with the official digital RMB system. Its main responsibilities include: ① Conducting compliant Know Your Customer (KYC) and anti-money laundering (AML) checks; ② Handle the deposit and withdrawal operations of the digital RMB, mapping the legal digital currency into controllable digital value that can be circulated on the chain; ③ Invoke the smart contract API provided by the central bank or the operating institution to offer fiat payment capabilities for on-chain contracts.

Identity authentication and permission management: Based on the Public Key Infrastructure (PKI) system, digital identity certificates are issued to each participant to achieve refined permission control. For instance, only when the logistics provider updates the logistics status can the core enterprise issue a payment commitment.

Risk Monitoring and Alert Module: Real-time monitoring of on-chain transaction behaviors, identification of abnormal patterns (such as frequent large transfers and related-party transactions) through rule engines and machine learning models, and timely alerts to relevant parties.

(3) Business application layer

The business application layer is oriented towards end users, providing friendly and intuitive Web or mobile operation interfaces, and encapsulating the complex underlying technologies into specific business functions.

Supply Chain Kanban and Traceability: It provides a full-chain visual view, allowing real-time query of goods location, transaction status, and historical traceability information.

Intelligent procurement and order management: Achieve on-chain creation, confirmation, status tracking and automated settlement of orders.

Digital debt financing platform: Suppliers can initiate financing applications based on core enterprise credit here and manage their digital accounts receivable certificates.

Movable property pledge financing platform: Manage the pledge, freezing and unpledge processes of warehouse receipts.

Big Data Risk Control Cockpit: Provides multi-dimensional risk data analysis views for financial institutions and core enterprises.

(4) Participants

All key players in the supply chain ecosystem join the consortium chain network as nodes and collaborate under unified rules.

3.2 Core Collaborative Mechanism

3.2.1 Trusted data evidence preservation and traceability mechanism

The trusted data evidence preservation and traceability mechanism aims to transform the scattered and easily tampered paper documents and system information offline into unified and trustworthy electronic evidence online, and build a trusted data chain that runs through the entire supply chain[22].

(1)Operation process and mathematical model

① Data atomization and hashing: For any business event E that needs to be documented (such as issuing an order), its related data set $D=\{d_1,d_2,...,d_n\}$ (such as order number, product list, amount, date) will be serialized and its hash value H(D) will be calculated through an encrypted hash function (such as SM3). The hash value is like the digital fingerprint of this set of data, and the hash value calculation formula is shown in Formula (1).

$$H(D)=Hash(d_1||d_2||...||d_n) \tag{1}$$

② Digital signature: The initiator of the event P_i (such as the core enterprise), signs the hash value with its own private key SK_i to generate the digital signature Sig_i, as shown in Formula (2).

$$Sig_i=Sign(SK_i,H(D)) \tag{2}$$

This signature attests to the authenticity and non-repudiation of the data source.

③ Data on the chain: Package structured transaction data, and its core content is shown in Formula (3).

$$Tx_{Record}=Transaction_{ID},Timestamp,P_i,H(D),Sig_i,Previous_{Hash},CID(Point\ to\ the\ IPFS\ file) \tag{3}$$

This transaction is packaged into a block after consensus and permanently recorded on the distributed ledger.

④ Traceability verification: When any authorized participant needs to verify data, they can recalculate the hash value H(D) of the original data and compare it with the H(D) stored on the chain. If they are consistent, it proves that the data has not been tampered with. Meanwhile, use P_i's public key to verify the validity of Sig_i.

The above-mentioned mechanism ensures the integrity, authenticity and timeliness of all key data on the supply chain, providing an indisputable factual basis for subsequent automatic payments and financing.

3.2.2 Programmable payment and automatic settlement mechanism

The programmable payment and automatic settlement mechanism utilizes the programmability of the digital RMB to code payment conditions and achieve automated and intelligent management of capital flow through smart contracts. Its core business process is shown in Figure 3.

