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BLOCKCHAIN-BASED COLLABORATIVE MANAGEMENT OF JOB SHOP SUPPLY CHAIN

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Abstract
Blockchain supports free and reliable transactions of the production material supply chain (PMSC). However, few scholars have combined the blockchain with supply chain management. Based on blockchain, this paper explores the collaborative management of material supply chain for production and manufacturing job-shops (PMJs). Specifically, a collaborative management model was constructed, and the execution of the smart contract between PMJ and production material supplier (PMS) was explained. Then, the Stackelberg game between PMJ and PMS in the model was analysed, and the calculation method of the total benefit of PMS and PMJ was derived, under the information sharing mode of the blockchain-based PMSC model. Through trust evaluation, the dishonest companies were identified in the PMSC. To ensure the safe and reliable data sharing between the companies in our model, the probability for the dishonest companies to participate in smart contract was reduced, making it less likely for false shared data to appear in the chain. The effectiveness of the proposed blockchain-based model for the collaborative management of PMSC was proved through simulations.
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Key Words: Blockchain, Production Materials, Supply Chain, Collaborative Management

1. INTRODUCTION

Supply chain management in an important part of the management of production and manufacturing companies [1-6]. The cost of production materials accounts for more than half of the standard cost for most products generated in production and manufacturing job-shops (PMJs) [7-12]. Therefore, the competition between production and manufacturing companies is essentially the contest between production material supply chains (PMSCs). The quality of PMSC management directly bears on the quality, cost, and completion time of the products of the PMJ, and even affects the selling profit of the products. Therefore, the optimization of PMSC management must be prioritized in company management.

The application of blockchain technology to supply chain management ensures that the upstream and downstream companies of the PMSC can carry out cooperative transactions freely and reliably, providing an effective solution to the thorny issue of tracing production materials on the supply chain [13-18]. Although blockchain technology can improve PMSC management in an all-round way, the direct application of the technology will suppress the consensus-making efficiency, and lower the fault tolerance [19-28]. Before introducing the blockchain to the PMSC, it is necessary to improve the smart contract and consensus mechanism, with the aim to optimize the effect of collaborative management.

To solve the problems in the supply chain production and distribution (P&D) system, Büyüközkan et al. [22] combined system analysis and system simulation into a realistic optimization scheme, and promoted the scheme to various companies. Focusing on supply chain management, the P&D system was optimized from the strategy, tactic, and operation aspects of supply chain management, through system analysis, system simulation, case analysis, and comparative research. Kleinknecht [23] recognized the dual role of intellectual capital, which is characterized by human capital, relationship capital, and structural capital, in

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improving the sustainable production of companies, and proposed to motivate sustainable production directly or indirectly through supply chain management driven by the blockchain. Gu et al. [24] put forward a new structure of the supply chain system, and illustrated the real-world production process with a labelled directed acyclic hypergraph. By labelling all the parts of multicomponent products, a timestamp was automatically added to protect the supply chain data.

The blockchain can formally supervise the entire supply chain without going from one place to another. Drawing on the Internet of Things (IoT), machine learning and blockchain technology, Kusi-Sarpong et al. [25] presented an evaluation system for the supply chain network production capacity, facilitating the acquisition of data in real time, and the automatic evaluation of company production capacity. The blockchain technology supports open and distributed data storage and sharing, and enables fair and automatic data transactions. In the light of the features of the blockchain system, Madhwal et al. [26] detailed the supply chain governance mechanism for agricultural products based on blockchain technology. Under the basic framework of blockchain, the functional framework was designed for the governance of agricultural supply chain. Furthermore, the trust mechanism and contract mechanism of the blockchain-based agricultural supply chain governance were analysed.

So far, blockchain management and performance have been fully analysed at home and abroad, providing theoretical support to the sharing of supply chain information. However, the existing studies on the blockchain mainly consider the application of the blockchain in finance, and rarely combine the blockchain with supply chain management. To fill the gap, this paper explores the collaborative management of material supply chain for PMJs based on blockchain. The main contents are as follows: Section 2 elaborates on the advantages of blockchain-based collaborative management mechanism of the PMSC, constructs a collaborative management model, and demonstrates the execution of the smart contract between PMJ and production material supplier (PMS). Section 3 analyses the Stackelberg game between PMJ and PMS in the model, explains the order of moves of the two parties, and derives the calculation method of the total benefit of PMS and PMJ, under the information sharing mode of the blockchain-based PMSC model. Section 4 identifies the dishonest companies in the blockchain-based PMSC model by trust evaluation, reduces the probability for the identified dishonest companies to participate in smart contract, making it less likely for false shared data to appear in the chain. In this way, the companies in the proposed blockchain-based PMSC model can share data safely and reliably.

