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GAME STUDY ON SYNERGISTIC EFFECT OF BUILDING SUPPLY CHAIN BASED ON BLOCKCHAIN

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Abstract. Due to the unique nature of the construction industry, incorporating supply chain information has been challenging, affecting profit margins and competitiveness. The implementation of blockchain, as a decentralized digital technology, can facilitate the optimal performance of the construction supply chain. In order to measure the economic benefits generated by the synergy effect in the procurement process of the construction supply chain. This paper sorts out the existing problems of the construction supply chain, utilizing the Stackelberg game theory, a game model is established to measure the potential positive effects of incorporating blockchain into the construction supply chain. A preference function incorporating information sharing and competitiveness is used to compare the traditional model with the blockchain mode, in order to quantitatively analyze potential benefits. The findings indicate that blockchain can enhance supplier competitiveness, while improving supply chain participants' profits, if the cost of implementation is controlled effectively. By enhancing information sharing and quality assurance, inventory costs for general contractors may be reduced. Consequently, blockchain can enable supply chain participants to achieve synergistic effect that enhance the overall value of the construction supply chain.

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1. Introduction

The construction industry is one of the most fragmented industries in the world due to the highly specialized nature of its operations and processes and the large number of stakeholder participants. As a result, most construction projects are one-off and unrepeatable, and its supply chain is more decentralized and complex than that of the manufacturing industry. The theory of supply chain management, first proposed by Peter Drucker, refers to the coordination of internal and external resources of a company to jointly satisfy consumer demand. The current research on supply chain involves industrial economy [1–4], emission reduction [5–7], information risk and demand uncertainty [8–10] and so on. Construction supply chain (CSC) is a typical pull process, according to customer orders to complete the construction, with complexity, temporary, centralized characteristics, compared to the industrial manufacturing industry, the construction industry, the product type of large volume, production sites fixed a project, according to the customer customization carried out by the non-standard, non-replicable, difficult to mass production of the project. CSC has the characteristics of strong

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network flexibility, integrated management, unstable participants, etc. The main problems faced in the material management and procurement links are divided into the following three points: (1) CSC has a long full life cycle, information multi-source heterogeneity, and the traditional supply chain with a fixed supply line is different, and its supply line will be changed with the different locations of the project, and subsequently need to re-adjust the supply of resource network and select new. The supply routes will change with different project locations, which requires readjustment of resource network supply and selection of new participants. This part of the resource reconstruction will lead to problems such as difficult to count the equipment and material usage and easy to accumulate materials. (2) Although the vertical integration with the general contractor as the core optimizes the information transfer, most of the data and information are concentrated in the core nodes, and the other participants have a single source of information, especially the information trust problem between non-adjacent links is highlighted [11], which is easy to lead to schedule delays due to untimely supply. (3) The supply chain management method is not mature enough, and the improvement of the comprehensive competitiveness of the supply chain has not been taken as a strategic goal [12], and it is difficult to keep a check on the quality level of the equipment and materials, the accuracy of the equipment delivery time, and the proficiency of the equipment installation.

Generally speaking, CSC takes the general contractor or professional contracting let as the core, but also involves suppliers and designers, the task of each enterprise is relatively independent, the members of each node of the CSC are formed only because of the project, the relationship is relatively loose. Currently, the profitability of construction projects is largely limited by the procurement process, the cost of engineering materials accounted for 60%–70% of the total cost of the project, in the face of the digital transformation and high-quality development requirements, the defects of the procurement management link is magnified and thus affect the survival of enterprises. At present, most construction enterprises adopt centralized procurement, but the lack of systematic procurement processes and related supply chain financial support, causing the long-term separation of financial supply chain and physical supply chain in the construction industry. The COVID-19 epidemic caused by the supply chain disruption [13]. It further highlights the problem that the construction supply chain is difficult to achieve integration. On the one hand, scholars analyze the integration motivation, resilience, risk and other influencing factors of the construction supply chain, screen key indicators and put forward targeted suggestions for the management process [14], on the other hand. Scholars are committed to BIM, GIS, Internet of Things and other technologies to improve information management in the CSC. However, the above research mainly focuses on the optimization of the participants' information access, and there is a lack of research on the economic benefits generated by the synergistic effect of the information, resources, and business between the participants.

This paper adopts the Stackelberg game model to construct a mathematical model of the synergistic effect of blockchain and CSC, and improves the preference function for information sharing and comprehensive competitiveness, which are lacking at the current stage of the research of the CSC, and quantifies the application of blockchain technology in the demand function to analyze. Through quantitative analysis of the impact of the combination of blockchain and CSC on participants, the economic benefits and competitiveness of blockchain are analyzed. In addition, considering the special situation that not all participants adopt blockchain, the trend direction brought by synergistic effect is sorted out by numerical analysis, and the value embodiment, application conditions and response strategies of blockchain are clarified, so as to discuss the changes in competitiveness, profitability, and demand for products of the CSC after the introduction of blockchain technology compared with the traditional model.

