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A blockchain and IoT based lightweight framework for enabling information transparency in supply chain finance

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ABSTRACT

Supply Chain Finance (SCF) refers to the financial service in which banks rely on core enterprises to manage the capital flow and logistics of upstream and downstream enterprises. SCF adopts a self-testing and closed-loop credit model to control funds and risks. The key factor in a successful SCF service is the deployment of SCF business-oriented information systems that allow businesses to form partnerships efficiently and expedite cash flows throughout the supply chain. Blockchain Technology (BCT) featuring decentralization, tamper-proofing, traceability, which is usually paired with the Internet of Things (IoT) in real-world contexts, has been widely adopted in the field of finance and is perfectly positioned to facilitate innovative collaborations among participants in supply chain networks. In this paper, we propose a BCT and IoT-based information management framework (named BC4Regu), which works as the regulatory to improve the information transparency in the business process of SCF. With BC4Regu, the operation cost of the whole supply chain can be significantly reduced through the coordination and integration of capital flow, information flow, logistics and trade flow in the supply chain. The contributions in this paper include (1) proposing a novel information management framework, which leverages Blockchain and IoT to solve the problem of information asymmetry in the trade of SCF; (2) proposing the technical design of BC4Regu, including the Blockchain infrastructure, distributed ledger-based integrated data flow service, and reshaped SCF process; and (3) applying BC4Regu to a group of scenarios and conducting theoretical analysis by introducing the principal-agent model to validate the BC4Regu.

1. Introduction

With the sharply increasing demand for corporate finance, Supply Chain Finance (SCF) has become a popular approach for corporate financing [1,2]. The core enterprises in the supply chain are bundled with upstream and downstream suppliers/distributors to provide financial services. The main financing routes for Small-Medium Enterprises (SMEs) include: commercial financing from enterprises in the supply chain, financing from commercial banks, and financing through the securities market. However, due to the small scale and poor operational management, SMEs usually can only seek for financial support through commercial financing [1].

In the context of traditional SCF, with the credit endorsement by core enterprises, financial institutions (e.g., banks) are willing to provide financing services (e.g., receivable financing, factoring services, inventory financing, etc.) to tier-one suppliers/distributors. There are many tier-two and above suppliers/distributors who are difficult to meet financing requirements due to the lack of direct connection with the core enterprises [1]. In practice, the risk management in SCF mainly focuses on the enterprises that apply for financing and their respective transactions. However, the authenticity of the parties involved, transaction data, and the underlying assets is often difficult to verify [3]. Moreover, such a business environment with diversified participants and complex business processes makes it more challenging to control risks than general financial businesses [4,5].

In an SCF transaction, there are many transaction records (such as orders, accounts receivable, invoices, accounts payable, financial pledges, etc.) among different parties. These records are usually

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generated in a peer-to-peer manner and only visible to directly related parties. For example, as the Enterprise Resource Planning (ERP) system is usually not accessible for the enterprises in the supply chain, it is difficult for the indirectly related parties (such as upstream and downstream SMEs) to obtain the complete information in a transaction [6]. Therefore, the indirect trade information between upstream and downstream SMEs and core enterprises cannot be tracked effectively, which leads to the problem of "Information Silo" [7,8]. Moreover, the SMEs usually do not possess enough IT capability to digitalize the internal management or automate the external collaboration with business parties, rendering SMEs difficult to join the supply chain ecology [9,10].

Technology plays an important role in supporting the business processes of SCF. The capabilities enabled by information technology allow businesses to come together and simplify the workflows throughout the supply chain management, facilitating various kinds of financing transactions from account payable financing to reverse securitization [11]. Nevertheless, some barriers that incur high set-up and transaction costs negatively impact on adoption and the value created for the supply chain ecosystem and its participants. Nakamoto (2008) first proposed the concept of Blockchain Technology (BCT), which consists of technical elements such as digital signatures, proof of work, timestamps, distributed ledgers, peer-to-peer networks [12]. Banerjee (2018) combines BCT with ERP systems to discuss how BCT can be used to improve the transparency of ERP systems [7]. Many researchers emphasized that the combination of BCT, the Internet of Things (IoT) and other technologies can ensure the authenticity and trustworthiness of data while acquiring customer information at low cost and high frequency, solving the problems of information asymmetry and weak traceability in traditional SCF [13–16]. In this paper, we propose a BCT-based SCF information management solution named BC4Regu, which facilitates efficient regulation towards the information flow and business process while strengthening the process management and reducing operational risks/costs in SCF. By leveraging distributed ledger, BC4Regu constructs a digital asset ledger that is difficult to tamper with. By introducing smart contracts to process management, the traditional financing processes could be efficiently optimized.

The main contributions of this paper include:

- Based on distributed ledger and IoT, we propose the digitalization of the underlying financial assets (e.g., debts, bonds, bills, documents, etc.) and transaction tracking services, which solves the problem of right registration of financial assets in the supply chain ecology.
- Based on BCT, we propose an efficient integration and sharing service for commercial information, logistic information, capital flow and information flow (4 in 1) to address the problem of “Information silos”. With this service, we establish a whole process tracking mechanism to ensure that the transaction process is credible, transparent, and traceable.
- We optimize the business model of SCF based on smart contracts to realize the credit disassembly of core enterprises and efficient transmission among suppliers/distributors. The core enterprise can register the credit and debt relationships with its suppliers/distributors on the Blockchain platform and form digital assets that can be split and traded among the supply chain.

The rest of this paper is organized as follows: Section 2 introduces the related work. Section 3 introduces the design rationale, architecture and implementation of BC4Regu. Section 4 discusses the use cases of SCF business scenarios reshaped by BC4Regu. Section 5 presents the theoretical analysis from the economic perspective for the adoption of BCT in SCF. Finally, Section 6 concludes the paper.

2. Related works

2.1. Supply Chain Finance

The concept of the SCF was introduced by Timme et al. (2000) [17]. Berger et al. (2006) proposed a new concept of SME financing, believing that ordinary commercial lending service ignores the key elements of the overall effect of the supply chain [3]. The new idea of SCF is proposed to change the traditional financing methods and help SMEs solve their financing problems. Lamoureux (2008) emphasizes the positive effect of supply chain construction on optimizing of finance and capital [18]. Basu et al. (2012) focus on an enterprise to study its prepayment model. Through a large number of numerical analyses, they proved that the prepayment financing model was meaningful while facing uncertain future cash flow changes [19].

So far, there are diverse business models and financing models in SCF. Hartley (2000) first proposed the prepayment financing model [20], Leora (2004) proposed the inventory chattel pledge model, and constructed the reverse factoring financing [21]. Receivables-based financing is an early-stage model, with which upstream suppliers often use credit sales to attract core enterprises. However, this approach inadvertently increases the liquidity pressure of upstream enterprises in the supply chain because the accounts receivable generated by credit sales cause a lag in cash collection and also generate the possibility of write-downs. Therefore, in order to enhance the ability of suppliers to sustain their business, receivables-based financing has become a mainstream solution for upstream enterprises. Factoring and reverse factoring are receivable [18]. Inventory financing is also known as warehouse financing. The inventory assets of many enterprises usually occupy a large amount of operating funds, in order to reduce inventory cost and obtain a certain amount of liquidity, and enterprises will pledge their inventory to obtain financing. Inventory financing includes static pledge credit, warehouse receipt pledge credit, etc. Prepayment is the product of the downstream enterprises' behavior of paying for goods in advance to purchase raw materials and semi-products needed for production from upstream enterprises [1]. The funds of downstream enterprises are easily occupied by upstream enterprises for long time, and it usually results in the short-term fund shortage for downstream enterprises. In order to reduce the cost of capital occupation, downstream enterprises will pledge the prepaid goods for financing.

2.2. Blockchain technology

Satoshi Nakamoto (2008) proposed the digital currency "Bitcoin" in a paper entitled "Bitcoin: A Peer-to-Peer Electronic Cash System" [12]. BCT is mentioned for the first time in this paper. Blockchain is a database that connects blocks of data sequentially with the engagement of timestamp technology, and it is also a tamper-proof the management of procurement contracts infrastructure and distributed computing paradigm that uses a chain block structure to verify and store data. It employs a distributed consensus mechanism to append and update data, and facilitates scripting code (i.e., smart contract) to program and manipulate records in the ledger [22]. Blockchains are generally divided into two categories: permissioned and unpermissioned Blockchains. The unpermissioned Blockchain is the public Blockchain, and each node in the public Blockchain can access data and has equal privilege on the ledger (e.g., Bitcoin). The permissioned Blockchain can be further divided into the alliance Blockchain (consortium) and the private Blockchain, and only the permitted nodes of both types of Blockchains can perform the operation of bookkeeping.