2. BLOCKCHAIN-BASED COLLABORATIVE PMSC MANAGEMENT

For PMSC companies, the key to establish mutual trust is to develop a flat, efficient, and self-trusting supply chain information sharing model. With advantages of self-trust and collective maintainability, blockchain technology can adapt well to the trust construction between PMSC companies, and effectively improve the cooperation efficiency between each company and PMJ.

PMSC is a group of multiple stakeholders. If the stakeholders want to share information related to their own interests, the sharing process must be highly secure. Based on asymmetric encryption and smart contract, the blockchain can technically ensure the authenticity and reliability of the shared information, while limiting the information sharing authority of each company.

PMSC involves cross-regional and inter-departmental businesses. Thus, the PMSC information sharing model must be able to integrate all shared information efficiently into high quality information. By virtue of peer-to-peer transmission, smart contract, and consensus algorithm, the blockchain can create a distributed communication architecture based on each company, and realize the efficient integration and sharing of information in the chain.

In the PMSC, the companies both cooperate and compete with each other. The blockchain can provide an authentic, credible, timely, and complete environment for information sharing. In the environment, the shared information is effective and fully utilized, and the competition and benefit distribution mechanisms are reasonable and fair, making the PMSC more competitive.

In a blockchain-based PMJ production project, the PMSC companies responsible for supplying the project materials should provide the information of procurement, inventory, and distribution in a timely manner. The collected images and videos should be converted into digital signals for further analysis, using barcodes, sensors, radio frequency identification (RFID), and other technologies. In reality, the PMSC companies need to share private information related to their own interests, under the premise of mutual trust, to prevent their confidential information from being stolen by other companies. Concerning the establishment of mutual trust between PMSC companies, the PMJ production project can exchange digital information using the public and private keys of each company, in the context of the collaborative management of blockchain and supply chain. For the information safety of the PMSC, the data shared by the companies can be encrypted by asymmetric encryption algorithms, in order to ensure the safety and completeness of shared information.

The traditional PMSC management mode includes complex and diverse manual processing links. If these links cannot share information timely, it would be impossible to satisfy the demand for production materials, or complete the production project within the schedule. This paper adopts the smart contract technology of the blockchain to develop a more intelligent PMSC management process.

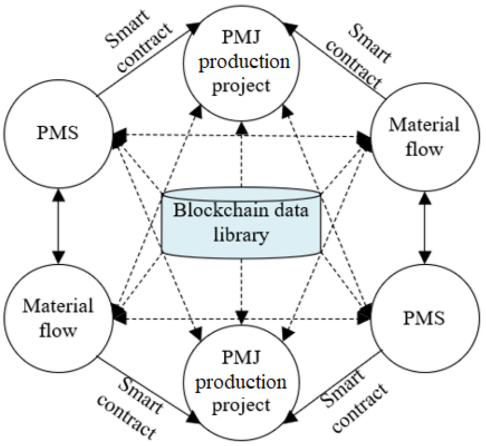


Figure 1: Structure of the blockchain-based model for the collaborative management of PMSC.