2. The application of blockchain in supply chain

Blockchain was first proposed by Satoshi Nakamoto, which is mainly used to solve the trust and security problems of transactions. Through intelligent contracts, consensus mechanisms and other technologies, it can achieve open and transparent, decentralized, traceable, and tamper-resistant functions. Blockchain can achieve flat information transmission in the CSC; strengthen procurement and material management in the process of construction projects, and promote inventory liquidation and material information re-verification costs; reduce intermediate links and reduce costs [15, 16]. Nowadays, blockchain is mostly used in the financial and energy fields, and the combination with the supply chain is also in the application stage. In 2016, Walmart cooperated with IBM to study the application of blockchain in the field of food safety, JD and Tsinghua University subsequently joined the project to track the food supply chain based on the blockchain technology, to prevent foodborne diseases, and to establish an ecosystem for food safety in China [17, 18]; international freight giants FedEx and United Parcel Service have joined the Blockchain in Trucking Alliance (BiTA) to utilize a blockchain platform to also enable a locker system for digital currency payments on top of efficiently tracking the parcel shipping process; JD began in 2017 to exploring the field of blockchain traceability, as of February 2019, more than 700 brands have accessed the JD Global Blockchain Traceability Program, with more than 1.3 billion pieces of uploaded data, which have been applied in the traceability of commodities for precise poverty alleviation, food traceability, cross-border commodity traceability, second-hand commodity traceability, and the traceability of commodities in the field of fashion [19]. In 2018, Maersk and IBM cooperated to launch a blockchain trade platform (TradeLens), which is an open and neutral industry platform built on the basis of blockchain, hoping to achieve a leap in supply chain digitization through the TradeLens project, and to promote efficient and safe global shipping trade, but by November 30, 2022, Maersk and IBM jointly decided to stop the operation TradeLens, which did not fulfill the full range of industry collaboration needs and did not reach the expected level of commercial viability based on the trust issues of sensitive data and the pressure of business competition.

At present, there are few application cases of blockchain in CSC, and scholars analyze blockchain technology more from the theoretical point of view. Nawari discusses the integration of blockchain with BIM to strengthen network data security and provide more reliable data storage and permission management [20]; Hamledari studies the payment of crypto tokens instead of legal tender in engineering projects problem, and the study shows that crypto assets can facilitate the integration of product supply chain and financial supply chain in construction projects [21]. Jun discusses the application of blockchain in construction supply chain in terms of Notarization, Transaction, and Provenance, respectively, in order to achieve the management of documents and contracts, construction quality, and material resource management in engineering [22]; Cao [23] and others analyzed the advantages of blockchain application in construction supply chain, constructed a preliminary system architecture and described the application process for the problem of insufficient information sharing. Li *et al.* consider the feasibility of different types of blockchain with the supply of construction materials, analyze the transaction process and storage methods and provide examples [24]. Lu *et al.* design four types of smart contracts with smart buildings as the research object in order to solve the interaction between on-chain and off-chain of the blockchain system in the construction supply chain in the context of on-site assembly services [25]. However, improving information sharing, transaction process, and process management will promote the synergistic relationship among the participants, and scholars have already proposed quantitative research methods for different supply chain synergistic effects. Yang and Zhou [26] established an economic model of profit maximization before and after the merger of enterprises through supply chain networks, and proposed a quantitative method to quantify the synergistic effect after the merger after adding the consideration of environmental factors. Mao *et al.* [27] constructed a system dynamics model based on the framework of "BIM-synergy bodies" to realize the value-added of engineering construction, and studied the synergistic effect of the collaborative body system of engineering construction in the context of BIM. Comparing and analyzing the current research on blockchain in the field of construction supply chain, although a large number of qualitative analyses have demonstrated that blockchain technology is expected to achieve the synergistic effect, which makes the overall benefit of the CSC greater than the sum of the individual components, there is a lack of quantitative analysis. The limitation also suggests several key research needs:

(1) Whether the application of blockchain technology can bring tangible competitiveness and value enhancement to CSC.
(2) How do participants in CSC determine whether they want to use blockchain technology.

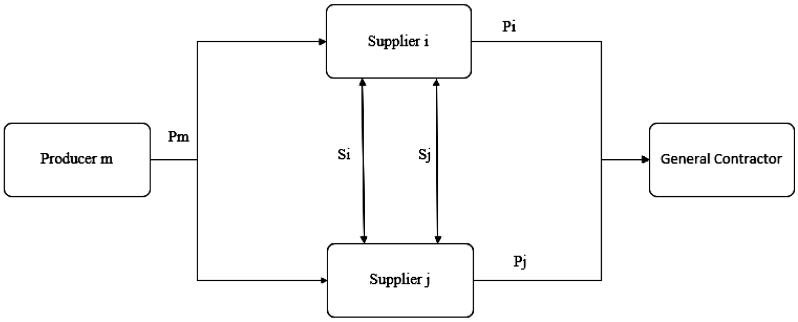

FIGURE 1. Two-stage supply chain model.

3. Model framework

Although the construction supply chain involves many subjects, in order to facilitate the description of the role played by the blockchain, this paper only considers the secondary supply chain composed of a single manufacturer and suppliers i and j. The Stackelberg game is utilized in the supplier's decision-making process, where the manufacturer assumes the role of the leader and the supplier as the follower. The ultimate objective is to maximize the manufacturer's profitability. Different from the manufacturing supply chain, the general contractor of the construction supply chain, as a manager, in order to avoid the problems of untimely performance and lax cost control in the procurement process, which affect the cost, schedule and quality of the project, not only requires the supplier to provide the required equipment and materials, but also requires the comprehensive competitiveness of its product distribution and equipment installation s_i and s_j to ensure the target control of the project. The manufacturer m determines the price (p_m) of the product according to the unit cost c of the equipment manufacturing and the market environment. Suppliers i and j determine their own purchase quantity D_i and D_j and sales price p_i and p_j according to the manufacturer's pricing and the general contractor's comprehensive competitiveness requirements. The model is shown in Figure 1.