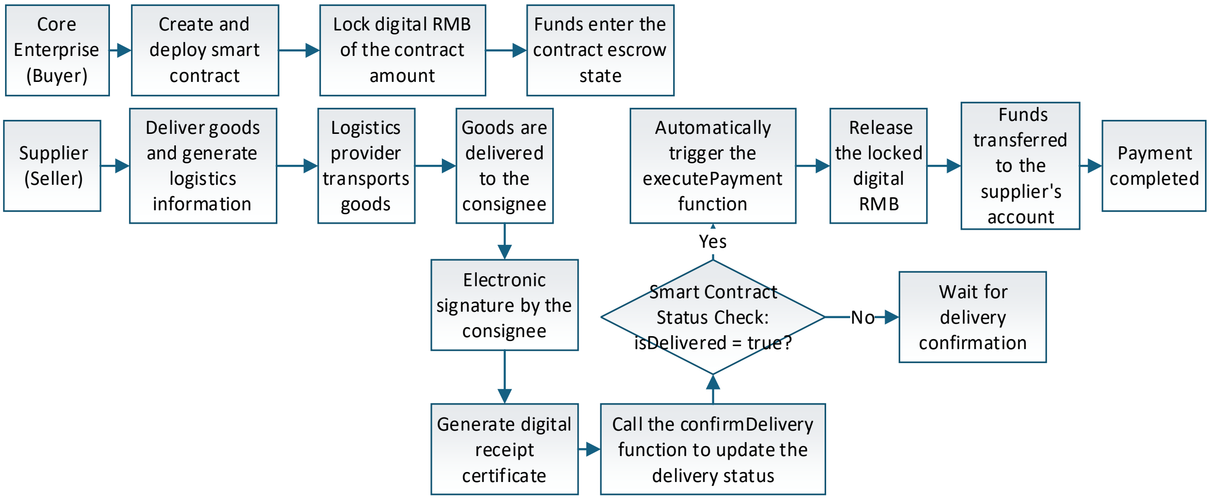

Figure 3: Core Business flowchart

As can be seen from the above figure, its core business processes are mainly divided into three stages:

(1) Phase One: Contract Initialization and fund locking

① Contract creation: The core enterprise (buyer) creates and deploys smart contracts to the blockchain network in accordance with the terms of the procurement contract.

② Fund locking: While deploying the contract, the core enterprise transfers the digital RMB of the contract amount to the contract address for locking.

(2) Phase Two: Logistics Execution and Status Update

① Goods shipment: The supplier ships the goods as stipulated in the contract, and the logistics provider begins the transportation process.

② Delivery confirmation: After the goods are delivered, the consignee shall conduct an electronic signature for receipt and generate an unalterable digital certificate.

③ Status Update: The logistics provider calls the confirmDelivery function to upload the hash value of the off-chain receipt voucher, and the status of the smart contract changes to delivered.

(3) The third stage: Automatic payment and fund settlement

① Condition check: The smart contract automatically checks the isDelivered status and triggers the payment logic when the conditions are met.

② Fund transfer: The locked digital RMB is transferred to the supplier's account through a specific function

③ Status update: After the payment is completed, the isPaid status is updated to true and the PaymentExecuted event is triggered.

3.2.3 Multi-level creditor's rights transfer and financing mechanism

The multi-level creditor's rights circulation and financing mechanism is the core mechanism to solve the financing difficulties of small and medium-sized enterprises. This mechanism can transform the high-quality credit of core enterprises into a digital asset that can be split, circulated and financed on the chain. Its sequence diagram is shown in Figure 4.