In the early phase, Blockchain is adopted to enable people who do not trust each other to make payments directly using bitcoins without the intervention of an authority [22]. Its features such as decentralization, cross-border payments, have brought a significant impact on traditional finance. Buterin (2014) first proposed the Ethereum, which combines the smart contracts and BCT [23]. It allows users to edit and run smart contracts based on Ethereum and develop various kinds of decentralized applications. Swan (2015) argued that BCT has the potential to completely disrupt the traditional credit form and become a key technology for the fourth industrial revolution [24]. The BCT-based systems are capable of reshaping the financial industry to get rid of inefficiencies and high costs caused by manual operation, complex processes, and non-uniform standards, and to make disruptive changes in the traditional financial industry. For example, the traceability feature of BCT has been widely used in supply chain management, logistics, as well as the IoT [47–50].

Nasdaq (2015) announced when launching Linq [25] a Blockchain platform for private equity transactions, which significantly reduced labor costs and avoids errors that can be caused by manual operations. Ripple developed the Interledger platform (https://www.w3.org/community/interledger) - a cross-chain protocol that aims to create a global unified payment standard and streamline cross-border payment processes. Chen et al. (2020) introduced the BCT to the automotive retail supply chain industry to improve the operational efficiency [26]. Guo et al. (2020) introduced the adoption of BCT in the used car industry [27]. Chen et al. (2021) introduced the adoption of BCT in the supply chain of electronic material to increase the efficiency of the management of procurement contracts [28]. IBM's Autonomous Decentralized Peer-to-peer Telemetry (https://www.ibm.com/downloads/cas/2NZLY7XJ) proposes an even higher integration level by combining the Internet of Things (IoT) with BCTs. Once the product completes the final assembly, it can be registered in the Blockchain network representing its beginning of creation so that the product remains a unique entity within that Blockchain network throughout its life cycle when it is transferred from one owner to another.

3. Solution

3.1. The design rationale

The Blockchain was originally developed to realize the circulation of digital currencies, and it contains a token mechanism that simplifies the process of fund transfer from one to another [33–36]. The smart contract is capable of facilitating a broader range of software routines, and it could represent financial instruments and securities on the Distributed Ledger (DL) without the involvement of a central information system. Blockchain and DL could be used to realize the digital token and event registrations among the procedures of SCF. A digital token could be used as a representative of an asset in the real world (e.g., stocks) [37,38]; moreover, its ownership could be tracked on a specified Blockchain network, while transactions are executed and validated by the Blockchain network (e.g., consortium). Meanwhile, event registrations could be used to securely store data, which is a group of hashes of standardized information. The hash value on the Blockchain network could prove the existence of given facts (e.g., trade facts) at a specific time and that the one who (e.g., identity information) agreed on these facts by signing [39–41].

In this paper, BC4Regu aims to facilitate efficient regulatory towards the information and procedures (such as credit exposure, collateral, price fluctuation and repayment) while strengthening process management and reducing operational risks/costs in SCF. As shown in Fig. 1, all parties involved in the SCF transaction can join the supply chain financial service platform as a reciprocal role. BC4Regu runs on a consortium Blockchain network. The core enterprises, financial institutions and upstream/downstream SMEs exchange data and complete transactions through smart contracts. As shown in Table 1, the right and obligation of each role are as follows:

3.2. The architecture of BC4Regu

As illustrated in Fig. 2, the BC4Regu architecture consists of layer1: BCT-enabled capabilities, layer2: DLT-based Data Integration, layer3: reshaped SC management processes. In layer1, the data layer encapsulates the underlying technology of the Blockchain including the block structure, asymmetric cryptography, timestamps and data blocks. The network layer implements the P2P (peer-to-peer) data transmission and verification mechanism. The consensus layer implements the consensus algorithm between each network node. The contract layer implements

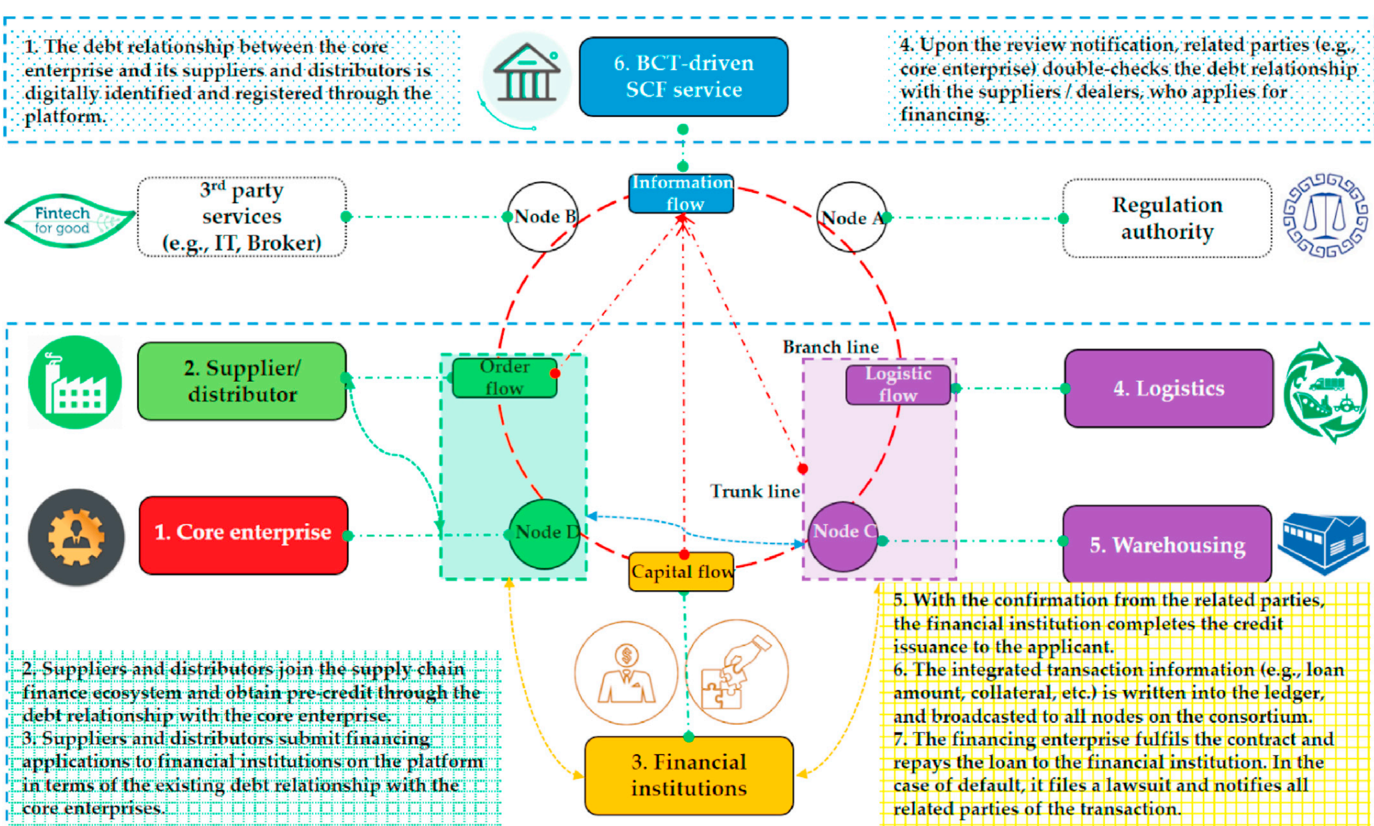

Fig. 1. The conceptual diagram of business interaction among parties in the SCF ecosystem.

Table 1
The right & obligation for each party in the SCF ecosystem.