Through the derivation analysis of parameters s_i, s_j and p_m, the equilibrium solution of the corresponding parameters and the algebraic expression of the profit and demand of the corresponding supply chain members are obtained. The sensitivity analysis of the application of blockchain in the construction supply chain is carried out by the method of parameter assignment. Explore the application conditions of blockchain technology and the improvement of profitability and competitiveness. Before the analysis of related demand functions, the following assumptions need to be met:

Assumption 1. *According to whether the supplier can obtain the exact owner-related needs and material procurement information from the general contractor, the fluctuation range of the number of equipment materials purchased is determined to be λ. The construction supply chain combined with the blockchain enables the exchange of engineering information. At this time, if it can be effectively obtained, $\lambda \neq 0$. On the contrary, if it cannot be effectively obtained, $\lambda = 0$.*

Assumption 2. *If the manufacturer is unable to obtain the equipment and material demand information from the supplier or the general contractor in time, an additional unit inventory cost c_1 is required.*

Assumption 3. *In order to better highlight the impact of blockchain technology on the construction supply chain, supplier i may use blockchain technology, but supplier j will never use blockchain technology.*

Assumption 4. *The establishment of coopetition relationships between nodes in the construction supply chain network is generally guaranteed by increasing mutual understanding and formulating contracts that have a penalty mechanism for the breaching party [28]. Blockchain technology can help the formation of trust mechanisms* *through information exchange and the enforcement of smart contracts. Therefore, for the construction supply chain, a linear function can be used to represent the relationship between the general contractor's preference for supplier i and the application degree of blockchain [29], that is:*

$$\theta = \tau k \theta_0 + \theta_0 \tag{1}$$

where: $\theta_0 (0 < \theta_0 < 1)$ *is the initial preference of the general contractor for supplier* i. $\tau (0 < \tau < 1)$ *is the application of blockchain to the general contractor preference elasticity coefficient.* $k(0 < k < 1)$ *refers to the application of blockchain technology by participants in the construction supply chain. When* $k = 0.3$, *30% of the nodes involved in the supplier's interior have applied blockchain technology. When 70% of the transportation and installation information is not on the chain, it will affect the degree of information disclosure and sharing of the entire construction supply chain, thus affecting the preference of the general contractor.*

Assumption 5. *Since the supplier's sales price* p *and comprehensive competitiveness* s *have a significant impact on the demand for equipment materials* D, *they should be included in the demand function. For two competing suppliers* i *and* j, *in order to simplify the calculation does not consider the influence of the sales price of both sides on each other, but all reflect on the change of their comprehensive competitiveness, the demand functions of the equipment materials of suppliers* i *and* j *are defined as [30–33]*

$$D_i = \theta(a - bp_i) + \beta s_i + \eta(s_i - s_j) + \lambda \tag{2}$$

$$D_j = (1 - \theta)(a - bp_j) + \beta s_j + \eta(s_j - s_i) + \lambda. \tag{3}$$

$a \gg b, \beta, \eta > 0$, α *is the basic demand for equipment and materials,* b *is the price elasticity coefficient,* b *is the comprehensive competitiveness elasticity coefficient,* η *is the demand correction substitution coefficient caused by the change of the comprehensive competitiveness of both sides. In order to ensure the non-negativity of the algebraic expression of the subsequent equilibrium solution, the numerical value of* a *is much larger than the other parameters. The specific numerical setting can be seen in Section 5. Supplier's comprehensive competitiveness* s *includes the accuracy of equipment delivery time, equipment material quality level and equipment installation proficiency.*

Assumption 6. *Manufacturers and suppliers make rational decisions based on complete information, regardless of shortage costs. There is a nonlinear correlation between the comprehensive service fee including the installation and distribution of equipment and materials and the comprehensive competitiveness* s_i *and* s_j *of suppliers* i *and* j *[15], which are expressed as:*

$$c_{si} = \frac{1}{2}\omega_i s_i^2 \tag{4}$$

$$c_{sj} = \frac{1}{2}\omega_j s_j^2. \tag{5}$$

ω_i, ω_j *represents the comprehensive service cost elasticity coefficient,* $\omega_i > 0$, $\omega_j > 0$.

Assumption 7. *The construction supply chain can reduce part of the decision-making cost for the participants due to the characteristics of blockchain information sharing. The decision-making cost is also related to the application degree of the blockchain. The higher the application degree, the better the information exchange degree, and the less the decision-making cost required by the participants on the chain. For the convenience of calculation, the decision costs of all participants is:*

$$c_d = (1 - k)\varphi. \tag{6}$$

φ *is the decision cost of construction supply chain members to obtain relevant information of other participants,* $\varphi > 0$.

4. Model formulation and solution

4.1. Supply and demand game analysis of traditional construction supply chain

There are some problems in the traditional construction supply chain, such as the backlog of equipment and materials, the delay of construction period, the difficulty of quality control and the difficulty of material consumption statistics. Due to the great difference between the management platform and the actual demand of the existing construction supply chain, the information flow between different management departments is difficult, and it is difficult for suppliers and manufacturers to obtain the real demand of the owner in time. The fluctuation range of the predicted purchase quantity of equipment and materials is $\lambda = 0$. In addition, manufacturers are prone to oversupply when they lack information, resulting in additional payment of unit inventory cost c_1. In the traditional mode, the blockchain application degree $k = 0$, and the superscript N indicates that the blockchain technology is not used. Therefore, the profit functions of manufacturer m, supplier i and j are:

$$\prod_{m}^{N} = (p_m - c - c_1)D - \varphi \tag{7}$$

$$\prod_{i}^{N} = (p_i - p_m - c_{si})D_i - \varphi \tag{8}$$

$$\prod_{j}^{N} = (p_j - p_m - c_{sj})D_j - \varphi. \tag{9}$$

Proposition 1. *In the traditional supply and demand game, all participants do not use blockchain technology. Assuming that the supplier is the leader and the manufacturer is the follower, the game equilibrium results are as follows:*