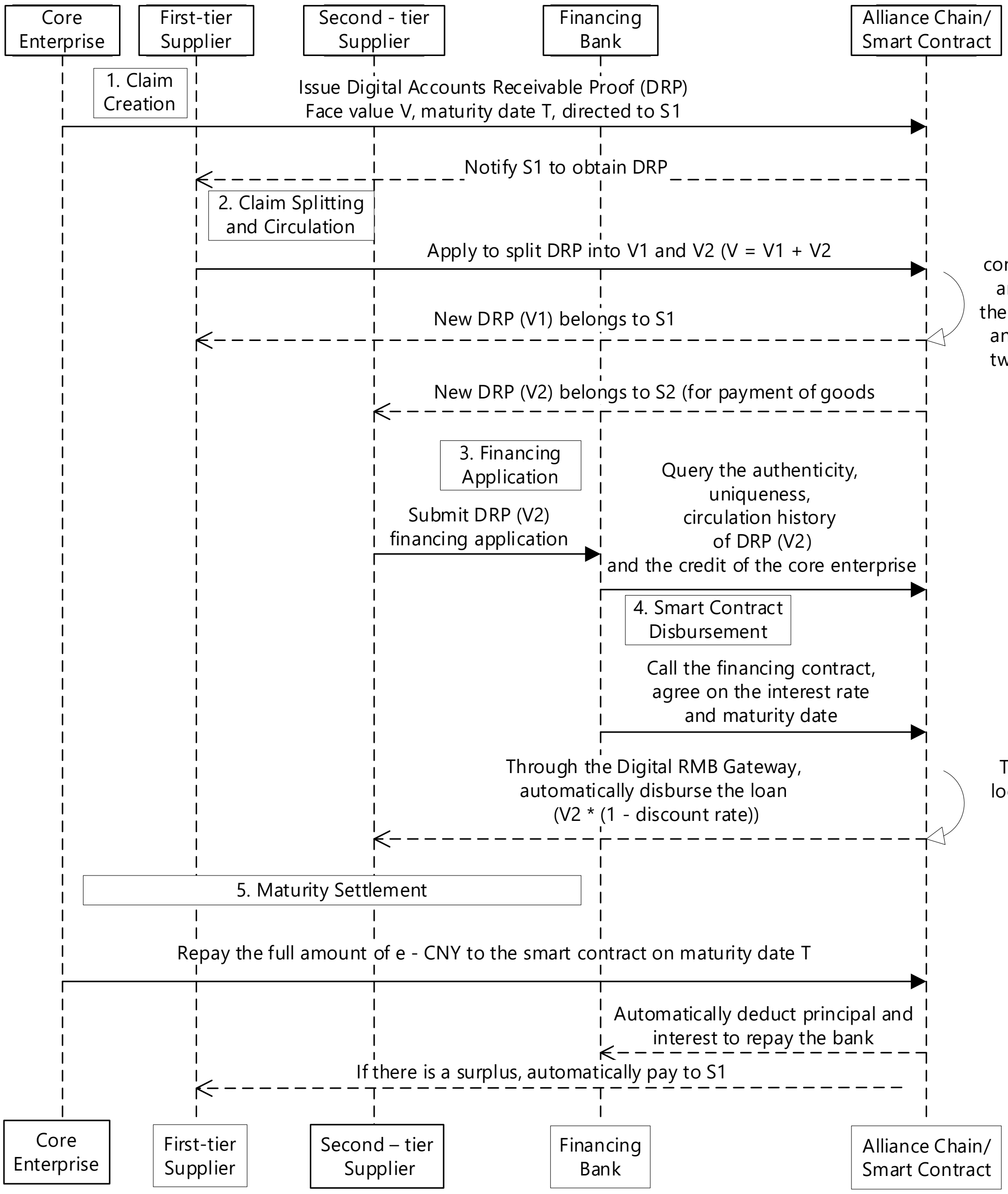

Figure 4: shows the multi-level circulation and financing sequence diagram of digital creditor's rights based on blockchain

(1) Core mathematical model

The core mathematical model of this mechanism is the debt splitting model 23. Let the digital accounts receivable certificate issued by the core enterprise to the first-level supplier S_1 be A, with a face value of V and a maturity date of T. When S_1 needs to pay the purchase price to the secondary supplier S_2, A can be split into two new vouchers, as shown in Formula (4).

$$A \rightarrow \{A_1, A_2\} \tag{4}$$

Among them, the face value of A_1 is v_1 and it belongs to S_1. The face value of A_2 is v_2 and it belongs to S_2. The split must satisfy the conservation of face value, that is $v_1+v_2=V$.

The smart contract will destroy the original certificate A and simultaneously create and issue A_1 and A_2. This process can continue recursively, and A_2 can be further split by S_2

to pay S_3, as shown in Formula (5).

$$V=\sum_{i=1}^{k} v_i \tag{5}$$

Here, v_i is the face value of the i-th sub-certificate.

(2) Risk prevention and control design

① Uniqueness and anti-double-spending: Each certificate and its sub-certificates have a globally unique identifier on the chain. When smart contracts are split or financed, they immediately mark or destroy the original vouchers, fundamentally eliminating the fraud risk of the same asset being repeatedly financed in multiple financial institutions.

② Credit penetration: Based on the final payment commitment of the core enterprise, all sub-vouchers A_i share its credit. Banks are willing to finance remote suppliers such as S_2 and S_3 not based on their own credit, but on unalterable credit certificates on the chain that can be traced back to the core enterprises.

③ Automatic Clearing: At expiration, the smart contract will automatically initiate a payment request to the core enterprise. The received digital RMB will be automatically liquidated to all current certificate holders in accordance with the proportion of $\{v_1,v_2,...,v_k\}$.

4 Risk Prevention and Control Model and collaborative Benefit assessment

This chapter aims to construct a quantitative mathematical model to evaluate the proposed solution from two dimensions: technical risk and commercial benefit. On the one hand, it is to control systemic technical risks by improving the consensus algorithm; On the other hand, it is to quantify the commercial value brought by the plan by establishing a benefit assessment model.

4.1 Consensus Risk Control Model Based on Improved PBFT

In the consortium chain environment, the consensus algorithm is the core for maintaining system consistency and security, and its performance and robustness are directly related to the risk level of the entire system. The classic Practical Byzantine Fault Tolerance (PBFT) consensus algorithm, although it can tolerate no more than one-third of Byzantine nodes, when the node scale expands, its $O(N^2)$ (polynomial level) communication complexity will bring serious performance bottlenecks and delay risks. It is difficult to support high-frequency supply chain finance business [24]. Therefore, this paper proposes a dynamic representative election PBFT algorithm based on credit rating (Reputation based PBFT, R-PBFT). This model significantly improves performance and reduces consensus risk while maintaining the security of BFT by introducing economic incentives and dynamic committee mechanisms..

4.1.1 Model Definition and Assumptions

①N: The total number of nodes in the consortium chain network.

② $P=\{p_1,p_2,...,p_N\}$: The collection of all nodes.

③$R_i(t)$: The credit score of node p_i at time t is a dynamically changing value that reflects the reliability of the node's historical behavior.

④M: A fixed size of the consensus Committee (Committee), and M≪N, which is responsible for implementing efficient PBFT consensus.

⑤f: The maximum number of Byzantine nodes that the system can tolerate, according to the PBFT principle, requires $M\geq 3f+1$.

4.1.2 Dynamic Update Mechanism for Credit Scores

The credit score of a node is a quantitative reflection of its historical behavior. Therefore, an event-based scoring system should be designed.

