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RESEARCH ARTICLE

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Collaborative adoption of blockchain technology: A supply chain contract perspective

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Abstract The outbreak of COVID-19 has significantly affected the development of enterprises. In the post-pandemic era, blockchain technology has become one of the important technologies to help enterprises quickly gain market competitiveness. The heavy investment required of supply chain stakeholders to employ blockchain technology has hindered its adoption and application. To tackle this issue, this study aims to facilitate the adoption of blockchain technology in a supply chain consisting of a core enterprise and a small/medium-sized enterprise through an effective supply chain contract. We analyze the performance of a cost-sharing (CS) contract and a revenue-sharing (RS) contract and propose a new hybrid CS-RS contract for better performance. We conduct comparative analyses of the three contracts and find that the hybrid CS-RS contract can more effectively incentivize both parties to reach the highest level of blockchain technology adoption and achieve supply chain coordination.

Keywords blockchain, collaborative adoption, cost sharing, revenue sharing, hybrid contract

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1 Introduction

The COVID-19 pandemic has brought significant challenges to the development of the world economy. It has disrupted the supply networks of many middle and downstream enterprises and increased their operational costs (Liu et al., 2022a). At the same time, it has prompted companies to re-evaluate their global value chains and improve their supply chain network resilience. As one of the strategies to maximize the use of information and communication technologies in business, digital transformation can enable enterprises to improve organizational flexibility, better adapt to the changes and pressures of the external environment, and provide technical support for supply chain resilience by improving their agility, ecology, and intelligence (Rozak et al., 2021). As an essential part of digital transformation, the emerging technology of blockchain has been advocated in supply chain management. The adoption of blockchain technology can facilitate the digital transformation and development of enterprises, especially small/medium-sized enterprises (SMEs) in the post-COVID-19 era (Rozak et al., 2021).

Blockchain has the characteristics of decentralization, traceability, non-tampering, distrust, openness, and transparency (Swan, 2015; Appelbaum and Smith, 2018). These characteristics can lay a solid trust foundation for various parties in supply chains (Meng et al., 2018; Mengelkamp et al., 2018; Zou et al., 2020). Programs in the blockchain can provide reliable computing support for trusted storage (Omohundro, 2014; Rimba et al., 2020), which improves data credibility and offers technical support for solving credit problems in the information age (Claudia et al., 2018). The adoption of blockchain technology in supply chains can improve the integration and collaboration among enterprises and reduce demand uncertainty, thus optimizing their operational performance (Aslam et al., 2021).

However, the popularization of blockchain technology in the supply chain still faces significant difficulties. Among them, the greatest hindrance to the promotion of blockchain technology is its high development and usage costs (Rimba et al., 2020). Specifically, the development requirements of blockchain technology are high, and the technical design is complex. Many aspects of blockchain development require high development costs, including coordination between the smart contract deployment and execution, as well as software program development (Rimba et al., 2020). Such a financial burden to enterprises becomes the biggest obstacle to their participation in blockchains.

To alleviate the cost pressure of blockchain technology development and promote its development in the supply chain field, enterprises have begun to develop blockchain technology collaboratively. Collaboration means that an enterprise seeks innovative resources from external sources or establishes a cooperative development mechanism with other enterprises (Gong et al., 2021). In the supply chain, many SMEs are inclined to cooperate with core enterprises. For the SMEs, on the one hand, the development cost and investment are huge. Cooperation with core enterprises in the supply chain for technology development can help alleviate the development cost pressure on SMEs and reduce their financial burden. Blockchain technology has inherent advantages in supply chain credit management, which helps improve the credit value of SMEs in supply chain transactions. It provides technical support to solve the financing difficulties caused by credit problems. On the other hand, the adoption and development of blockchain technology have become an important strategy when engaging in supply chain competition (Ricciardi et al., 2018; Aslam et al., 2021). The technology investment of core enterprises can also provide technical support for the technology development of SMEs, which plays a certain positive role in improving the blockchain technology development capability. For the core enterprises, developing blockchain technology solely with internal development resources is difficult due to increasingly complex and fierce market competition. Cooperating with the SMEs can help them obtain information, knowledge, and technology (Bellamy et al., 2014). Therefore, the collaboration between core enterprises and SMEs contributes to the development and application of blockchain technology in supply chains. When solving problems of high technology development cost, supply chain contracting is an effective way to achieve collaborative development (Zhang and Liu, 2008; Gong et al., 2021). The use of supply chain contract means the distribution of benefits, rights, and responsibilities. Contracting in terms of cost and income can help SMEs alleviate the development cost problem and is beneficial to ensure effective supply chain coordination. This paper thus discusses the collaborative development of blockchain technology from the perspective of contract coordination. It analyzes how to effectively encourage participants in a supply chain to develop blockchain technology through supply chain contract design to help enterprises maximize their performance.