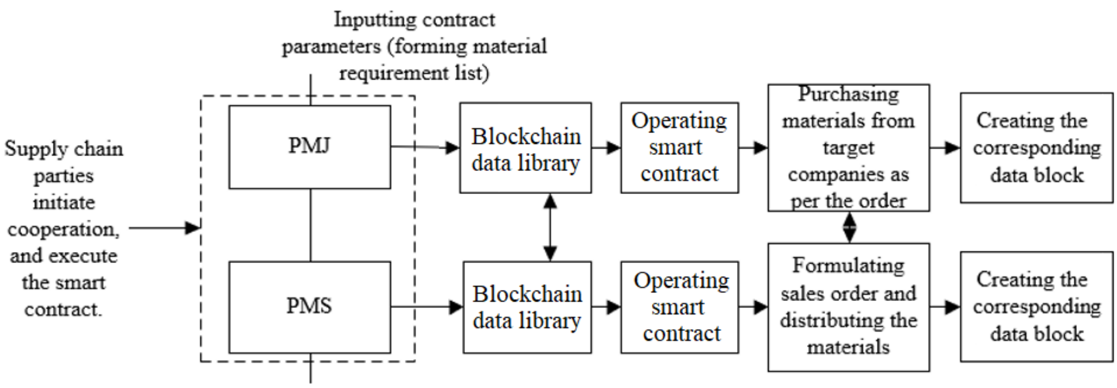


Figure 2: Execution process of smart contract.

Fig. 1 illustrates the structure of the blockchain-based model for the collaborative management of PMSC. The blockchain-based collaborative management of PMSC covers two phases: In the first phase, the PMS enters the blockchain, and configures the block smart contract. In the second phase, the contents of the smart contract are materialized, including pricing, and stock tacking.

The proposed PMSC model is a chain of the production links in a specific production project of PMJ, which are arranged in time order. Once a company generates a new smart contract, the contract contents of the previous block will be covered by the new block, i.e., each new block contains all the information of the previous block. As per its own needs, the PMS can expand the smart contract. For example, the PMS can set the condition for automatic integration of its material requirement information: the inventory of production materials falls short of the demand of the PMJ. The smart contract will be executed as soon as the contractual condition is satisfied. The execution process of smart contract is explained in Fig. 2.

3. GAME ANALYSIS

The nodes in the PMSC model can be divided into PMJ and PMS. The two parties are engaged in a Stackelberg game. The PMJ, as the leader, predicts the material demand according to the order quantity and production process, and determines the purchase time, as well as the type and quantity of the materials to purchase. The PMS, as the follower, designs the price and material supply strategy based on the PMJ's material demand information, with the goal to maximize its own benefit. Upon receiving the purchase information from PMJ, the PMS will offer a price for each type of materials. When the production is confirmed, the PMS will optimize the material price to maximize the company's expected price utility. Meanwhile, the PMJ will optimize the material purchase strategy to maximize the benefit of the production project. Based on the above assumptions, the order of moves between PMJ and PMS in the game is described in Fig. 3.

As shown in Fig. 3, the PMJ and the PMS move in the following order during the game:

(1) The PMS appears in the initial phase of production material procurement.

(2) The PMJ predicts material demand according to order quantity, and production process, obtains the PMS discount factor through a survey, generates the PMS pricing function based on historical data, and then analyses the historical material prices offered by the PMS.

(3) The PMJ publicly announces the purchase quantity and dynamic purchase strategy for production materials.

(4) Upon receiving the PMJ's purchase information, the PMS calculates the expected price utility of the company, and decides whether to offer a price for material supply to the PMJ.

(5) The PMS offers a price or leaves.

(6) The Stackelberg game between the two parties ends.

The PMJ predicts material demand according to order quantity, and production process, and then purchases a quantity E of production materials form the PMS. Then, the PMS determines the price P_1 per unit of materials, according to the quantity of purchased materials. The production cost of the PMS per unit of materials is denoted by D_1; the selling price determined by the PMJ per unit of materials is denoted by P_2; the extra inventory cost of the PMS per unit of materials is denoted by D_2; the oscillation range of the purchase quantity is denoted by α; the benefits of PMS and PMJ are denoted by R_1 and R_2, respectively; the total benefit is denoted by R_3; two constant parameters are denoted by ψ_1 and ψ_2. If the oscillation range of the purchase quantity is available, then α is nonzero; otherwise, α is zero. The relationship between the quantity of production materials and the selling price per unit of materials can be expressed as:

$$E = \psi_1 - \psi_2 P_2 + \alpha \tag{1}$$

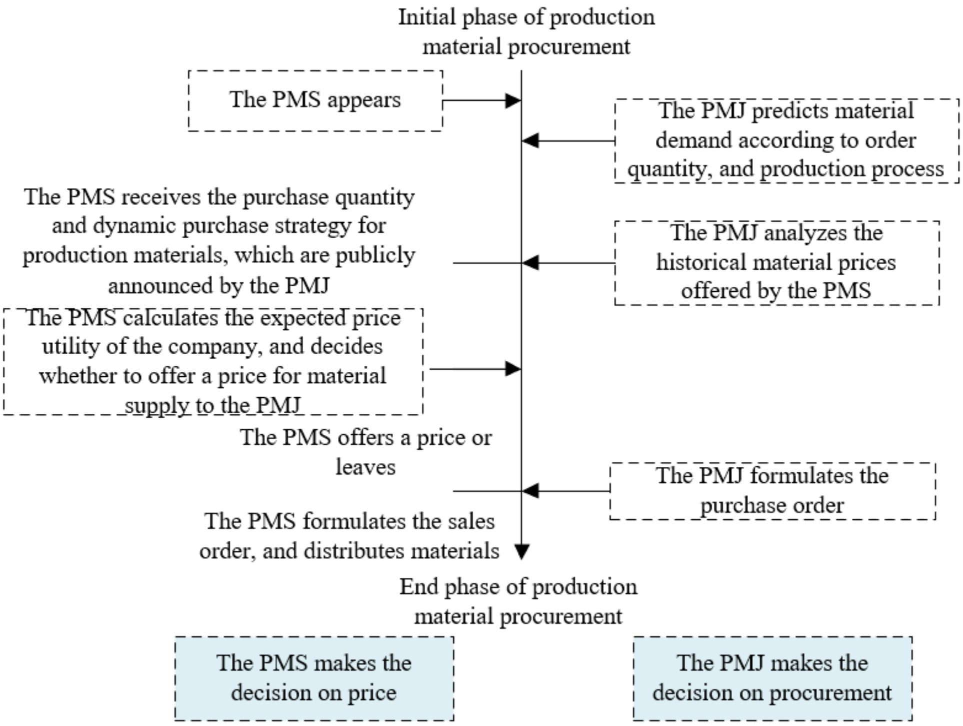


Figure 3: Order of moves in the game.

Under the information sharing mode of the blockchain-based PMSC model, all the information provided by PMJ and PMS are updated, and shared with other nodes. Thus, any node of the PMSC can acquire the latest, complete information shared by any other node at any time. In the ideal condition, the PMS does not need to manage the inventory. In the real world, however, it is necessary to consider a safety inventory that incurs no extra cost. In the latter case, the benefits of PMS and PMJ can be respectively calculated by:

$$R_1 = (P_1 - D_1)E = (P_1 - D_1)(\psi_1 - \psi_2 P_2 + \alpha) \tag{2}$$

$$R_2 = (P_2 - P_1)E = (P_2 - P_1)(\psi_1 - \psi_2 P_2) \tag{3}$$

Comparing the PMSC management modes before and after the introduction of blockchain technology, the PMSC nodes gain more benefits under the blockchain-based information sharing environment. In this case, the total benefits of PMS and PMJ can be calculated by:

$$R_3 = \frac{3(\psi_1 + \alpha - \psi_2 D_1)^2}{16\psi_2} \tag{4}$$

In the PMJ material supply chain composed of PMS and PMJ, the PMSC companies can obtain more benefits under the mode of sharing the information about operation, purchase, price, and supply than under the traditional supply chain management mode. Therefore, the collaborative management strategy between blockchain and supply chain is superior to the traditional management mode of supply chain, and effectively enhances the overall benefit of the supply chain.

4. TRUST EVALUATION

To ensure the safe and reliable data sharing between the companies in the blockchain-based PMSC model, this paper identifies the dishonest companies in the chain through trust evaluation. Then, the probability for the identified dishonest companies to participate in smart contract was reduced, making it less likely for false shared data to appear in the chain. The trust between

PMS and PMJ was determined based on the number of satisfactory collaborations, and the number of unsatisfactory collaborations between the two parties. The trust of the blocks created by each company was measured by the number of true and false blocks created by that company. The trust of the check blocks of each company participating in PMSC block check was derived from the check numbers of true and false blocks of that company.