Role	Right & obligations
Platform operator	SCF operation platform is responsible for the collection, verification, publishing and recording of all entities, contracts, transactions, receipts and various types of data flows on the consortium. It provides underlying Blockchain services, and ensures the normal operation of the alliance Blockchain network. It also gains revenue in the process of asset trading, financing services and operation management (e.g., membership fee).
Financial institutions	Financial institutions refer to traditional institutions such as banks that provide financial services, and in this context, it also includes commercial banks, factoring companies, trust companies, Internet finance (P2P) companies, etc. They can obtain credible data and high-quality business via the platform, increase profits and reduce transaction risks.
Core enterprises	Through the supply chain financial service platform, core enterprises can help SMEs suppliers and distributors solve the financing problems in the supply chain. In turn, the efficient improvement of SMEs can optimize the capital structure of the core enterprises, and further help core enterprises capture more market share.
Financing enterprises	Financing enterprises usually are SMEs, who are suppliers/distributors in the supply chain. They have a close business connection with the core enterprises. Via this platform, they can benefit from the credit disintegration of the core enterprises, improve the capital flow rate and optimize cash flow, ease the situation of capital breakage in the short-to-medium term.
Logistics and warehouse enterprises	Logistics and warehouse enterprises provide pledged inventory storage and material transportation services. They keep the right of withdrawal and monitor the price of goods. And financial institutions dynamically update the amount of financing credit according to the information provided by them. Meanwhile, logistics and warehouse enterprises can also provide financial services and play the role of fund providers in the supply chain.
Third-party IT service providers	Third-party information technology service providers can behave on behalf of the enterprises in the supply chain and promote these enterprises' business, with the help of their own business strategies and information technology, such as big data, artificial intelligence, etc.
Regulators	Regulators in this platform are reversed for the regulatory authority. Since BCT is still in the initial development stage, most BCT-based applications are running out of the supervision, in order to cope with the future regulatory demand, the role of regulator is set in advance in this solution and rules are formulated to maintain the development of BCT in the financial industry.

the programmability of the SCF platform. The application layer describes the application contexts that are supported by BC4Regu. The layer2 focuses on the digitalized registration of financial assets, the integration and tracking of multiple data flow in SCF business. With layer2, BC4Regu enables core enterprises to complete registration, splitting and transfer of financial assets in the supply chain ecology, and further supports the registration of purchase orders, warehouse receipts, prepayments and other assets. In layer3, we aim to reshape the procurement and fulfilment processes for approved payable financing.

3.3. The Blockchain technical implementation service

Distributed ledger uses a block structure to store data. It contains two types of data: block data and state data. The block data refers to the transaction information stored through a chain structure, which ensures the immutability and traceability of user transactions. Block data is mainly linked in a chain in the form of blocks, and all blocks are linked in a chain in an orderly manner, and each block points to its parent block. State data is a series of Key-Value (KV) pairs, and when a transaction is executed, a set of KV pairs needs to be updated. While the block data grows, the state data is frequently updated but does not grow. Therefore, in this solution, we adopt a hybrid storage mechanism, using a text-based storage engine to handle block data and a key-value pair storage engine (with high random write and sequential read performance) for state data, so as to separate the block data and state data to ensure that the read/write performance will not be affected when the data volume rapidly increases. Block data consists of a data header (which records the meta-information) and a data body (the transaction information). Due to the large volume of transaction information, the data body usually occupies a much larger volume than the data header, but the data header is more frequently accessed. The data header contains the version number of the Blockchain platform, the rules, the address of the previous block (also called "hash of parent block"), the hash value of the current block, a random number, which is used for the process of consensus, the time-stamp and the Merkle root [42].

The Merkle tree structure is utilized to store all the transaction data in the block. For instance, there are four transactions (Ta, Tb, Tc and Td). Ta contains the information regarding the financing enterprise, such as its electronic business license, business status, business scope, administrative permit, etc. Tb contains credit audit records, such as credit amount, enterprise endorsement, credit approval. Tc contains debt settlement records, such as debt confirmation, debt transfer, etc. Td contains repayment method information, such as principal first, interest first, etc. The hash function can transform a binary value of a string into a fixed-length binary value through hash calculation, and this fixed-length binary value is called hash value. In this solution, we use the digest algorithm SM3 [31] for hash calculation. The hash value of these allows CNs to easily access the platform and focus the Merkle tree, and a 32-bytes hash value is generated based on these leaf nodes as the root of the Merkle tree and stored in the data header.

Asymmetric encryption is mainly used in the scenarios of message encryption, digital signature and login authentication. When the supplier sends transaction information to the core enterprise, firstly, the core enterprise uses a specific algorithm (e.g., SM2) to generate the public key and private key, while the public key is published to the public and the private key is kept strictly by itself. After the supplier gets the public key of the core enterprise, it encrypts any message it sends, and transmits the ciphertext encrypted by the public key to the core enterprise through the Internet. The core enterprise receives the message and decrypts the ciphertext with its own private key to get the specific information that the supplier wants to send. The digital signature is essential to ensure the security of network communication [43–45]. The digital signature can ensure the integrity and authenticity of information transmission on the Blockchain, and prevent forgery of transactions. In BC4Regu, the financing enterprise generates the public and private keys with specific algorithms (i.e., SM3), then, encrypts this digest file with its own private key to generate the digital signature of the plaintext. Then, the digital signature and the plaintext are packaged together and sent to the core enterprise, which uses the hash function to calculate the digest of the plaintext received, and then decrypts the additional digital signature of the plaintext with the public key published by the financing enterprise to generate the digest, and compares these two digests to confirm the authenticity of digital signature by the financing enterprise.

BC4Regu implements the P2P (peer-to-peer) network communication, message mechanism and verification mechanism. The communication security between nodes is ensured by the Transport Layer Security protocol (TLS), which can guarantee the security of information transmission at the transport layer. In the P2P network topology for the consortium network, these parties, such as BC4Regu, core enterprises and financial institutions, are defined as full nodes, which keep the integrated DL in the Blockchain network. Technically, the financing enterprises are not so important as the core enterprises or financial institutions for the management of the Blockchain network, so they are defined as light nodes, which are only required to keep essential information of the DL.

With the consideration of reliability, performance and security in the context of SCF (the total number of nodes is small and the network scale

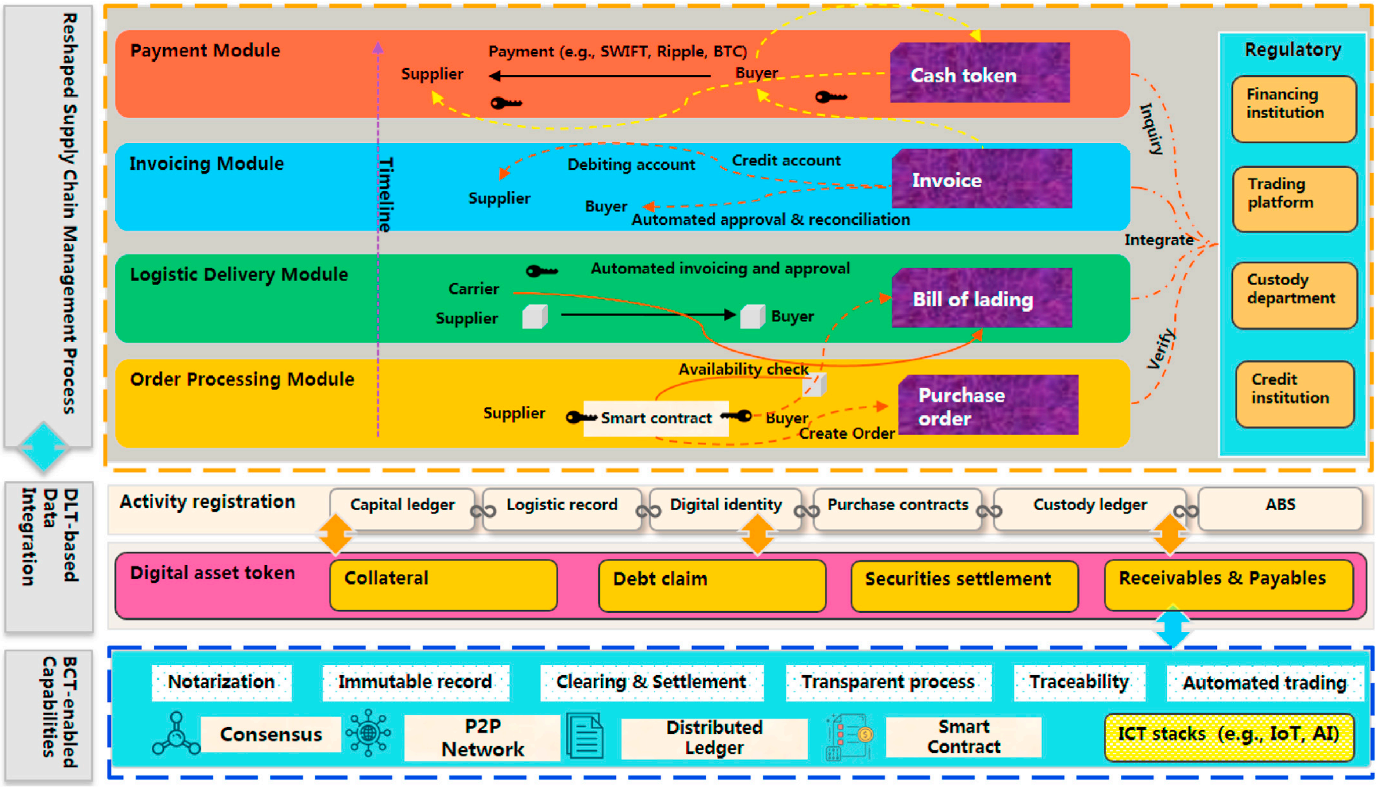

Fig. 2. The technical architecture of BC4Regu.