(1) Credit update formula

The credit update formula is shown in Formula (6).

$$R_i(t+1)=R_i(t)+\Delta R \tag{6}$$

Among them, ΔR is determined by the behavior of the node during the consensus period, mainly including the following behaviors: ① Successful consensus and block generation: If the node participates honestly in this round of consensus and completes the block generation correctly, then $\Delta R=+\delta_1$ ($\delta_1>0$). ② Effective behavior reward: If a node actively reports and verifies a double-spending attack, then $\Delta R=+\delta_2$. ③ Penalty for malicious or ineffective behavior: If a node is confirmed to have malicious behavior (such as broadcasting conflict messages), then $\Delta R=-\delta_3$ ($\delta_3\gg\delta_1$); If a node times out and does not respond during the consensus process, then $\Delta R=-\delta_4$; ④ Credit decay: To prevent nodes from remaining in a dominant position for a long time due to the credit accumulated in the early stage, which could lead to the system becoming static and weaken the incentive effect on new nodes and their recent behaviors, a slight time decay factor γ ($0<\gamma<1$) is introduced. In each long period T, $R_i(t+1)=\gamma\cdot R_i(t)$ is applied to encourage nodes to remain active and honest continuously.

When the credit score $R_i(t)$ of a node is lower than the system threshold R_{min}, the node will be temporarily deprived of the qualification to participate in the consensus and enter the observation period.

4.1.3 Dynamic Committee Election Algorithm

In the dynamic committee election algorithm, the consensus committee C is not fixed but is elected dynamically at regular intervals (for example, every 100 blocks) based on the overall performance of the nodes, effectively preventing the centralization of power and the corruption of committee nodes.

(1) Election probability model

The probability $Prob_i$ of node p_i being selected into the committee is positively correlated with its credit score. The Softmax function is used to calculate this probability to ensure that nodes with high credit have a higher chance of being selected, while all nodes have a small probability of participating, maintaining the openness and fairness of the system[25]. The formula is shown in Formula (7).

$$Prob_i=\frac{e^{R_i(t)/T}}{\sum_{j=1}^{N} e^{R_j/T}} \tag{7}$$

Among them, T is the distribution adjustment factor. This parameter controls the randomness level in the selection process by adjusting the smoothness of the probability distribution: a higher T makes the probability distribution more uniform (stronger exploratory), and a lower T makes the probability more concentrated on high-credit nodes (stronger explosibility). The system can dynamically adjust T according to the stable state of the network. The R-PBFT consensus process interacts with the credit mechanism, as shown in Figure 5.