In the PMSC model, the improved EigenTrust algorithm is adopted to record the collaborations between PMS and PMJ. Once a collaboration is complete, the PMJ will evaluate the collaboration service provided by the PMS, and, on this basis, rate the trust of that party in collaboration. The mean of collaboration scores reflects the trust of that company in PMSC collaborations. Let O_i be the trust of company i in PMSC collaborations; d_{ij} be the trust between company i and the PMJ in the j^{th} collaboration; N be the total number of collaborations between company i and the PMJ. Then, we have:

$$O_i = \frac{\sum_{j=1}^{N} d_{ij}}{N} \tag{5}$$

To enhance the probability of satisfactory collaboration between each company and the PMJ, the trust of the blocks created by a company that often creates false blocks should be reduced, making it less likely for that company to create blocks. The quality of blocks created by a company can be characterized by a pair of parameters (e_i, s_i), where e_i and s_i are the number of true and false blocks created by company i, respectively. If the block submitted by company i to the PMSC is false, the e_i value will be increased by 1; If the block submitted by company i to the PMSC is true, the s_i value will be increased by 1. Let $\sigma^1{}_i$ be the tolerance of the PMJ to the false blocks created by company i. Then, the trust of the blocks created by company i can be calculated by:

$$NO_i = \begin{cases} \dfrac{\sigma_i^1 + s_i - e_i}{s_i + e_i + 1}, e_i < s_i \\ 0, e_i \geq s_i \end{cases} \tag{6}$$

$\sigma^1{}_i$ can be calculated by:

$$\sigma_i^1 = \begin{cases} 1, e_i = 0 \\ 0, e_i \geq 1 \end{cases} \tag{7}$$

Eq. (6) shows that, when $e_i = s_i = 0$, NO_i equals 1. When e_i is greater than 1, and s_i remains constant, the NO_i value decreases with the growing number of false blocks submitted by company i. After e_i surpasses s_i, the NO_i value will be zero. As long as e_i remains constant, the greater the s_i, the larger the NO_i. To maximize NO_i, a company must create as many true blocks as possible, while avoiding creating false blocks.

Similarly, more companies participating in block check should make true block checks, in order to enhance the probability of satisfactory collaboration between each company and the PMJ. If a company often makes false block checks, the probability for that company to participate in block check should be reduced. The number of false and true block checks by company i can be illustrated by a pair of parameters (q_i, d_i). If company i makes a false block check, the q_i value will be increased by 1; if company i makes a true block check, the d_i value will be increased by 1. Let $\sigma^2{}_i$ be the tolerance of the PMJ for the false block check made by company i. Then, the trust of the block checks by company i can be calculated by:

$$UO_i = \begin{cases} \dfrac{\sigma_i^2 + d_i - q_i}{d_i + q_i + 1}, q_i < d_i \\ 0, q_i \geq d_i \end{cases} \tag{8}$$

σ^2_i can be calculated by:

$$\sigma_i^2 = \begin{cases} 1, q_i = 0 \\ 0, q_i \geq 1 \end{cases} \tag{9}$$

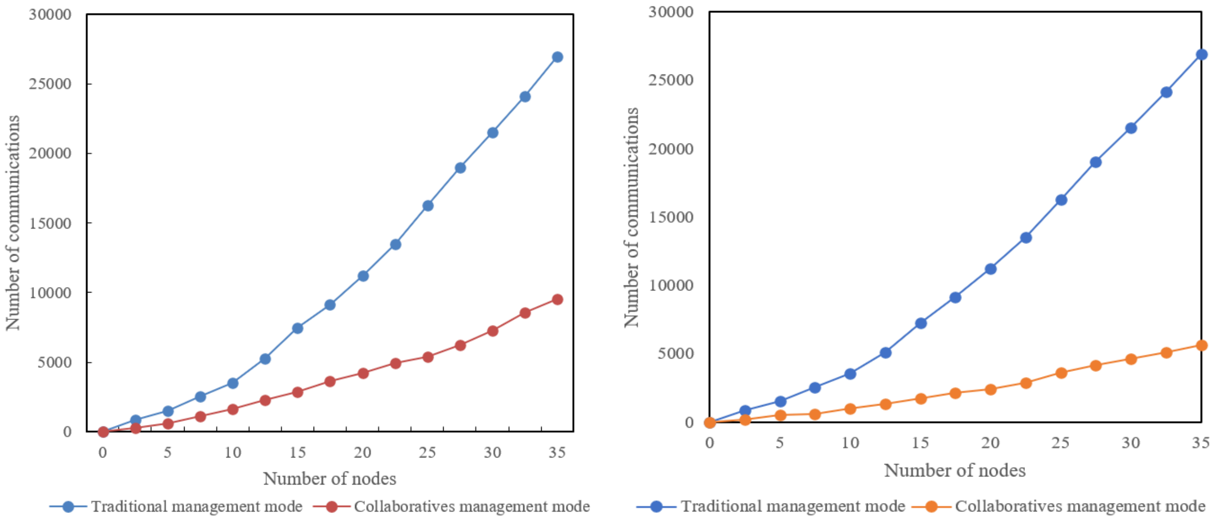
when $q_i = d_i = 0$, UO_i equals 1. When q_i is greater than 1, and d_i remains constant, the UO_i value decreases with the growing number of false block checks made by company *i*. After q_i surpasses d_i, the UO_i value of company *i* will be zero. As long as q_i remains constant, the greater the d_i, the larger the UO_i. To maximize UO_i, a company must make as many true block checks as possible, while avoiding making false block checks.