is limited), we utilize the PBFT [32] as a consensus algorithm. Different types of nodes may undertake different tasks on the Blockchain network. In this solution, the nodes are grouped to Validate Nodes (VN), Non-Validate Nodes (NVN) and Common Nodes (CN) according to its functional definition. VN involves in the consensus process in the Blockchain network, and it is eligible for voting rights. NVN does not involve in the consensus process in the Blockchain network, and it relies on VNs to ensure the final consistency in the Blockchain network. The NVNs are still involved in the process of ledger bookkeeping. Such a design allows CNs to easily access the platform and focus on the workflow of SCF business without the extra workload.

3.4. DLT-based dataflow integration

In this solution, as illustrated in Fig. 3, the DLT-based dataflow integration of purchase order, capital flow, logistic flow and document record is built. The purchase order, containing records associated with shipping, billing data from the buyer, and partnership in a transaction, is a commitment (to the supplier) to purchase specific goods with specified terms. In the delivery phase, the transfer order and related delivery receipts for the warehouse management will be created. Once the shipment is launched, a post would be generated by the supplier, and the sales order would be updated with the detailed information for delivery. After the goods are delivered to the buyer, a correspondent good receipt document will be created by matching the delivery document with its associated purchase order. Besides, the bill of lading issued by the carrier along with the delivered goods will be used as proof of shipment for Incoterms obligations. In the capital flow, the payment method and bank account information will be recorded.

In BC4Regu, data is equivalently stored among peers in the consortium network, and no single peer could tamper with them. A history of a set of immutable could create a possession chain, which provides a clear indication of provenance and allows the tracking of traded goods. Moreover, this mechanism could eliminate the need for data enrichment, reconciliations and disputes amongst counterparties. For each participant in the transaction, it is capable of intentionally revealing trusted data to another counterparty before formally executing the trade time. In this way, relevant parties could possess more certainty and thus reduce credit

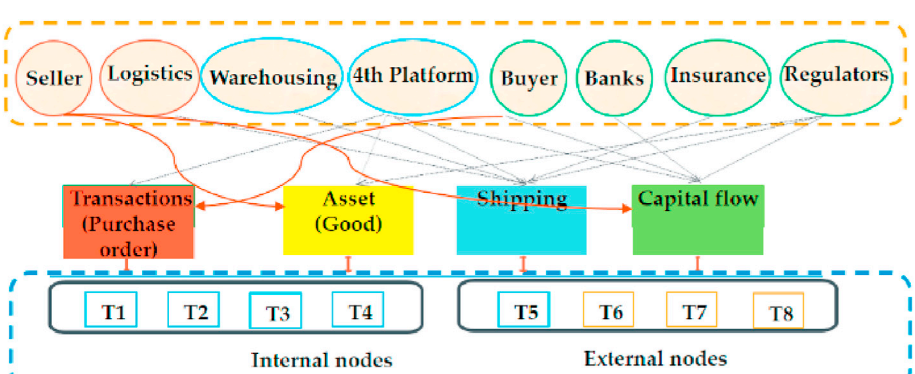

Fig. 3. The schematic diagram of the DLT-based data integration service.

risks.

BC4Regu builds a fully integrated and automated trade platform, via which goods and their correspondent records are definitely identified and transparently tracked among the supply chain ecosystems. Moreover, the combination of Blockchain and IoT makes it possible to track the supply chain operation in the real world and dynamically monitor the risk exposures at each phase in the shipping process. Tracking the product along the shipping process is already feasible by using IoT devices to collect relevant data (e.g., humidity, temperature, location, etc.) to the interested parties in a trade transaction in the background. BC4Regu could provide availability and transparency to interested parties in SCF and generate authoritative records as the basement of further smart contracts-based automation (e.g., the generation invoice, billing, etc.).

3.5. Supply chain management process

As illustrated in Fig. 2, the principal supply chain management processes (including the purchase, delivery, invoicing and payment, etc.) are reshaped in BC4Regu. At the start of the supply chain processes, a buyer initiates a purchase to the supplier, which will then trigger the sales processing from the seller's side. The purchase orders will be tracked by the digital identifier while they are on the BC4Regu.

Once the delivery receipts were registered on BC4Regu, the data of the purchase order, bill of lading and invoice would be matched by smart contracts, which could enable the consistency of specifications of goods among these documents and allow an automated and reliable invoice approval. The historical records of these trades provide perfect audibility for the regulator.

The event that an order becomes due for delivery will trigger the shipping process. In such a process, BC4Regu will initiate a transfer order and create its correspondent delivery document. The sales order will be updated with status information accordingly. Once the goods arrived on the buyer's side, BC4Regu will inspect the delivery document along with the correspondent purchase order and thus generate a good receipt. The traditional paper flow is a critical process involving manual operations that are subject to human error, or even theft and fraud. BC4Regu replicates such a standard supply chain workflow, and upgrade the paper flow to the version that is stored electronically in the Blockchain network. So that BC4Regu is capable of keeping track of the material flow at each step, as well as the corresponding paper flow. Moreover, BC4Regu provides a convenient interface of custody for a specific good/product along with the supply chain ecosystem, with which related information is accessible for interested parties to verify the authenticity of the good/product tracked along the supply chain, and provide assurance against counterfeits.

The tokenization of invoices by BC4Regu aims to address the issues of double financing and fraud. BC4Regu can register the invoice-related information on the DL. The information of each invoice would be saved in the Blockchain network, time-stamped and hashed to create a unique identifier. Once the same invoice was attempted to be sold twice in the supply chain network, the previous financing transactions would be presented to all interested parties while verifying invoice; therefore, the issue of double financing could be easily addressed. After an invoice is tokenized in BC4Regu, the investor who finances the invoice could ensure that it is not previously sold, therefore reducing credit risks. It should be emphasized that forming a tokenized invoice requires the active engagement (i.e., complete the digital signature on the invoice) of the counterparts by BC4Regu.

4. Reshaping the business workflow of SCF

4.1. Compliance obligations

The People's Bank of China has established a set of Anti-Money-Laundry (AML) policies for financial institutions, which includes 1) customer identification data and transaction, 2) suspicious transaction reporting and 3) large-amount transaction reporting. By the AML legal system, the Know-Your-Customer (KYC) is a legal obligation that financial institutions and their staff must strictly follow. A well-design KYC mechanism could simplify the workflow of SCF business and be particularly beneficial for those transactions involving multiple banks if we could avoid the duplicative effort of the checks. BCT is a promising technology for this application context, and it is capable of creating shared and trusted KYC ledger, with which the banks participating in SCF business could speed up the KYC compliance, thus offering better financing rates to financing enterprises. In a consortium network, it allows other financial institutions to access trusted information sources regarding the new customers (such as IDs, occupations, family members, etc.).