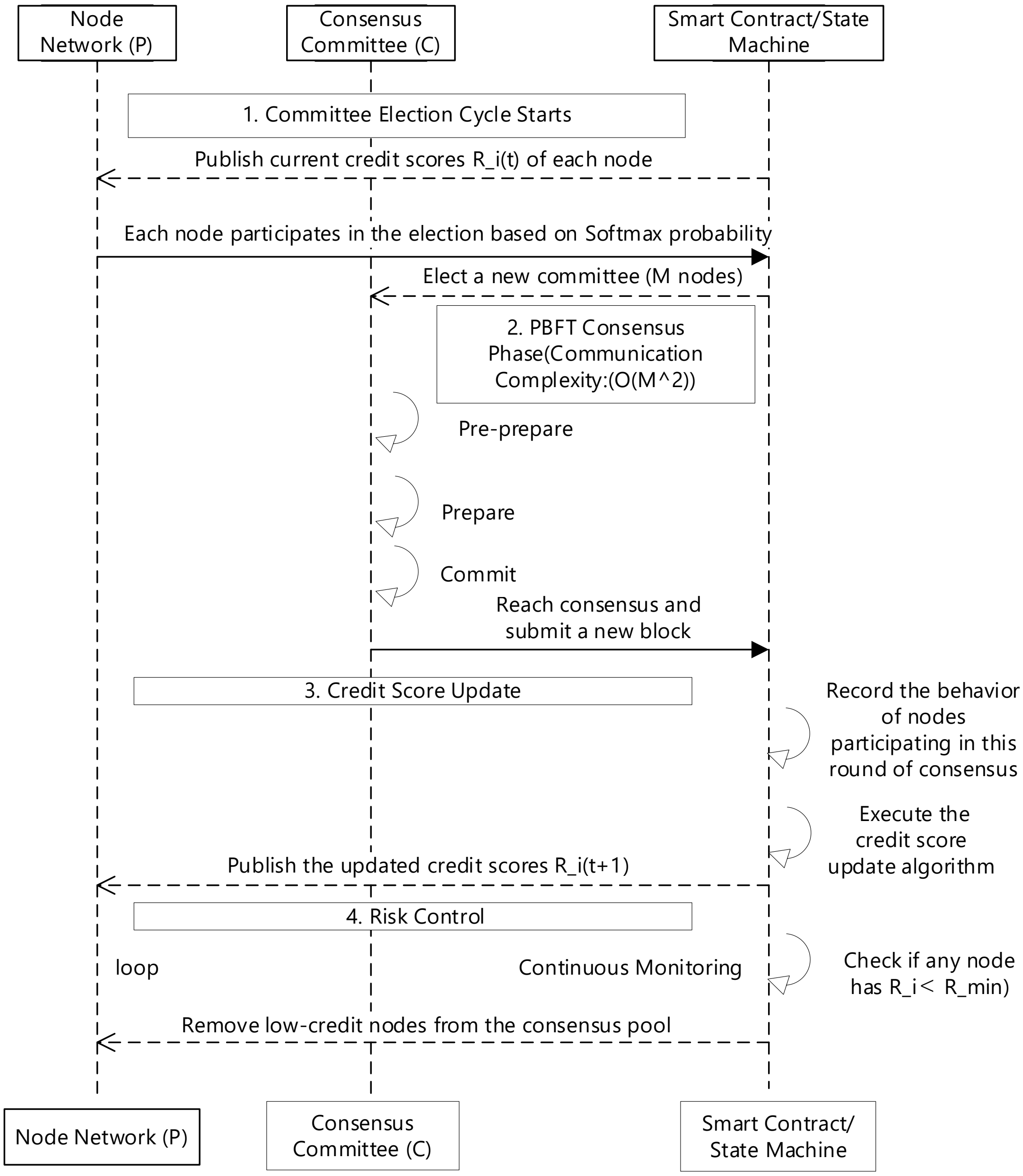

Figure 5: Interaction Diagram of R-PBFT consensus Process and credit Mechanism

4.1.4 Risk Control Benefit Analysis

(1) Performance improvement: The communication complexity is reduced from $O(N^2)$ to $O(M^2)$. Assuming N=100, M=21, the communication load is reduced by approximately $(100^2-21^2)/100^2=95.6\%$, the transaction throughput (TPS) is increased by an order of magnitude, and the consensus delay is significantly reduced.

(2) Enhanced security

① Byzantine fault tolerance: Within the committee, PBFT is still followed. As long as the number of Byzantine nodes in the committee does not exceed the limit, the system is safe.

② Resistance to Witch attacks: Malicious nodes find it difficult to enter the committee by creating a large number of witch nodes because the election probability is linked to the long-term accumulated credit score, and accumulating credit requires costs and time.

③ Resistance to long-range attacks: Due to the regular replacement of committees and the accumulation of credit scores based on the longest chain principle, it is difficult for attackers to reconstruct history to tamper with the composition of the committee.

④ Incentive compatibility: The model aligns the individual rationality of nodes (pursuing higher credit scores to obtain rewards and power) with the collective goal of the system (safety and efficiency), forming a benign self-reinforcing ecosystem.

4.2 Quantitative Evaluation Model for Supply Chain Synergy Benefits

In order to scientifically assess the commercial value brought by this plan, a comprehensive quantitative evaluation model for collaborative benefits has been constructed. This model transforms multi-dimensional and abstract collaborative benefits into quantifiable comprehensive indices.

4.2.1 Key Performance Indicator (KPI) System

The Key Performance Indicator (KPI) system selects the four most core dimensions of indicators in supply chain finance.

(1) Capital turnover efficiency (δ_1, with a cycle of T_{new} under the new scheme), as shown in Formula (8).

$$\delta_1=\frac{T_{\mathrm{base}}-T_{\mathrm{new}}}{T_{\mathrm{base}}}\times 100\% \tag{8}$$

(2) Financing cost (δ_2, which is C_{new} under the new plan), as shown in Formula (9).

$$\delta_2=\frac{C_{\mathrm{base}}-C_{\mathrm{new}}}{C_{\mathrm{base}}}\times 100\% \tag{9}$$

(3) Risk cost (δ_3, F_{new} under the new scheme), as shown in Formula (10).

$$\delta_3=\frac{F_{base}-F_{new}}{F_{base}}\times 100\% \tag{10}$$

(4) Operational efficiency (δ_4): It can be measured by the increase in the average number of orders processed per person or the average processing time per transaction, as shown in Formula (11).

$$\delta_4=\frac{E_{new}-E_{base}}{E_{base}}\times 100\% \tag{11}$$

4.2.2 Comprehensive Benefit Evaluation Model Based on AHP

Since the importance of each indicator to the overall benefit varies, the Analytic Hierarchy Process (AHP) is adopted to determine the weights of each indicator.

(1)Step 1: Construct the judgment matrix

Invite industry experts (such as supply chain managers, risk control officers from financial institutions, and scholars) to conduct pairwise comparisons of the indicators and construct A judgment matrix A based on the 1-9 scaling method, as shown in Formula (12).

$$A=\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \tag{12}$$

(2) Step 2: Calculate the weight vector

Calculate the maximum eigenvalue $\lambda_{\max}$ of the judgment matrix A and its corresponding eigenvector W, and normalize the eigenvectors to obtain the weight vector $\boldsymbol{w}=[w_1,w_2,w_3,w_4]^T$ of each index.

(3) Step 3: Consistency test

Calculate the consistency ratio $CR=\frac{CI}{RI}$, where $CI=\frac{\lambda_{\max} n}{n\text{-}1}$ and RI are the average random consistency indicators. When CR<0.1, it is considered that the consistency of the judgment matrix is acceptable.

(4) Step 4: Calculate the comprehensive synergy benefit index

Combine the improvement rates of each standardized indicator with their weights to calculate the comprehensive synergy benefit index S, as shown in Formula (13).

$$S=\boldsymbol{w}\cdot\delta=w_1\cdot\delta_1+w_2\cdot\delta_2+w_3\cdot\delta_3+w_4\cdot\delta_4 \tag{13}$$

Among them, $\delta=[\delta_1,\delta_2,\delta_3,\delta_4]$ is the improvement rate vector of each KPI.