To sum up, the global trust TR of company *i* in the PMSC model can be established based on the trust in collaboration, the trust of creating blocks, and the trust of block check:

$$TR_i = O_i + NO_i + UO_i \tag{10}$$

5. SIMULATIONS AND RESULTS ANALYSIS

Unlike traditional supply chain management, the blockchain-based collaborative management of the PMSC adopts the consensus mechanism, which assumes that all companies participating in material supply are consensus nodes. The assumption prevents the transmission of massive invalid shared information, and ensures the probability of satisfactory collaborations between each company and the PMJ. Firstly, the authors simulated the number of communications under traditional supply chain management and blockchain-based collaborative management of the PMSC. Fig. 4 shows the simulation results.



1) Group 1 2) Group 2

Figure 4: Number of communications under different management modes.

As shown in Fig. 4, when there were relatively few companies, the PMJ and PMS communicated not frequently in different production projects under different management modes. In each group, with the growing number of nodes, the two management modes differed more and more significantly in terms of the number of communications between PMJ and PMS.

Table I: Simulation results under the traditional management mode.

Serial number of PMSs	1	2	3	4	5
Interval between production links	3.25	3.68	3.07	2.63	2.84
Number of production links	5	2	4	3	1
Distribution interval of production materials	1.25	1.96	1.38	2.42	2.08
Operation cost	615.27	582.94	681.29	584.18	484.71
Quantity of production materials			1352		
Operation cost per unit of time			4815.62		
Serial number of PMSs	**6**	**7**	**8**	**9**	**10**
Interval between production links	2.69	3.01	2.25	2.54	2.87
Number of production links	4	5	6	4	3
Distribution interval of production materials	2.16	2.54	2.38	2.85	2.65
Operation cost	696.28	684.25	589.84	596.21	674.38
Quantity of production materials			1527		
Operation cost per unit of time			4576.19		

Table II: Simulation results under the collaborative management mode.

Serial number of PMSs	1	2	3	4	5
Interval between production links	2.95	2.71	2.28	2.06	2.84
Number of production links	5	2	4	3	1
Distribution interval of production materials			1.62		
Operation cost	462.15	408.69	437.28	368.64	317.28
Quantity of production materials			583		
Operation cost per unit of time			421.69		
Serial number of PMSs	**6**	**7**	**8**	**9**	**10**
Interval between production links	2.651	2.01	2.56	2.14	2.75
Number of production links	4	5	6	4	3
Distribution interval of production materials			1.24		
Operation cost	471.52	411.35	422.57	389.67	328.55
Quantity of production materials			498		
Operation cost per unit of time			414.78		

During the intern at the Material Department of a production and manufacturing company, the demand for 10 kinds of production materials was collected, which are supplied by 10 different PMSs. Based on the collected demand data, the proposed model was simulated on LINGO 16.0 (cracked version). The operation cost of the supply chain, and the distribution interval of production materials were compared between different management mode. Tables I and II show the simulation results under the traditional and collaborative management modes, respectively. The comparison reveals the variation of supply chain operation cost between different management modes.