(1) *The optimal comprehensive competitiveness of suppliers i and j and the optimal selling price of manufacturer m are:*

$$s_i^{N^*} = \frac{\beta}{b\theta\omega_i} \tag{10}$$

$$s_j^{N^*} = \frac{\beta}{b(1-\theta)\omega_j} \tag{11}$$

$$p_m^{N^*} = \frac{a + b(c + c_1)}{2b} + \frac{\beta^2}{4b^2\theta\omega_i} + \frac{\beta^2}{4b^2(1-\theta)\omega_j}. \tag{12}$$

(2) *The optimal demand of suppliers i and j are:*

$$D_i^{N^*} = \frac{\theta[a - b(c + c_1)]}{4} + \frac{\beta}{4b}\left[\frac{\beta + 2\eta}{\theta\omega_i} - \frac{2\eta}{(1-\theta)\omega_j}\right] - \frac{\theta\beta^2}{8b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right] \tag{13}$$

$$D_j^{N^*} = \frac{(1-\theta)[a - b(c + c_1)]}{4} + \frac{\beta}{4b}\left[\frac{\beta + 2\eta}{(1-\theta)\omega_j} - \frac{2\eta}{\theta\omega_i}\right] - \frac{(1-\theta)\beta^2}{8b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]. \tag{14}$$

(3) *The optimal selling prices of suppliers i and j are:*

$$p_i^{N^*} = \frac{3a + b(c + c_1)}{4b} + \frac{\beta}{4b^2\theta}\left[\frac{3\beta + 2\eta}{\theta\omega_i} - \frac{2\eta}{(1-\theta)\omega_j}\right] + \frac{\beta^2}{8b^2}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right] \tag{15}$$

$$p_j^{N^*} = \frac{3a + b(c + c_1)}{4b} + \frac{\beta}{4b^2(1-\theta)}\left[\frac{3\beta + 2\eta}{(1-\theta)\omega_j} - \frac{2\eta}{\theta\omega_i}\right] + \frac{\beta^2}{8b^2}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]. \tag{16}$$

(4) *The optimal profits of manufacturer m, supplier i and supplier j are:*

$$\prod_m^{N^*} = \frac{1}{2b}\left\{\frac{a-b(c+c_1)}{2} + \frac{\beta^2}{4b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]\right\}^2 - \varphi \tag{17}$$

$$\prod_i^{N^*} = \frac{\theta}{b}\left\{\frac{a-b(c+c_1)}{4} + \frac{\beta}{4b\theta}\left[\frac{\beta+2\eta}{\theta\omega_i} - \frac{2\eta}{(1-\theta)\omega_j}\right] - \frac{\beta^2}{8b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]\right\}^2 - \varphi \tag{18}$$

$$\prod_j^{N^*} = \frac{1-\theta}{b}\left\{\frac{a-b(c+c_1)}{4} + \frac{\beta}{4b(1-\theta)}\left[\frac{\beta+2\eta}{(1-\theta)\omega_j} - \frac{2\eta}{\theta\omega_i}\right] - \frac{\beta^2}{8b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]\right\}^2 - \varphi. \tag{19}$$

Proof. Firstly, the inverse functions of formulas (2) and (3) on the selling price are obtained by the undetermined coefficient method, that is:

$$p_i = \frac{\theta a + \beta s_i + \eta(s_i - s_j) - D_i}{b\theta} \tag{20}$$

$$p_j = \frac{(1-\theta)a + \beta s_j + \eta(s_j - s_i) - D_j}{b(1-\theta)}. \tag{21}$$

According to the backward induction method, substituting equation (20) into equation (8) and equation (21) into equation (9), the first-order partial derivatives of D_i and D_j respectively, and finally get the results:

$$D_i = \frac{\theta a + \beta s_i + \eta(s_i - s_j) - b\theta p_m}{2} - \frac{1}{4}b\theta\omega_i s_i^2 \tag{22}$$

$$D_j = \frac{(1-\theta)a + \beta s_j + \eta(s_j - s_i) - b(1-\theta)p_m}{2} - \frac{1}{4}b(1-\theta)\omega_j s_j^2 \tag{23}$$

$$D = D_i + D_j = \frac{a + \beta(s_i + s_j) - bp_m}{2} - \frac{1}{4}b\theta\omega_i s_i^2 - \frac{1}{4}b(1-\theta)\omega_j s_j^2. \tag{24}$$

Secondly, in order to obtain the relationship between p_m, s_i, s_j and the preference coefficient θ of the general contractor, equation (24) is substituted into equation (7) to obtain:

$$\prod_m^N = (p_m - c - c_1)\left[\frac{a + \beta(s_i + s_j) - bp_m}{2} - \frac{1}{4}b\theta\omega_i s_i^2 - \frac{1}{4}b(1-\theta)\omega_j s_j^2\right] - \varphi. \tag{25}$$

The first-order partial derivatives of p_m, s_i, s_j are calculated respectively. By observation, it can be found that since $\partial\prod_m^N\big/\partial p_m < 0$, $\partial\prod_m^N\big/\partial s_i < 0$, $\partial\prod_m^N\big/\partial s_j < 0$, when $\partial\prod_m^N\big/\partial p_m = 0$, $\partial\prod_m^N\big/\partial s_i = 0$, $\partial\prod_m^N\big/\partial s_j = 0$, $\prod_m^N$ takes the maximum value. At this point, the optimal comprehensive competitiveness of suppliers i and j can be obtained, as shown in equations (10) and (11), and then the optimal selling price of the manufacturer is shown in equation (12).