Although existing studies analyze the influencing factors that affect the blockchain application in SMEs (Nayak and Dhaigude, 2019; Kumar Bhardwaj et al., 2021), a research gap remains in the collaborative development of blockchain between core enterprises and SMEs in supply chains. By analyzing blockchain technology, this paper establishes a supply chain contract model to coordinate the collaborative development of blockchain technology between a core enterprise and an SME, discusses the design of supply chain contracts to realize the optimal collaborative development of blockchain technology, and provides insights for enterprises to develop blockchain technology cooperatively. Specifically, we answer the following questions: i) What is the optimal development level of blockchain technology and supply chain profit under centralized and decentralized decision-making mechanisms when no agreement exists between the core enterprise and SME? ii) Can the introduction of cost-sharing (CS) and revenue-sharing (RS) contracts improve the development level of blockchain technology and the profit of the supply chain? iii) How can supply chain contracts be designed to maximize supply chain profits?

The results indicate that i) CS and RS contracts can achieve a certain degree of coordination for the collaborative blockchain technology development under certain conditions and improve the blockchain development level and profit of the core enterprise and the SME. ii) The coordination ability of CS contract is better than that of RS contract, but compared with centralized decision making, neither contract can achieve coordination. iii) The hybrid CS-RS contract designed in this paper can achieve optimal coordination and maximize the supply chain profit. Moreover, the optimal coordination effect decreases when risk aversion is considered.

In addition, we obtain useful managerial insights by extending our basic model. First, the blockchain development level of the core enterprise and SME is lower under the condition of uncertain demand. The higher the risk aversion degree, the greater the demand fluctuation and the lower the profit. Second, the regulation effect of the two-part tariff (TPT) contract is lower than that of the CS-RS contract, and the blockchain development level and supply chain utility of the enterprises under the TPT contract are lower. Third, supposing that the market demand is only affected by the lowest blockchain development level of the party in the supply chain, the optimal blockchain development level and supply chain utility of enterprises in the supply chain are reduced. Fourth, when considering the impact of information asymmetry on the SME, the optimal blockchain development level and supply chain utility of enterprises in the supply chain are improved.

The research contribution of this paper mainly includes the following two aspects. First, this paper extends the supply chain contract theory to the research of blockchain development, which provides a new solution for promoting the blockchain development in the supply chain. Second, we innovatively put forward a hybrid CS-RS contract to realize the optimal coordination of the supply chain that differs from the traditional contract models in the previous literature (Chao et al., 2009; Huang et al., 2016; Zhou et al., 2020). In so doing, we provide an innovative contract model for the research of blockchain technology development contract as well as a new research idea for the research of supply chain contract.

This study also makes an important contribution to enterprises' participation in the development practice of blockchain technology. The proposed CS-RS contract can achieve the coordination of supply chain within a certain range and solve the cost problem hindering the development of the blockchain technology. Our results highlight the significance of coordinating the cooperative development using contracts for the development of innovative technology and provide insights for enterprises that decline their participation in blockchain due to its high development cost.

The rest of this paper is organized as follows. Section 2 is a literature review in which relevant studies on the concept and development of blockchain technology, supply chain collaboration research, and supply chain contracts are summarized and analyzed. Section 3 elaborates on the collaborative development model and its basic assumptions. Section 4 compares the coordination effects of traditional CS and RS contracts and proposes a new hybrid contract. Sections 5, 6, and 7 present the numerical studies, the model expansion, and the result discussion, respectively. Section 8 concludes the paper and provides corresponding managerial insights.