As illustrated in Fig. 4, with BC4regu, we reshape the workflow of KYC compliance to avoid duplicative execution of KYC process by sharing existing check records and broadcasting them in a consortium network so that other financial institutions would no longer perform the same process since adequate records have existed. Historical check records will be used as proof that the bank that completes the KYC has done it yet. the core process of KYC authentication includes: 1) Initial submission: when a user submits KYC authentication information to a financial institution for the first time, the financial institution is responsible for authentication and writes the KYC information to the DL after it has been signed by the institution. 2) KYC information reading and updating: when the user's authentication information needs to be updated, it is authenticated again by the financial institution and then updated in the DL to ensure the timely reliability of the information. 3) KYC information anti-counterfeiting: when the customer information is found forged, incorrect or with illegal contents, the institution can identify and highlight the customers and transactions, and further corrector shut down the related transactions to control risks and conduct compliance if necessary. BC4regu ensures the traceability and verifiability of KYC information from collection to each update. The financial transactions initiated by financial institutions are required to be synchronized to the DL so that the regulator(s) can supervise the transaction in progress or afterwards. Any financial institution that joins the network can get consistent information from any other financial institutions and regulators on the consortium network as long as the authenticated KYC information is stored in the Blockchain. The encrypted records could be updated in a real-time manner so that all financial institutions engaged with a particular transaction are updated instantly. With the completion of registration, no single participant could tamper with the records in the shared ledger, which provides a trusted KYC ledger, and interested parties can access to information in the ledger. This instrument could significantly speed up the process of KYC and finally reduce the compliance costs.

4.2. Simplified financing models

The accounts receivable financing is a typical scenario applicable for BCT. By generating a set of tamper-evident digital credentials of accounts payable of core enterprises and trade counterparties, which are issued in accordance with certain rules among nodes in the consortium. In the initial stage (data uploading), financial institutions and commercial banks sign a cooperation agreement, and the data of key points such as business flow, contract flow, logistics and capital flow retrieved from the ERP system from core enterprises are directly uploaded to the consortium Blockchain [46]. Financial institutions will open credit of a certain amount according to the asset of core enterprises. In the stage of supplier recommendation, core enterprises upload the data of tier-one suppliers who may have accounts receivable. The financial institutions will audit the compliance of the suppliers recommended by core enterprises. For the tier-one suppliers who are approved by the financial institutions, they can recommend their upstream tier-two suppliers to the financial institutions, and so on. In the stage of financing application, with the core enterprise's confirmation, the tier-one suppliers who have formed

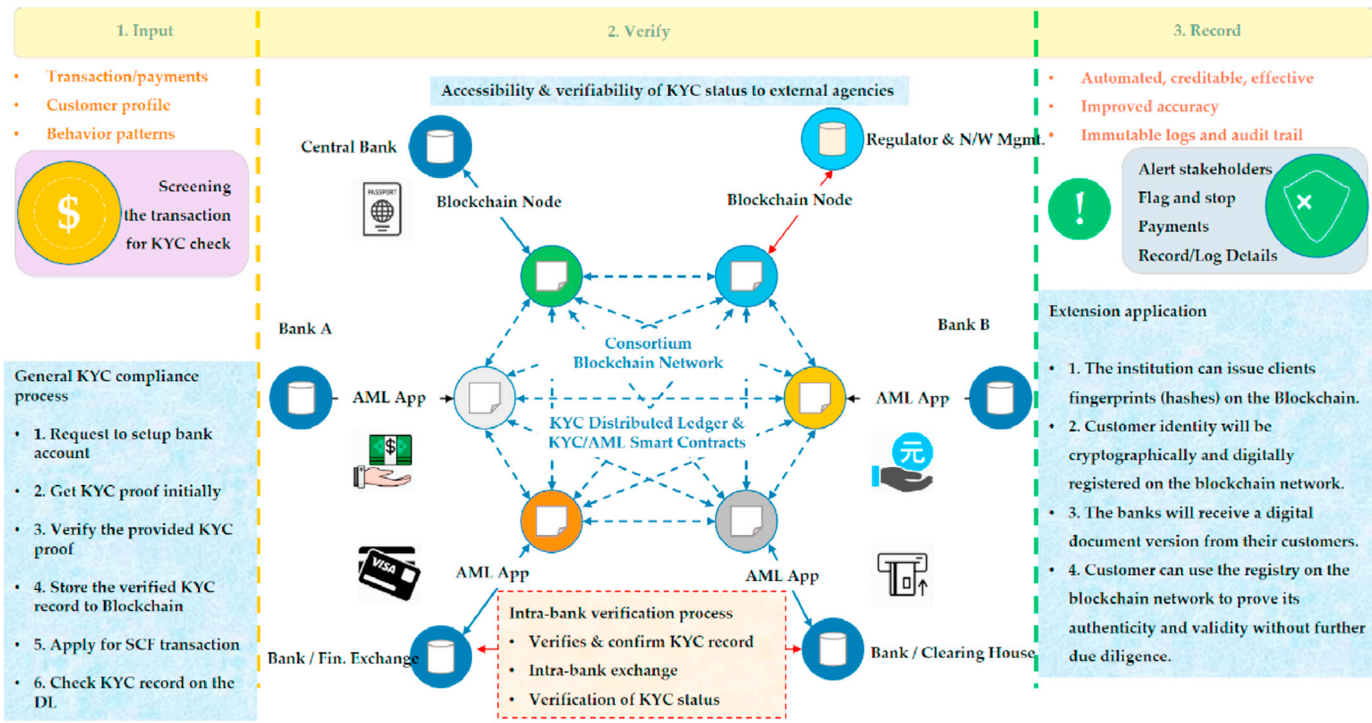

Fig. 4. The KYC workflow powered by BC4regu

accounts receivable can apply for financing from the financial institutions, or split the confirmed accounts receivable to the tier-two suppliers. The financial institution confirms with the core enterprise's acknowledgement, and requests the copies of invoices, statements and other relevant documents from the supplier. Then, it further confirms that the core enterprise's account for payment is a special supervisory account that has been opened and signs a contract, then it can start to release the funds. In the stage of debit due, when the loan expires, the core enterprise will directly repay the funds to the financial institution. In case of overdue, the fund provider would initiate a loan call until the amount is fully repaid.

In the solution shown in Fig. 5, the information of upstream/downstream enterprises, business relationships, trade contracts and debt information in the supply chain can be made public and transparent to

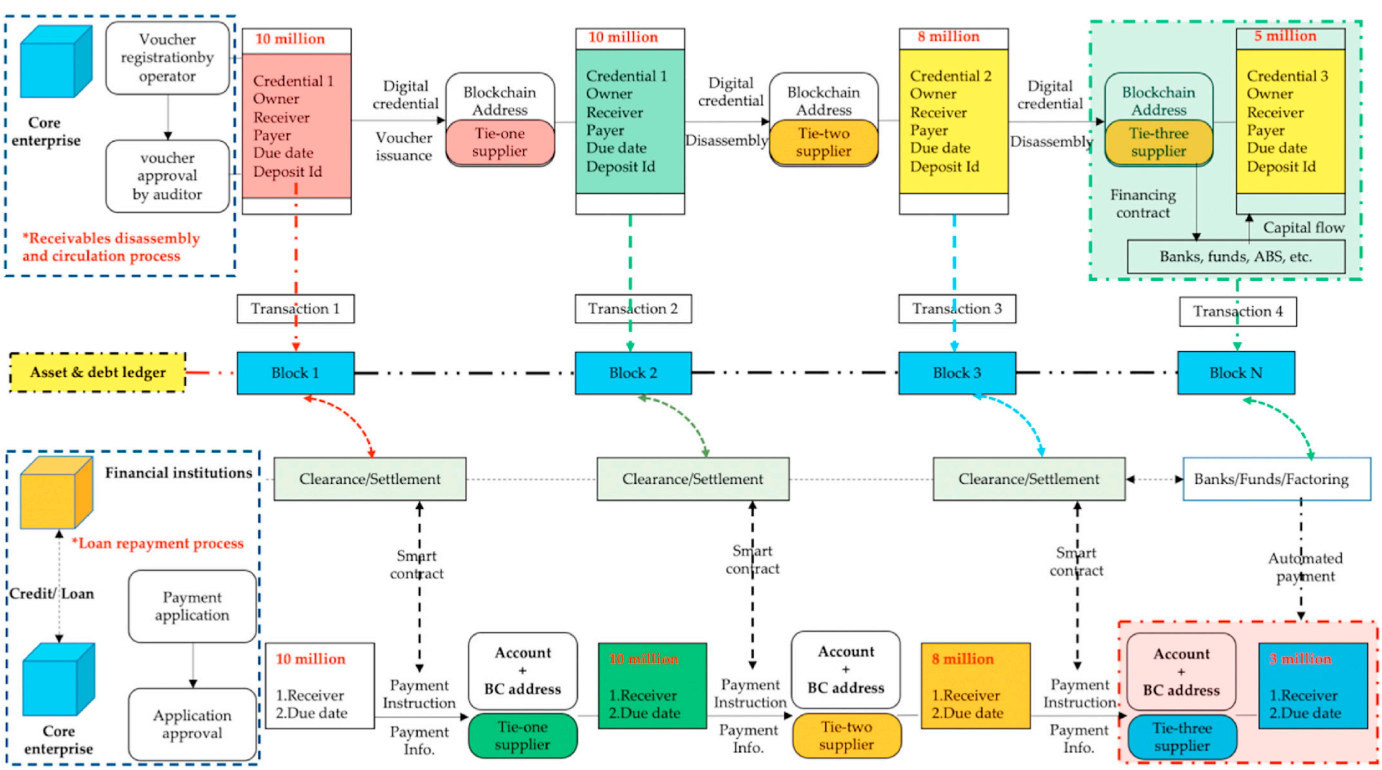

Fig. 5. The diagram of (core enterprise's) credit disassembly and circulation workflow.