By substituting equations (10)~(12) into equations (22) and (23), the optimal demand of suppliers i and j can be obtained as shown in equations (13) and (14). Similarly, the optimal selling prices of suppliers i and j can be obtained by substituting them into equations (20) and (21), as shown in equations (15) and (16). Among them, the optimal total demand is:

$$D^{N^*} = \frac{a-b(c+c_1)}{4} + \frac{\beta^2}{8b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]. \tag{26}$$

Finally, by substituting the equations (26) and (12) into equations (7), (13) and (15) into equations (8), (14) and (16) into equation (9). The optimal profits of manufacturer m, supplier i and j are shown in formulas (17), (18) and (19) respectively. □

4.2. Supply and demand game analysis of blockchain-based construction supply chain

The combination of construction supply chain and blockchain technology improves information flow through information traceability and information exchange, improves logistics through the security and transparency of information sharing process, and improves capital flow through the timeliness and invariance of smart contracts. The characteristics of decentralization are just in line with the characteristics of the flexibility of the construction supply chain network. It links scattered subcontractors, suppliers, etc., and ensures that the information on the chain is open to all participating nodes under the premise of ensuring the authenticity of the information on the chain. It can effectively improve the accuracy of demand forecasting, so the fluctuation range of equipment and material procurement quantity is $\lambda \neq 0$. Similarly, manufacturers will also avoid the risk of oversupply of storage, the unit inventory cost is $c_1 = 0$. Assuming that the blockchain application degree of the participants on the chain is k, once the blockchain technology is used, the necessary cost c_B for assembly and maintenance needs to be paid, and the superscript B indicates that the blockchain technology is used. At this point, the profit functions of the manufacturer m, the supplier i and the j are:

$$\prod_m^B = (p_m - c)D - (1-k)\varphi - c_B \tag{27}$$

$$\prod_i^B = (p_i - p_m - c_{si})D_i - (1-k)\varphi - c_B \tag{28}$$

$$\prod_j^B = (p_j - p_m - c_{sj})D_j - \varphi. \tag{29}$$

Because supplier j does not use blockchain technology, its profit function is the same as that of the traditional model, but affected by the preference degree θ and comprehensive competitiveness s_i of supplier i, the total profit will also change due to the use of blockchain technology, so the superscript is also B.

Proposition 2. *Considering the Stackelberg game of supply and demand under blockchain technology, the participants use blockchain technology to a certain extent except supplier j. Assuming that the supplier is the leader and the manufacturer is the follower, the game equilibrium results are as follows:*

(1) *The optimal comprehensive competitiveness of suppliers i and j and the optimal selling price of manufacturer m are:*

$$s_i^{B^*} = \frac{\beta}{b\theta\omega_i} \tag{30}$$

$$s_j^{B^*} = \frac{\beta}{b(1-\theta)\omega_j} \tag{31}$$

$$p_m^{B^*} = \frac{a+\lambda+bc}{2b} + \frac{\beta^2}{4b^2\theta\omega_i} + \frac{\beta^2}{4b^2(1-\theta)\omega_j}. \tag{32}$$

(2) *The optimal demands of suppliers i and j are:*

$$D_i^{B^*} = \frac{\theta(a-bc)+\lambda(2-\theta)}{4} + \frac{\beta}{4b}\left[\frac{\beta+2\eta}{\theta\omega_i} - \frac{2\eta}{(1-\theta)\omega_j}\right] - \frac{\theta\beta^2}{8b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right] \tag{33}$$

$$D_j^{B^*} = \frac{(1-\theta)(a-bc-\lambda)}{4} + \frac{\beta}{4b}\left[\frac{\beta+2\eta}{(1-\theta)\omega_j} - \frac{2\eta}{\theta\omega_i}\right] - \frac{(1-\theta)\beta^2}{8b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]. \tag{34}$$

(3) *The optimal selling prices of suppliers i and j are:*

$$p_i^{B^*} = \frac{3a+bc}{4b} + \frac{\lambda(2+\theta)}{4b\theta} + \frac{\beta}{4b^2\theta}\left[\frac{3\beta+2\eta}{\theta\omega_i} - \frac{2\eta}{(1-\theta)\omega_j}\right] + \frac{\beta^2}{8b^2}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right] \tag{35}$$

TABLE 1. Benchmark parameter simulation results.

	Traditional model	Blockchain model		Traditional model	Blockchain model
s_i^*	2.67	2.54	p_i^*	54.11	55.19
s_j^*	1.90	1.94	p_j^*	43.95	44.29
D_i^*	8.96	10.48	$\prod_m^*$	569.80	599.90
D_j^*	15.32	15.01	$\prod_i^*$	113.86	124.36
D	24.29	25.49	$\prod_j^*$	147.73	144.50
p_m^*	30.28	30.49	$\prod_{sc}^*$	683.66	724.26

$$p_j^{B^*} = \frac{3a+bc+\lambda}{4b} + \frac{\beta}{4b^2(1-\theta)}\left[\frac{3\beta+2\eta}{(1-\theta)\omega_j} - \frac{2\eta}{\theta\omega_i}\right] + \frac{\beta^2}{8b^2}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]. \tag{36}$$