2 Literature review

Basing on the keywords "blockchain development" and "contract", we search the literature since the emergence of the blockchain concept in 2008 through the Web of Science Core Collection and obtain a total of 1465 articles. By reading and summarizing these articles, the number of core journal articles about blockchain technology has risen year by year since 2016. However, more articles focus on the research mechanism, main characteristics, and applications of blockchain technology. By reviewing these studies, we observe a research gap in how to promote blockchain technology development from the perspective of supply chain management. This section provides a detailed review and analysis of the development and application of blockchain technology, collaborative research in supply chains, and supply chain contract coordination.

2.1 Development and application of blockchain technology

The COVID-19 pandemic has exposed that traditional supply chain network design is no longer effective, highlighting the importance of supply chain resilience. As one of the cutting-edge technologies to help enterprises recover quickly in the post-pandemic era, blockchain technology is conducive to the improvement and recovery of enterprises and supply chain networks (Shi et al., 2021). Blockchain technology is a relatively developed emerging distributed accounting technology (Babich and Hilary, 2020). Given its advantages in breaking the traditional information monopoly, ensuring the authenticity and traceability of data, and solving the problem of data security and trust in big data (Li et al., 2017; Karafiloski and Mishev, 2017; Cai et al., 2018), it has been gradually expanded from the financial industry to other industries (Christidis and Devetsikiotis, 2016). In most supply chains, purchasers may be able to monitor certain operational aspects of their suppliers at tier 1, but rarely at tier 2 and above. The emergence of blockchain technology increases the possibility of obtaining real data from higher-level suppliers (Babich and Hilary, 2020). Furthermore, in real transactions, upstream and downstream enterprises of supply chains may need to share sales or procurement data to reduce the bullwhip effect and other negative influences on supply chains (Dolgui et al., 2020; Xu et al., 2021). To solve this problem, traditional databases generate substantial marginal costs and transaction costs, but the application of blockchain technology can reduce transaction costs, remove the intermediary role, and provide support for information exchange and security between enterprises (Pereira et al., 2019; Schmidt and Wagner, 2019). To this end, the development of blockchain technology is particularly crucial for supply chain development.

Blockchain technology emerged in 2016. Many enterprises announced they would invest in the development of blockchain technology, but most of the projects were interrupted within a year (Browne, 2017). The development cost and technological uncertainty of blockchain technology hindered their large-scale development (Babich and Hilary, 2020). One of the important consequences of a decentralized blockchain is that the database versions may be inconsistent. Therefore, enterprises sharing the same network need a consensus mechanism to ensure the convergence of the blockchain technology application versions. The key problem with this approach is that it requires a leader to steer this behavior (Babich and Hilary, 2020). The leadership role of core enterprises is particularly important in the development of blockchain technology cooperation between the core enterprise and the SME. So far, the research on blockchain technology development has been carried out from the aspects of development framework, functional architecture, application, classification of blockchain platform development, and others

(Zeng and Zhang, 2019; Zhao, 2019; da Cunha et al., 2021; Xiao et al., 2021). Detailed research on the collaborative development of blockchain technology in supply chains is lacking. From the perspective of blockchain technology development, this paper applies supply chain contracts to implement collaborative development among enterprises, which is significant for the development and promotion of blockchain technology in supply chains.

2.2 Supply chain collaboration

Supply chain collaboration is an important method to realize resource sharing, solve the problem of development cost, and improve enterprise development cooperation and innovation (Powell et al., 1996; Cao et al., 2010; Li et al., 2014; Liu et al., 2018; 2022b; Um and Kim, 2019). Collaboration is the sharing of tangible and intangible resources between interconnected businesses to achieve the growth of enterprise value (Thomas, 1997). In a supply chain, it is the mutual sharing of business data, joint product forecasting, and planning by two or more independent enterprises to meet the needs of end customers (Simatupang and Sridharan, 2004). Supply chain collaboration promotes the smooth development of business cooperation via coordination and cooperation among enterprises at each node in the supply chain, thus enhancing the competitiveness of the whole supply chain (Manthou et al., 2004; Liu et al., 2021c). Regarding the collaborative relationship of the supply chain, existing articles mostly start from the collaborative perspective of supply chain participants, exploring the impact of the collaboration between suppliers (Huang et al., 2016) and upstream and downstream enterprises (Barratt, 2004) on supply chain performance. These studies focus on the upstream and downstream relationship of the supply chain, assuming that enterprises are in an equal position (Barratt, 2004; Huang et al., 2016). However, the supply chain is usually composed of the core enterprise and the SME, in which the former has relatively strong scale and strength to lead the supply chain operation, whereas the latter acts as a follower due to its weak resources and scale. An unequal supply chain structure needs to be further addressed in the study of supply chain collaboration.