4.2.3 Return on Investment (ROI) Analysis

In addition to the comprehensive benefit index, traditional ROI analysis can also be conducted to provide a more direct financial basis for decision-making. The ROI formula is shown in Formula (14).

$$ROI=\frac{\sum(Benefit)\text{-}\sum(Cost)}{\sum(Cost)}\times 100\% \tag{14}$$

Among them, $\sum(Cost)$ represents the total cost of implementing this plan, including system development, deployment, operation and maintenance, training, etc. $\sum(Benefit)$ represents the total revenue brought by the plan, which can be estimated by monetizing the benefit index S.

Through the above model, enterprises can conduct a forward-looking and quantified benefit assessment of the introduction of the blockchain-based digital RMB supply chain collaboration solution, thereby making more scientific strategic decisions. This model not only proves the economic feasibility of the solution but also provides a clear measurement standard for its continuous optimization.

5 Experiment and Result Analysis

To verify the effectiveness of the blockchain-based digital RMB supply chain collaboration scheme proposed in this paper, especially its core R-PBFT consensus algorithm and overall collaboration benefits, a series of experiments were designed and implemented.

5.1 Experimental Environment and Parameter Settings

5.1.1 Experimental Environment

(1) Hardware environment: A server equipped with an Intel Xeon Gold 6248R CPU @ 3.00GHz and 128GB RAM.

(2) Software environment: Ubuntu 20.04 LTS operating system, the core algorithm is implemented using Go language (v1.19), and Docker container technology is utilized to simulate distributed nodes.

(3) Blockchain framework: Customized development based on the Hyperledger Fabric framework, integrating the R-PBFT consensus algorithm proposed in this paper.

(4) Network Simulation: Use the Linux TC (Traffic Control) tool to simulate the real wide area network environment. Set the average network latency to 50ms and introduce a random packet loss rate of 5% to enhance the robustness of the experiment.

(5) Digital RMB gateway: It is implemented through an analog API interface, assuming a fixed processing delay of 20ms.

5.1.2 Parameter Settings

The key experimental parameters of this experiment are shown in Table 1.

Table 1: Configuration of Key Experimental Parameters

Parameter category	Parameter name	Parameter value	Explanation
Network topology	Total number of nodes (N)	100	Simulate a medium-sized supply chain alliance
	Committee size (M)	21	It is set according to the PBFT fault tolerance requirement (M ≥ 3f+1)
	Byzantine node ratio	5% - 25%	Used to test the robustness of the algorithm
Consensus algorithm	Classic PBFT	-	As a baseline comparison algorithm
	R-PBFT (This article)	-	Credit threshold R_{min}=50, initial credit R_{init}=100
	Consensus round	1000	Take the average of the consensus rounds of each experiment run
Transaction load	Transaction size	1 KB	Simulate typical supply chain transaction data
	Transaction sending rate	500 - 5000 TPS	Variable load, used for pressure testing
Supply chain experiment	Supply chain hierarchy	4	Core enterprises, Level 1, Level 2 and Level 3 suppliers
	Initial financing cost	8% annualized	The typical financing interest rate for small and medium-sized suppliers under the traditional model
	Order-to-cash cycle	60 days	The benchmark period in the traditional mode

5.2 Experimental Design and Evaluation Indicators

(1)Experiment One

Experiment One is a performance comparison experiment of consensus algorithms. The purpose of the experiment is to verify the advantages of the R-PBFT algorithm over the classical PBFT in terms of throughput, latency and robustness. The experimental design is as follows: ① In a network of 100 nodes, the classic PBFT and R-PBFT algorithms are deployed respectively; ② Gradually increase the transaction load (from 500 TPS to 5000 TPS), and measure the transaction throughput (TPS) and average consensus delay of the two algorithms; ③ Under a fixed transaction load (2000 TPS), gradually increase the proportion of Byzantine nodes (from 5% to 25%) to measure the consensus success rate of the system. The experimental evaluation indicators are as follows: ① Transaction Throughput (TPS) : The number of transactions successfully processed by the system per second; ② Average consensus delay: The average time from the submission of a transaction to its final confirmation; ③ Consensus success rate: The proportion of rounds where consensus is successfully reached in the presence of Byzantine nodes among the total rounds.

(2) Experiment Two

Experiment Two is the experiment on the synergy benefits of the supply chain. The purpose of the experiment is to quantitatively evaluate the improvement degree of the key performance indicators of the supply chain brought about by the scheme proposed in this paper. The experimental design is as follows: ① Construct a virtual supply chain model with a four-layer structure to simulate its transaction, financing and payment activities within 30 days; ② Operate the traditional mode (based on offline processes and traditional banking systems) and the mode proposed in this paper (based on blockchain and digital RMB) respectively; ③ Collect data on efficiency, cost, risk, etc. under the two modes, and calculate the KPI improvement rate $\delta_1,\delta_2,\delta_3,\delta_4$. The experimental evaluation indicators include the rate of improvement in capital turnover efficiency δ_1, the rate of reduction in financing costs δ_2, the rate of reduction in risk costs δ_3 and the rate of improvement in operational efficiency δ_4.