(4) *The optimal profits of manufacturer m, supplier i and j are:*

$$\prod_m^{B^*} = \frac{1}{2b}\left\{\frac{a+\lambda-bc}{2} + \frac{\beta^2}{4b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]\right\}^2 - (1-k)\varphi - c_B \tag{37}$$

$$\prod_i^{B^*} = \frac{1}{b\theta}\left\{\frac{\theta(a-bc)+\lambda(2-\theta)}{4} + \frac{\beta}{4b}\left[\frac{\beta+2\eta}{\theta\omega_i} - \frac{2\eta}{(1-\theta)\omega_j}\right] - \frac{\theta\beta^2}{8b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]\right\}^2 - (1-k)\varphi - c_B \tag{38}$$

$$\prod_j^{B^*} = \frac{1}{b(1-\theta)}\left\{\frac{(1-\theta)(a-bc-\lambda)}{4} + \frac{\beta}{4b}\left[\frac{\beta+2\eta}{(1-\theta)\omega_j} - \frac{2\eta}{\theta\omega_i}\right] - \frac{(1-\theta)\beta^2}{8b}\left[\frac{1}{\theta\omega_i} + \frac{1}{(1-\theta)\omega_j}\right]\right\}^2 - \varphi. \tag{39}$$

The proof is similar to the previous section, so omitted.

5. Numerical analyses

5.1. Parameter setting and data analysis

In this section, the above derivation is analyzed by MatlabR2017a, and the sensitivity analysis of the preference degree θ of the general contractor is carried out. Based on the parameter selection of the relevant literature [31, 33–36], it is assumed that the reference parameter is: $a = 100$, $b = 2$, $\omega_i = 2.5$, $\omega_j = 1.5$, $\beta = 4$, $\eta = 1$, $\theta_0 = 0.3$, $k = 0.5$, $\tau = 0.1$, $c = 5$, $c_1 = 1$, $\varphi = 20$, $\lambda = 3$, $c_B = 40$. In order to intuitively show the difference between the traditional mode and the blockchain mode of the construction supply chain, the sum of the profits of the participants on the chain is $\prod_{sc}^* = \prod_m^* + \prod_i^*$. Bring the benchmark parameters into the optimal solution, as shown in Table 1.

It can be seen from Table 1 that when blockchain technology is adopted, the most significant numerical change is the profit growth of manufacturer m and supplier i, indicating that blockchain technology helps chain participants effectively predict demand information by improving information interoperability, thus giving up conservative procurement strategies, reducing inventory costs and decision-making costs, so the demand and sales prices of both are improved. Although the demand for the entire construction supply chain has increased to a certain extent, since supplier j does not use blockchain technology, the general contractor naturally prefers supplier i with a high degree of information sharing, which also leads to a reduction in the demand for equipment provided by supplier j. In order to gain more market share, supplier j will actively enhance its comprehensive

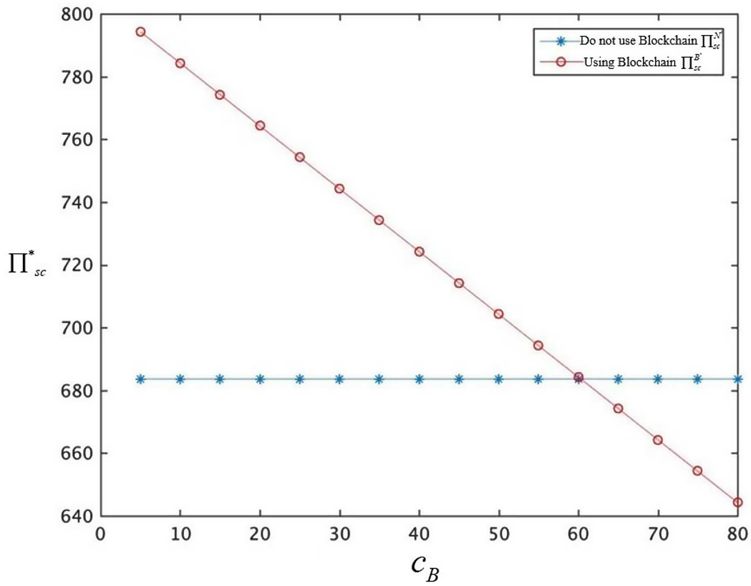

FIGURE 2. The impact of c_B on the total profit of the participants in the chain.

competitiveness and increase its own sales price, but the total profit is still a certain degree of decline compared with the traditional model. It can be seen that blockchain technology can bring tangible value enhancement to the construction supply chain. Although it is not the decisive factor for the value growth of the construction supply chain, it still helps the participants on the entire resource network to achieve synergies.

5.2. Sensitivity analysis of synergistic effect

5.2.1. Cost sensitivity analysis of blockchain application

The sensitivity analysis of the advantages and application conditions of blockchain technology for construction supply chain is carried out. The introduction of new technologies will inevitably bring about cost problems including resettlement and maintenance. Therefore, let $c_B \in [5, 80]$, the rest remains unchanged, and the above parameters are brought into equations (17), (18), (37) and (38) to obtain Figure 2. From Figure 2, it is easy to see that before and after the application of blockchain technology, the total profit of participants on the chain has increased significantly, but decreased with the increase of application cost. When $c_B > 60.3$, the profit generated in the blockchain mode is lower than that in the traditional mode, which means that no matter how the blockchain technology optimizes the information chain and contract relationship, due to its expensive application cost, the supply chain value cannot be improved. Only by controlling the application cost within a certain range can the enthusiasm of participants to use blockchain technology be improved.