As shown in Tables I and II, the collaborative management mode of the PMSC significantly reduced the overall cost of the supply chain from the level of traditional supply chain management mode. Compared with the traditional mode, the PMSs delivered materials faster with a shorter interval under the collaborative mode. This means the collaborative management of the PMSC can coordinate the supply and demand decisions of production materials in view of the global situation of the supply chain, realize timely information sharing, and greatly reduce the docking time and number of communications between PMJ and PMS, thereby enhancing the collaborative benefits of the PMSC.

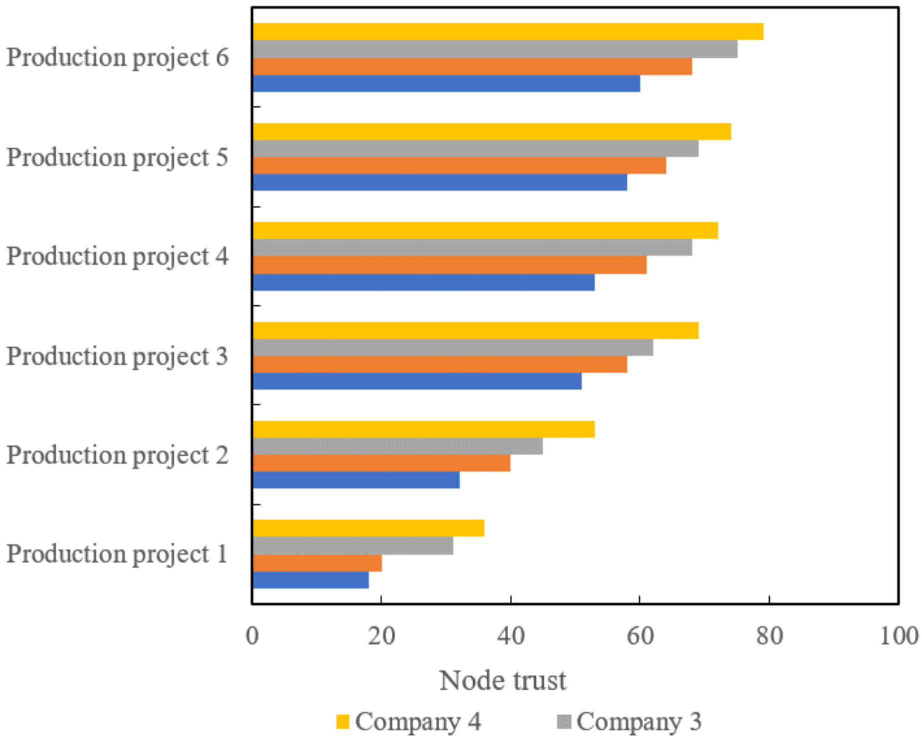


Figure 5: Node trusts of different PMSs for the same material.

Fig. 5 compares the node trusts of different PMSs for the same material. It can be observed that our strategy of identifying dishonest companies on the chain by trust evaluation makes it more likely for the PMJ to collaborate with companies with a high node trust, and significantly elevates the probability of satisfactory probability between the two parties. Company 4, with a high node trust in every production project, boasts a strong competitiveness.

6. CONCLUSIONS

This paper mainly investigates the collaborative management of PMJ material supply chain based on the blockchain. Firstly, a collaborative management model was constructed to display the execution process of smart contract between PMJ and PMS in the model. Then, the Stackelberg game between the two parties was analysed, and the calculation formula was derived for the total benefit of the two parties, based on the information sharing mode of the blockchain-based PMSC model. Through trust evaluation, the dishonest companies were identified in the PMSC. Then, the probability for the identified dishonest companies to participate in smart contract was reduced, such that the companies in the blockchain-based PMSC model can share data safely and reliably.

Next, the authors simulated the number of communications under traditional supply chain management and blockchain-based collaborative management of the PMSC. With the growing number of nodes, the two management modes differed more and more significantly in terms of the number of communications between PMJ and PMS. Furthermore, the operation cost of the supply chain, and the distribution interval of production materials were compared between different management mode, revealing the variation of supply chain operation cost between different management modes. Finally, the authors compared the node trusts of different PMSs for the same material. The results show that our strategy of identifying dishonest companies on the chain by trust evaluation makes it more likely for the PMJ to collaborate with companies with a high node trust.

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