alleviate mutual distrust in the financing transactions of SMEs., all the participants in the consortium can check the integrated information and transaction records of the financing enterprise. Under the information symmetry context, the tier-one suppliers/distributors can transfer debts within the valid amount and share debts with the next-tier suppliers/distributors to complete the transfer of the debt-creditor relationship. Financial institutions (e.g., banks, trusts, factoring companies, etc.) can accurately evaluate the debt risk of core enterprises, suppliers/distributors based on the debt-creditor information exposed in the platform, and provide personalized credit services for them. The process of splitting and transferring debts and claims is recorded on the distributed ledger. In case of disputes, the transaction process can be quickly retraced by checking the distributed ledger records, and the determination of liability will be clearly achieved.

5. Theoretical analysis

In this chapter, we analyzed the incentive mechanism by introducing the principal-agent model, which provides a theoretical basis for the application of the BCT in the SCF.

5.1. Problem description

The principal-agent problem arises from information asymmetry, in which the information-advantaged party is defined as “agent”, whereas the information-disadvantaged party is defined as “principal” [29]. The SCF transaction involves many parties, and there may be information asymmetry between each party, which also constitutes a principal-agent problem in different directions. In the accounts receivable model, the Blockchain information service platform is the principal and the core enterprise are the agent. In the inventory financing model, the manufacturer who gets the loan is the agent and the Blockchain information service platform is the principal. In the prepayment financing model, the purchase and sales contract may be falsified as well as the bills receivable [30]. Therefore, in this situation, the Blockchain information service platform is the principal and the core enterprise is the agent. Although the three kinds of supply chain financing modes differ in the operation process, they all essentially apply BCT to build incentive mechanism to solve the principal-agent problem in SCF. In the following, we take accounts receivable financing as an example to analyze the incentive mechanism with the adoption of BCT.

5.2. Assumption

5.2.1. Assumptions for the agent

- The effort level of the agent is represented by e, which includes various meanings, such as the effort of SMEs targeting cost reduction, the effort level of SMEs used to expand sales, etc.
- The effort cost function of the agent is represented by $c(e) = (f \cdot e^2)/2$, where $f > 0$ is the effort cost coefficient.
- The operating capacity of the agent is a, $a \in \left[\underline{a}, \bar{a}\right]$. Before the incentive contract provided by the Blockchain information platform is signed, *a* is unknown under adverse selection.
- The sales of the agent company are $q = ae + m + \varepsilon, \varepsilon \sim N(0, \sigma^2)$, σ^2 is the variance of ε, and *m* indicates the size of the technical maturity of the principal.
- For simplicity, we assume a linear relationship about the sales profit as $\pi = nq - (f \cdot e^2)/2, n > 0$ and *n* is the sales profit coefficient of the agent company.
- The agent firm is risk averse and the absolute risk aversion coefficient ρ is constant. The agent firm's return includes its own return and the incentive return given by the principal. The utility function of the agent firm's return is $U = -e^{-\rho(\pi + \pi_{extra})}$.

5.2.2. The assumption for principal

- The principal provides an incentive contract for the agent to increase the sales capacity, effort and sales revenue of agent by $\pi_{extra} = a \cdot q \cdot g(a)$. Where g(a) denotes the incentive provided by the principal for the unit sales of the agent according to its sales capacity, $g(a) > 0$, $g'(a) > 0$.
- The unit sales revenue earned by the principal at the agent is i. Therefore, the principal's net profit at the agent is $\pi_{client} = a \cdot q \cdot i - a \cdot q \cdot g(a) = a \cdot q \cdot [i - g(a)]$.
- The principal is risk neutral and aims to maximize its expected return.

5.3. Incentives in a symmetric information environment

In a symmetric information, the information can be fully shared among the parties in the SFC, at which the Blockchain system makes the whole chain realize full information transparency. For the core enterprise (agent), the upstream and downstream SMEs suppliers and the Blockchain information platform (principal), symmetric information means that the agency's work level and operational capacities are no longer private, but symmetric shared information. The parties in the symmetric information cannot gain extra benefit by hiding information, and each party aims at maximizing its own profit and eventually achieving the global optimum.

5.3.1. Model construction

According to the above assumptions, the expected return of the principal is $E\pi_{client} = E\{a \cdot q \cdot [i - g(a)]\}$, substituting $q = ae + m + \varepsilon$. $E\varepsilon = 0$, the expected return of the principal is

$$E\pi_{client} = E\{a \cdot (ae + m) \cdot [i - g(a)]\} \tag{1}$$

Similarly, the expected return by the agent is

$$E\pi_{agent} = E(\pi + \pi_{extra}) = [n + a \cdot g(a)] \cdot (a \cdot \varepsilon + m) - \frac{fe^2}{2} - \frac{\rho}{2}[n + a \cdot g(a)]^2 \sigma^2 \tag{2}$$

Under the assumption of maximizing its own profit, the agent will choose the optimal effort level e. In terms of the existence of the optimal effort level, the first-order partial derivative of $E\pi_{agent}$ with respect to e is positive and the second-order partial derivative is negative, indicating the existence of the maximum of the effort level. Then, from the uniqueness of the most effort level, let $\frac{\partial \pi_{agent}}{\partial e} = 0$ and obtain the first-order optimality condition for the effort level e as $e^* = \frac{a \cdot [n + a \cdot g(a)]}{f}$.

Accordingly, the optimized behavior in a Blockchain financing information platform can be represented as the following optimization problem with constraints.

$$\begin{aligned} & max\ E\pi_{client} = a \cdot (ae + m) \cdot [i - g(a)] \\ & s.t.\ E\pi_{agent} = [n + a \cdot g(a)] \cdot (a \cdot e + m) \\ & -\frac{fe^2}{2} - \frac{\rho}{2}[n + a \cdot g(a)]^2 \sigma^2 \geq 0 \end{aligned} \tag{3}$$

5.3.2. Model solving and analysis

According to the model, it can be seen that due to the existence of incentive subsidies, there is a contradiction between the expected returns of the principal and the agent. Based on the constraint of profit maximization of the principal, the expected return of the agent is equal to 0.

At this point, the above-obtained agent side SME's optimal level of effort is substituted into this equation to obtain the amount of sales incentive subsidy per unit of the agent-side firm in equilibrium as

$$g(a)^* = \frac{1}{a}\left[\frac{2m \cdot f}{f \cdot \rho \cdot \sigma^2 - a^2} - n\right] \tag{4}$$

Substituting the derived unit incentive results into the agent's optimal level of effort, we get

$$e^* = \frac{2m \cdot a}{f \cdot \rho \cdot \sigma^2 - a^2} \tag{5}$$

Substituting the unit incentive allowance amount and the optimal effort level into the principal's expected return formula, the principal's return at this point is

$$E\pi^*_{client} = \left[\frac{2m \cdot a^2}{f \cdot \sigma \cdot \sigma^2} + m\right] \cdot \left[g(a) \cdot a - \frac{2m \cdot f}{f \cdot \rho \cdot \sigma^2} + n\right]$$
$$g(a) > 0, g(a)^* > 0 \tag{6}$$

From the expressions of $g(a)^*$, e^* and $E\pi^*_{client}$ after the model solution results, it can be seen that the equilibrium unit incentive subsidy depends on m, a, f, ρ and uncertainty, and is positively influenced by m and a, and negatively influenced by f, ρ and uncertainty. Similarly, the magnitude of the optimal effort level of the agent SME is positively influenced by a and m, and negatively influenced by f, ρ, and uncertainty. It can also be seen that the principal's expected return in equilibrium is positively related to the BCT maturity *m*, the SME sales margin, and the net profit the principal receives at the SME.