5.2.2. Sensitivity analysis of blockchain application degree

Further, let $k \in (0, 1)$, the relationship between the degree of blockchain application and the profit of the participants on the chain can be obtained, as shown in Figure 3. In the blockchain mode, the total profit of participants increases with the increase of blockchain application. Part of the increase in profits comes from the reduction in the cost of participants seeking cooperation and participating in decision-making. This is because the blockchain improves the degree of information exchange, which reduces the cost of participants obtaining information, and also reduces decision-making errors caused by information asymmetry. In addition, with the use of smart contracts, the process management of material delivery, equipment safety and quality is

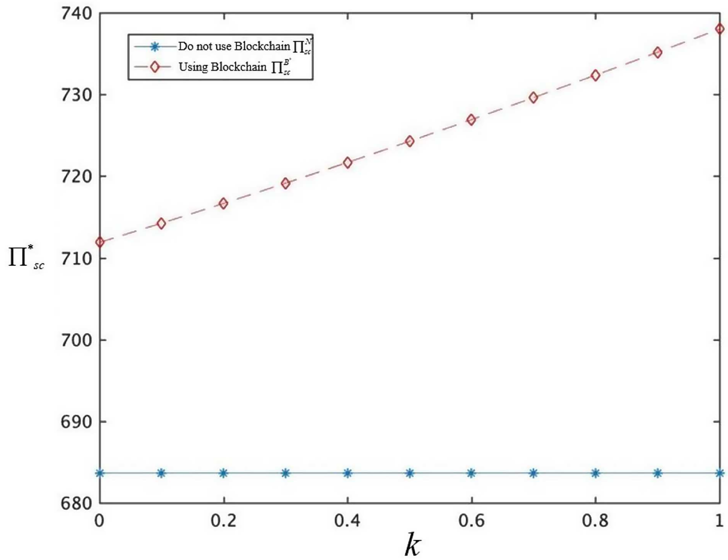

FIGURE 3. The impact of k on the total profit of the participants in the chain.

constrained, which is conducive to the establishment of collaborative relationships among construction supply chain participants.

5.2.3. Sensitivity analysis of general contractor preference degree

Another part comes from the influence of the general contractor's preference θ on the supplier's comprehensive competitiveness, sales price and equipment material demand. For sensitivity analysis, let $\theta_0 \in (0, 1)$, the other parameters remain unchanged, and bring them into the influence of the available preference degree of equations (10), (11), (30) and (31) on the comprehensive competitiveness of suppliers, as shown in Figure 4. Similarly, the impact of preference on supplier sales price and demand is shown in Figures 5 and 6. In the traditional model, with the increase of the preference for supplier i, the comprehensive competitiveness, sales price and demand show a downward trend, while the competitive supplier j shows an upward trend. It means that when the comprehensive competitiveness of both parties is the same, the party with low preference will lower the sales price than the former in order to ensure sufficient demand.

In the blockchain mode, following the improvement of information flow, capital flow and logistics, the demand for supplier i has a considerable increase. On the one hand, relying on blockchain to obtain sufficient owner demand information reduces inventory costs. On the one hand, reasonable prediction of this demand information increases the number of purchases. Even due to the influence of the blockchain application degree (k) on the preference degree (θ), some equipment materials that are originally responsible for the supplier j will be occupied, making its demand lower than the traditional mode. Although supplier j does not use blockchain technology, in order to ensure that its own profits are not damaged, it will enhance its comprehensive competitiveness. Therefore, in Figure 6, the demand curve of the blockchain mode supplier j almost coincides with the traditional mode after the comprehensive competitiveness is improved. It can be seen that the blockchain can achieve the coordination of construction supply chain participants to a certain extent, but it is not a key influencing factor. Without using blockchain technology, improving its comprehensive competitiveness can offset the impact of other participants and increase corporate revenue in the long run. Participants should first calculate the cost before considering the use of blockchain technology. If the cost of blockchain application exceeds the acceptable range of the enterprise, they will give up the use and invest in the improvement of comprehensive competitiveness.

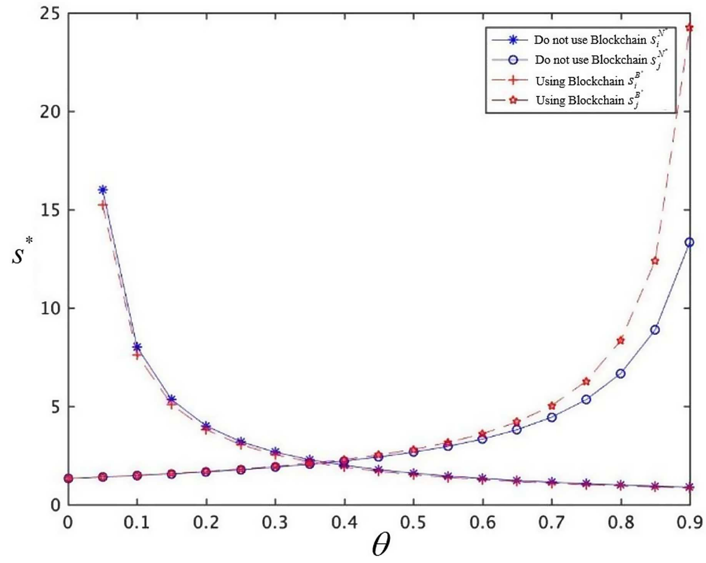

FIGURE 4. The impact of θ on the comprehensive competitiveness of suppliers i, j.