5.3 Experimental Results and Analysis

5.3.1 Analysis of Performance Results of Consensus Algorithms

(1) Throughput (TPS) comparison

The comparison of system throughput under different transaction loads is shown in Figure 6.

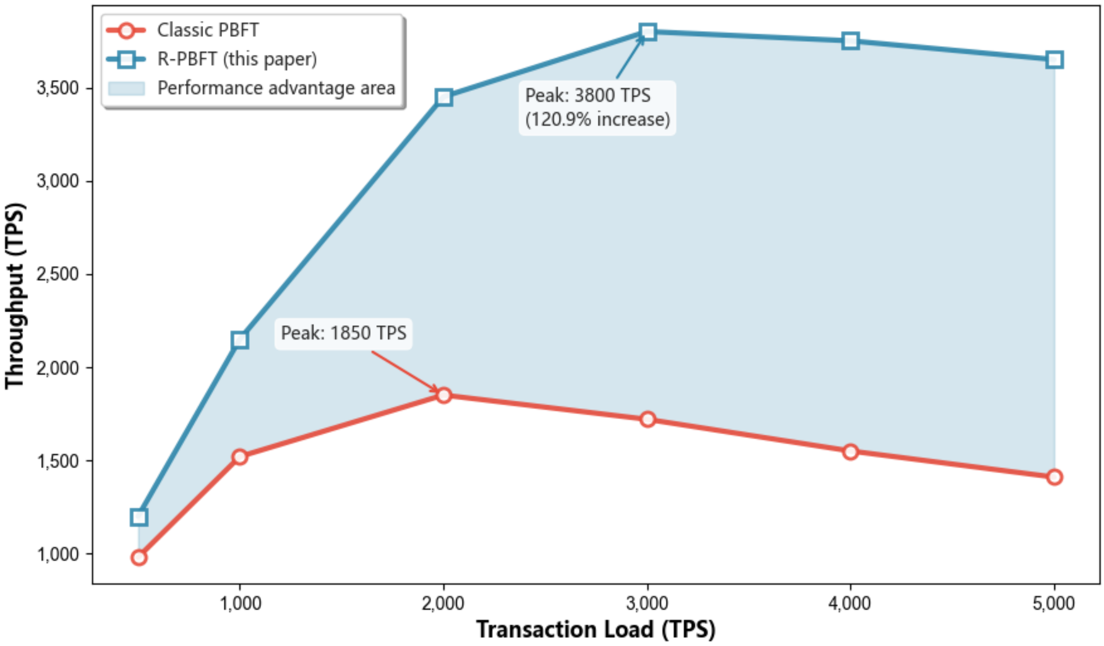

Figure 6: Comparison of system throughput under different transaction loads

It can be seen from the above figure that under low load (500 TPS), both algorithms can handle transactions well, but R-PBFT has shown a throughput advantage; As the load increases, the throughput of the classic PBFT peaks at around 2000 TPS (approximately 1850 TPS), and then the performance begins to decline due to network congestion caused by the communication complexity of $O(N^2)$. Due to the reduction of the consensus range of R-PBFT to a fixed 21 committee nodes, the communication complexity remains stable at $O(M^2)$. Its throughput continuously rises to approximately 3800 TPS and remains stable. Even under a load of 5000 TPS, there is no performance degradation, and the peak throughput reaches 2.06 times that of the classic PBFT.

(2) Comparison of consensus delay

The comparison of average consensus delay is shown in Table 2.

Table 2: Comparison of Average Consensus Delay (Unit: Milliseconds)

Transaction Load (TPS	Classic PBFT	R-PBFT (This article)	Latency reduction	Transaction Load (TPS	Classic PBFT
500	320	245	23.4%	500	320
1000	380	210	44.7%	1000	380
2000	420	185	56.0%	2000	420

It can be seen from the above table that the average consensus delay of R-PBFT is significantly lower than that of classical PBFT, and the advantage becomes more obvious as the load increases: Under a typical load of 2000 TPS, the latency of R-PBFT is 185ms, which is 56% lower than that of classic PBFT at 420ms. This is mainly because the committee mechanism significantly reduces the number of message broadcasts during the consensus process. When the load reaches 4000 TPS, the latency of the classic PBFT has risen to 720ms, which is difficult to meet the supply chain payment scenarios with high real-time requirements. However, the latency of R-PBFT remains stable at around 205ms, demonstrating excellent scalability.

(3) Robustness (against Byzantine nodes) test

The consensus success rate under different proportions of Byzantine nodes is shown in Figure 7.