5.4. Incentives under asymmetric information

An asymmetric information situation means that the information cannot be fully shared between the Blockchain information platform and the agent enterprise. In the early stage of not signing the contract, the Blockchain information platform cannot be informed of the operating capability level of the agent enterprises, and there exists adverse selection; after signing the cooperation contract, the principal cannot know the effort level of the agent SMEs, and there exists moral risk. As there is still information asymmetry, the principal and the agent will change their strategies in the game to maximize their own interests.

5.4.1. Model construction

It follows from the above that the principal's expected return to be $E\pi_{client}$ and the agent's expected return to be $E\pi_{agent}$. The agent SME chooses the optimal level of effort e^* to maximize its own profit, $\forall a \in \left[\underline{a}, \overline{a}\right]$, $e^* \in \text{argMax}E\pi_{agent}$. By solving the first-order linear condition, we get

$$e^* = (a \cdot [n + a \cdot g(a)])/f \tag{7}$$

Substituting e^* into $E\pi_{agent}$,we obtain

$$E\pi_{agent} = m \cdot [n + a \cdot g(a)] + \frac{a^2 \cdot [n + a \cdot g(a)]^2}{2f} - \frac{[n + a \cdot g(a)]^2 \sigma^2}{2} \tag{8}$$

For $\forall(a, \tilde{a}) \in \left[\underline{a}, \overline{a}\right]$, we get

$$E\pi_{agent} = m \cdot [n + a \cdot g(a)] + \frac{a^2 \cdot [n + a \cdot g(a)]^2}{2f} - \frac{\rho[n + a \cdot g(a)]\sigma^2}{2}$$
$$\geq m \cdot [n + a \cdot g(\tilde{a})] + \frac{a^2 \cdot [n + a \cdot g(\tilde{a})]^2}{2f} - \frac{\rho[n + a \cdot g(\tilde{a})]^2 \sigma}{2} \tag{9}$$

Therefore, the relationship between $\tilde{a}$ and a can be obtained as

$$a \cdot g(\tilde{a})\left\{\left(a^2/f - \rho \cdot \sigma^2\right) \cdot [n + a \cdot g(\tilde{a})] + m\right\} = 0 \tag{10}$$

For $\forall a \in \left[\underline{a}, \overline{a}\right]$,we get

$$a \cdot g(a)'\left\{\left(a^2/f - \rho \cdot \sigma^2\right)[n + a \cdot g(a)] + m\right\} = 0 \tag{11}$$

Thus, the principal offers incentives based on the purpose of maximizing expected returns as

$$maxE\pi_{client} = \int_a^a a \cdot (ae + m) \cdot [i - g(a)] \cdot f(a) da$$
$$s.t.\ e = \frac{a \cdot [n + a \cdot g(a)]}{f}$$
$$a \cdot g(a)\left\{\left(a^2/f - \rho \cdot \sigma^2\right) \cdot [n + a \cdot g(a)] + m\right\} = 0$$
$$E\pi_{agent} = m \cdot [n + a \cdot g(a)] + \frac{a^2 - [n + a \cdot g(a)]^2}{2f} - \frac{\rho[n + a \cdot g(a)]^2 \sigma^2}{2} \geq 0$$
$$g(a)' \geq 0 \tag{12}$$

The constraints come from the incentive compatibility mechanism under adverse selection and moral hazard of the agent SMEs and its individual rationality constraints.

5.4.2. Model solving and analysis

We analyzed the model for the two cases of $g(a)' = 0$ and $g(a)' \geq 0$, respectively.

Let $g(a)' = 0$, and $E\pi_{agent} \geq 0$, we get

$$m - \frac{1}{2}\left(\rho \cdot \sigma^2 - \frac{a^2}{f}\right)[n + a \cdot g(a)] \geq 0 \tag{13}$$

By solving the first order condition of $E\pi_{agent}$, we get

$$\frac{\partial E\pi_{agent}}{\partial a} = \frac{a}{f}[n + a \cdot g(a)]^2 + g(a)\left\{\left(\frac{a^2}{f} - \rho \cdot \sigma^2\right) \cdot [n + a \cdot g(a)] + m\right\} \geq 0 \tag{14}$$

This result indicates that the greater the operational capacity of SMEs, the greater the total expected return they can obtain.

When $g(a)' = 0$, $g(a)^{sb}_{si} = b$, b is a constant, SB (Second Best) refers to the suboptimal result when asymmetric information is available, and SI (Same Incentive) refers to the same incentive subsidy for SMEs with different operating capacities. Since SMEs with different operating capabilities can receive the same incentive subsidy, the principal cannot accurately identify the operating capabilities of SMEs and thus cannot achieve the optimal incentive.

When $g(a)' > 0$, our model is transformed into a dynamic programming problem.

$$maxE\pi_{client} = \int_a \hat{a}\, a \cdot (ae + m) \cdot [i - g(a)] \cdot f(a) da s.t.\ e = \frac{a \cdot [n + a \cdot g(a)]}{f} E\pi_{agent}$$
$$= m \cdot [n + a \cdot g(a)] + \frac{a^2 \cdot [n + a \cdot g(a)]^2}{2f}$$
$$- \frac{\rho[n + a \cdot g(a)]^2 \sigma^2}{2} \geq 0 \left(\frac{a^2}{f} - \rho \cdot \sigma^2\right) \cdot [n + a \cdot g(a)] + m = 0 \tag{15}$$

$\frac{a^2}{f} - \rho \cdot \sigma^2 < 0$, while $a < \sigma \cdot \sqrt{f \cdot \rho}$, we get

$$g(a) = \frac{m \cdot f}{a - (f \cdot \rho \cdot \sigma^2 - a^2)} - \frac{n}{a}$$
$$g(a)' = \frac{3m \cdot f \cdot a^2 - f^2 \cdot m \cdot \rho \cdot \sigma^2}{a^2 \cdot (f \cdot \rho - \sigma^2)^2} + \frac{n}{a^2} \tag{16}$$

By solving the first-order condition on a for $E\pi_{agent}$ and substituting $g(a)$ and $g(a)'$, we get

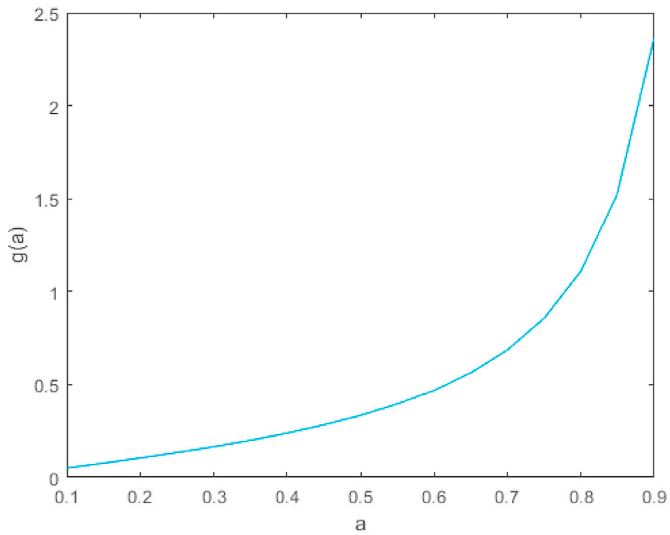

Fig. 6. The correlation between incentive and sales ability under differential incentive.