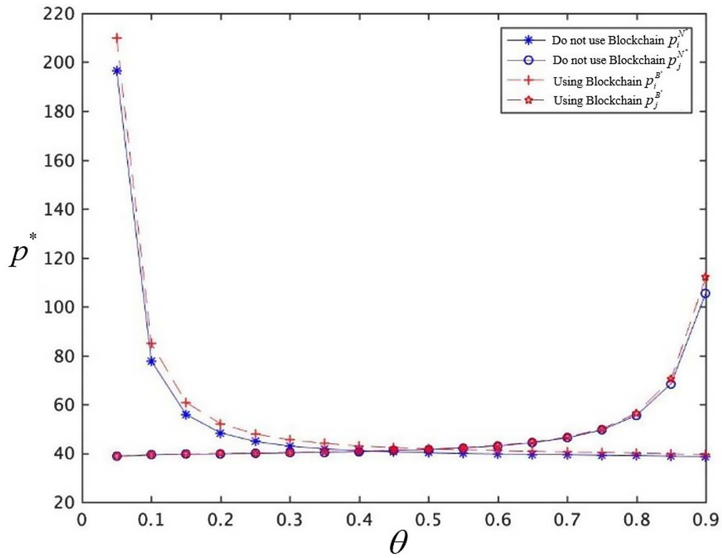

FIGURE 5. The impact of θ on price of suppliers i, j.

6. CONCLUSION

This paper constructs a Stackelberg game model of supply and demand in a two-stage supply chain, comparing the traditional mode with the blockchain mode. Accounting for the variables of competitiveness and information sharing enabled by blockchain technology, the preference and cost functions are improved. Examining the manufacturer's profit maximization as the decision-making criterion, this paper investigates the scenario in which participants do not simultaneously adopt blockchain, compares the profit and competitiveness of supply

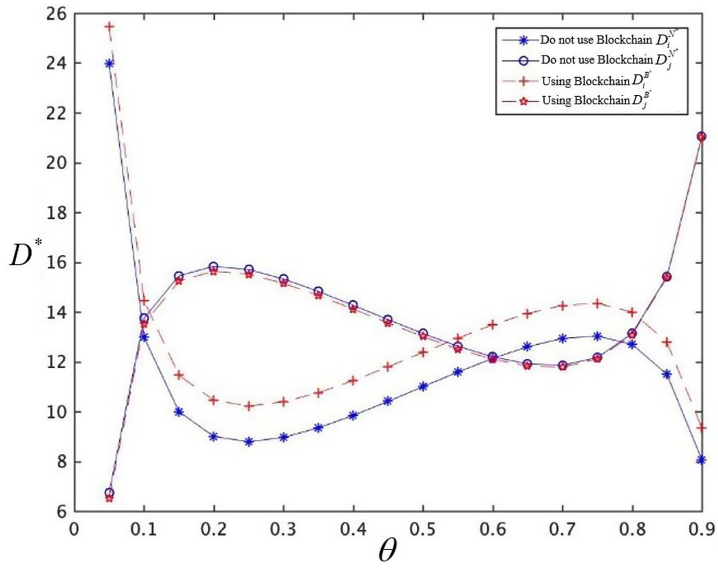

FIGURE 6. The impact of θ on demand of suppliers i, j.

chain members under the two modes, and verifies the model's accuracy *via* example analysis. Based on this, we draw the following conclusions:

(1) Blockchain technology addresses the pressing needs for collaborative information acquisition, security, and interactivity in the construction supply chain. By providing transparent transaction data and non-tamperable mechanisms, both the supply and demand sides can proactively adjust plans based on comprehensive records, reducing inventory costs and increasing order volumes during demand fluctuations. Different levels of information openness and equipment traceability in chronological order ensure procurement quality and enhance information sharing. This can influence the preferences of the general contractor, effectively improving the overall value, profitability, and competitiveness of the construction supply chain.
(2) When the general contractor embraces blockchain technology, its implementation can significantly reduce inventory redundancy and drive product demand. While there may be increased costs for both the demand and supply sides, this can ultimately result in enhanced profitability for the overall supply chain. However, given the existence of multiple suppliers in projects, the use of supply chain technology must consider competitive relationships between supply chains to avoid harm to the collective interests of the supply chain caused by malicious competition.
(3) The participants within the construction supply chain must evaluate if the expenses involved in implementing blockchain technology are reasonable for their operations. Furthermore, it's important to understand that blockchain adoption isn't obligatory; local governing bodies and organizations can play a role in encouraging the use of blockchain technology by reducing its application costs.
(4) Forgoing blockchain technology doesn't imply that it's impossible to remain competitive among other supply chain participants. Ensuring comprehensive competitiveness is vital, which includes quality control measurements, efficient logistics service, diverse product offerings, and dependable post-operation support, to guarantee their competitive edge and meet the varied demands of customers in the construction supply chain.

Compared to previous literature's theoretical analysis or blockchain's information sharing ability analysis, this paper develops a game model for the construction supply chain and provides an example analysis. By utilizing blockchain's information sharing ability, this paper examines its application to traditional supply chains.

Through the aforementioned example analysis, the paper visually illustrates the differences in profitability and competitiveness for supply chain members before and after blockchain implementation.

The constructed correlation function in this paper reflects a particular market environment. In reality, the procurement process for construction projects involves random and uncertain demands, and contract changes are also vital considerations. Additionally, this paper's game model only considers a single manufacturer and two suppliers. Therefore, future research should focus on studying the game model among multiple manufacturers and multiple suppliers while also accounting for market demand uncertainty.

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