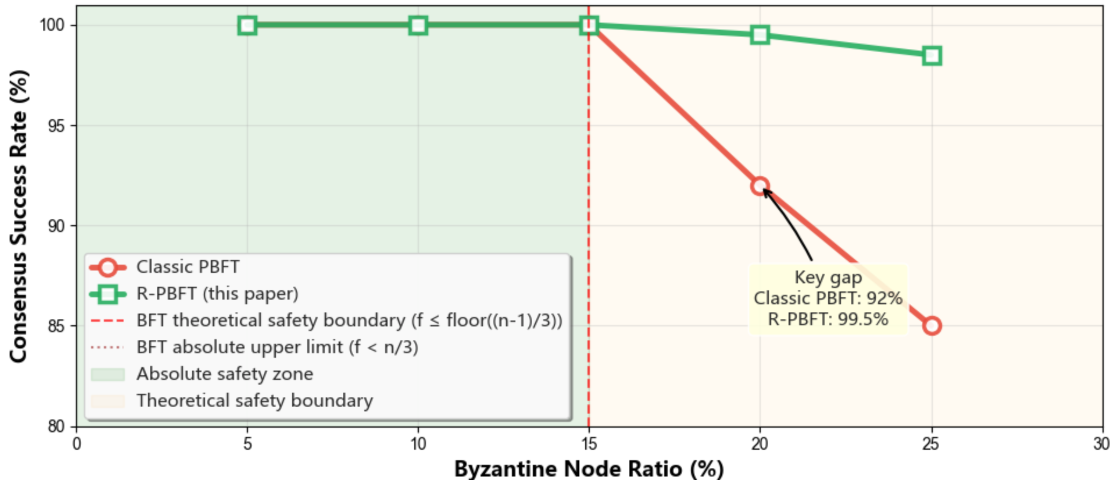

Figure 7: Consensus success rate under different proportions of Byzantine nodes

As can be seen from the above figure, when the proportion of Byzantine nodes is less than 15% (i.e., the number of Byzantine nodes in the committee is ≤ 3), both algorithms can maintain a consensus success rate of 100%, which is in line with the BFT theory. When the proportion of Byzantine nodes rises to 20%, the consensus success rate of classic PBFT begins to fluctuate, dropping to approximately 92%. This is because the existence of a large number of malicious nodes increases the probability of network partitioning and message conflicts. However, R-PBFT can still maintain a consensus success rate close to 100% when the proportion of malicious nodes is 20%, which proves the effectiveness of its credit mechanism: Malicious nodes have difficulty entering the consensus committee due to their low credit and are thus isolated from the core consensus process, greatly enhancing the robustness of the system.

5.3.2 Analysis of the Results of Supply Chain Synergy Benefits

Through the simulation of 30-day supply chain activities, operational data under two modes were collected, and the improvement rates of key indicators were calculated, as shown in Table 3.

Table 3: Comparative Analysis of Supply Chain Synergy Benefits

Key Performance Indicators (KPI	Traditional mode	The scheme model of this article	Improvement rate (δ)
Capital turnover efficiency (order to cash cycle)	60 days	18 days	δ1=+70.0%
Financing cost (annualized interest rate)	8.0%	4.5%	δ2=−43.8%
Risk cost (Incidence of fraud)	0.5%	0.05%	δ3=−90.0%
Operational efficiency (number of orders processed per person per day)	25 orders	65 orders	δ4=+160.0%

As can be seen from the above table, the order-to-cash cycle has been shortened from 60 days to 18 days, with an improvement rate of 70%. This is mainly due to the automatic reconciliation and payment achieved by smart contracts, eliminating the manual review, bill transmission and bank processing time in the traditional process. The average number of orders processed per person per day has increased from 25 to 65, with an improvement rate as high as 160%. This is mainly due to the data sharing and automated processes on the blockchain, which have liberated employees from repetitive and cumbersome verification work. The financing interest rate for small and medium-sized suppliers has dropped from 8% to 4.5%. This is mainly because the core enterprise credit has achieved trusted penetration through blockchain, and the immutability of on-chain data has reduced the risk control costs and risk premiums of financial institutions. The incidence of financing fraud has dropped from 0.5% to 0.05%, a decrease of 90%. This is mainly due to the anti-double-spending mechanism and full-process data traceability capability of blockchain, which make it almost impossible to hide fraudulent behaviors.

5.4 Experimental Conclusion

Through systematic experiments in this chapter, the following conclusions are drawn: Compared with the classical PBFT, the R-PBFT consensus algorithm proposed in this paper has significant improvements in both transaction throughput and consensus delay, and can effectively resist attacks from up to 20% Byzantine nodes, proving its technical feasibility in a supply chain environment with high concurrency and weak trust. Moreover, after the implementation of the plan, the core operational indicators of the supply chain were comprehensively optimized, especially in accelerating capital turnover, reducing financing costs and controlling risks, which proved that the plan has huge commercial application potential.

6 Conclusion

This article systematically studies the application of blockchain-based digital RMB in supply chain collaboration and risk prevention and control. By constructing a collaborative architecture integrating consortium chains, smart contracts and digital RMB, three core mechanisms, namely trusted evidence storage, programmable payment and creditor's rights transfer, were designed. An improved R-PBFT consensus algorithm and collaborative benefit evaluation model were proposed. Experiments have proved that this scheme can effectively improve system performance, reduce financial risks and enhance the collaborative efficiency of the supply chain. In the future, further research can be conducted on the interaction of assets and information among different supply chain consortium chains and with the backbone network of the digital RMB.

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