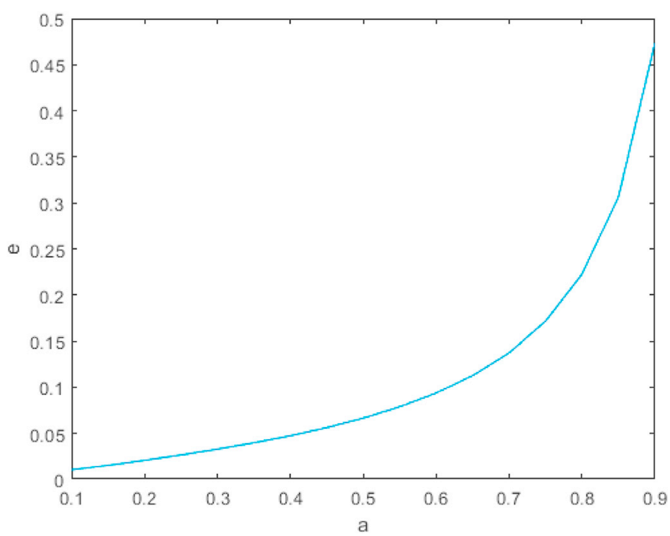

Fig. 7. The correlation between effort level and sales ability under differential incentives.

$$\frac{\partial E\pi_{agent}}{\partial a} = \frac{a}{f}[n + a\cdot g(a)]^2 + [g(a) + a\cdot g(a)']\left\{\left(\frac{a^2}{f} - \rho\cdot\sigma^2\right)\cdot[n + a\cdot g(a)] + m\right\} = \frac{m^2\cdot f^2\cdot a^2}{(f\cdot\rho\cdot\sigma^2 - a^2)^2\cdot f^2} \geq 0 \tag{17}$$

In this case, we can see that the expected return of the SME increases with the increase of the SME's own operating capacity as well. The principal incentive subsidy at this point is expressed as

$$g(a)^{sb}_{di} = \frac{m - f}{a\cdot(f\cdot\rho - \sigma^2 - a^2)} - \frac{n}{a} \tag{18}$$

The SB denotes the suboptimal choice under the asymmetric information environment, and DI (Differential Incentive) denotes the incentive subsidy given by the principal according to the different operating capabilities of SMEs. From the expression of $g(a)^{sb}_{di}$, we can see that the differential incentive subsidy under asymmetric information decreases with the increase of SME sales margin and SME effort level, and increases with the increase of BCT maturity *m*. Moreover, the effort level of SMEs

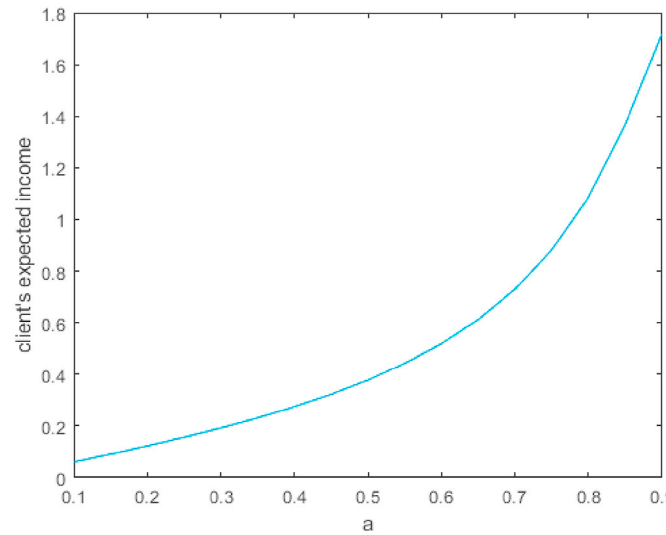

Fig. 8. The correlation between client's income and sales ability under differential incentives.

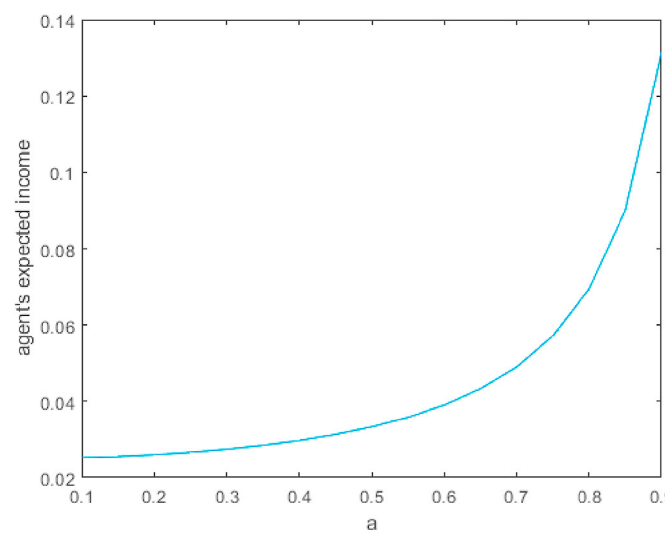

Fig. 9. The correlation between agent's income and sales ability under differential incentives.

increases with the increase of operating capacity in both cases of equal and differential incentives.

5.4.3. Simulation

We use MATLAB to simulate the incentive models under the symmetric and asymmetric information environments. We denote the operating capability of SME as a, and since a varies considerably depending on the field, size of SMEs, we analyze the impact on the relevant parameters by varying the value of *a* in order to support the above-mentioned conclusions. We set the maturity level of the BCT $m = 0.1$, $n = 0.5$, the effort cost factor $f = 5$, the principal's benefit from the agent $i = 6$, $\rho = 0.8$, and $\sigma^2 = 0.25$. Since the principal cannot efficiently identify SMEs with high operating capacity under the same incentive subsidy, we focus on how the subsidy amount g(a), the agent's effort level e, and the corresponding simulations were conducted to illustrate how the expected return was affected by the operating capability of the SME.

As shown in Fig. 6, the relationship between unit incentives and SME operating capability under the differential incentive subsidy mechanism is consistent with the results derived from the theoretical model. The differential incentives provided by the principal according to the operating capability of the SME are positively correlated with the operating capacity of the SME, and the incentives the agent receives from the principal increase when the operating capability of the SME improves.

As shown in Fig. 7, when the principal provides differential incentives, the improvement of the agent's own operating capability also leads to the improvement of the subjective effort level, which proves that the differential incentives promote and facilitate the upstream and downstream SMEs in the supply chain. At the same time, SMEs with stronger operating capability can effectively take advantage of information sharing under the engagement of BCT and proactively seek greater development.

As shown in Figs. 8 and 9, it can be seen that the expected revenue of both sides of the game increases with the increase of the agent's operating capacity. The introduction of the BCT in the supply chain financing business can effectively promote SMEs to improve their own operating capacity to obtain greater expected revenue. Meanwhile, the principal can benefit from the improvement of SMEs' operating capacity by providing BCT and incentive subsidies.

5.4.4. *Discussion*

Under the information symmetric environment, with the constraint of maximizing the expected returns of all parties, the incentive subsidy under the incentive-compatible mechanism is positively related to the maturity of BCT and the operational capability of SMEs, and negatively related to the effort level coefficient, absolute risk aversion coefficient and external uncertainty of SMEs. The optimal effort level of SMEs satisfying the incentive compatibility mechanism is positively related to their own operational capacity and the maturity of BCT, and negatively related to the effort level coefficient, absolute risk aversion coefficient and external uncertainty. The expected revenue of BC4Regu satisfying the incentive compatibility mechanism is positively related to the maturity of BCT, the profitability of the agent and the net profit received by the principal.

The differential incentive subsidy with asymmetric information is more effective than the equal incentive subsidy in differentiating SMEs with different operational capabilities and providing different incentives for SMEs. The amount of subsidy under equal incentive subsidy and the effort level of SMEs are both positively related to the operational ability of SMEs, but they cannot provide different incentives for SMEs with different operating abilities. The subsidy amount under differential incentive subsidy decreases with the increase of effort level and profitability, and increases with the increase of BCT maturity, and the SME effort level at the differential incentive scenario is also positively correlated with the SMEs operational capacity.

6. Conclusion

Technology plays a critically important role when encouraging SCF adoption for SMEs in China. In this paper, we propose a technical framework for the information management of SCF - BC4Regu, in which, BCT is facilitated for strengthening the information transparency and reshaping the business process in the SCF. Underlying technologies enabling several such features are introduced in detail. Moreover, the effectiveness and feasibility of BC4Regu are illustrated by use cases and supported by theoretical analysis. However, in this paper, the legal issues (e.g., the legal validity of the proof of ownership of asset tokens, smart contracts itself) that hinder the wide adoption of BCT in the SCF have not been explored. In the future, we will continue to consider the requirements of the financial and jurisdictional fields, with which SCF business driven by BCT could be further verified and highlight the opportunities by BCT.

Declaration of competing interest

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

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