For the collaborative objects of the supply chain, current research focuses more on collaborative innovation and sales of products. For example, Zhou et al. (2020) conduct a study on collaboration to deal with byproducts from two manufacturers and a downstream processing factory. The optimal capacity and price of both competition sides when the supply chain has limits are determined. Awasthy and Hazra (2020) analyze the coordination problem between service providers and suppliers in the provision of information technology services. Yatsuka et al. (2020) investigate how a collaborative strategy can be developed to maximize the satisfaction of multiple participants in a buyer-led supply chain. However, current research barely involves the collaborative development of blockchain technology. In view of the fundamental differences in trust between blockchain technology and other ordinary technologies, studying the collaborative development of blockchain technology is of definite significance.

2.3 Supply chain contracts

A supply chain contract is an effective way to ensure supply chain coordination. It refers to the provision of appropriate information and incentive to ensure coordination between buyers and sellers and optimize the performance of sales channels. Commonly used supply chain contracts include wholesale price, CS, and RS contracts.

With wholesale price contracts, manufacturers usually specify the wholesale price of products, and then the seller decides the purchase quantity for profit maximization (Spengler, 1950; Pasternack, 1985). Research and business practice show that how manufacturers provide certain incentives and share market risks can increase the order quantities (Kim et al., 2007; Yalabik et al., 2014; Heydari and Asl-Najafi, 2021). CS contracts are proven effective. They are usually applied to coordinate the problem of product quality improvement or service level improvement in the supply chain, with the purpose of motivating supply chain members to improve their technology development level by sharing costs (Chao et al., 2009; Leng and Parlar, 2010; Ghosh and Shah, 2015). RS contracts are also regarded as an effective incentive measure to coordinate supply chain members by promising to share some revenue after cooperation (Liu et al., 2021b). Mortimer (2000) show that RS contracts can increase the profit of the supply chain by approximately 7%. However, the disadvantages of RS contracts are that the management cost of contract execution is too high and their implementation may reduce the marketing enthusiasm of RS participants (Cachon and Lariviere, 2005). Comfortingly, hybrid contracts have a better coordination effect on the improvement of the overall profit of the supply chain. Yang and Du (2016) establish a hybrid contract model (i.e., a combination of RS contracts and quantity discount contracts) based on system dynamics. The results show that the hybrid contract is more conducive to improving the overall efficiency of the supply chain.

According to the studies mentioned above, wholesale price, CS, and RS contracts are widely adopted in the collaborative transformation of supply chains. The current literature mainly focuses on the contractual coordination of production and sales in the traditional supply chain though. The collaborative development of blockchain technology between the core enterprise and the SME is ignored and needs to be considered.

2.4 Summary of the literature review

As indicated from the above literature review, many scholars study the characteristics and applications of blockchain technology. However, insufficient attention is given to the collaborative adoption of blockchain technology. In addition, many studies employ supply chain contracts to promote innovation. Still, few articles focus on the supply chain coordination problem when both core enterprise and SME need to improve the development level of blockchain technology simultaneously. Table 1 compares our study with the four most relevant studies in the literature. Studies on the adoption of blockchain technology from the supply chain contract perspective are lacking. Therefore, analyzing the collaborative adoption of blockchain technology from the perspective of supply chain contracts is of great research value.

3 Model building

3.1 Problem description

To help solve the problem of collaborative adoption of blockchain technology between core enterprises and SMEs, we establish a Stackelberg game model in which a core enterprise acts as a leader and an SME as a follower. The reason for choosing this model is that, on the one hand, during technology development, a core enterprise is usually the leading force in the supply chain, and other enterprises play a follower role. Many practical cases in the real-world technology development of blockchain (e.g., JD Chain) are consistent with our model. On the other hand, the Stackelberg model can depict the leader–follower relationship, which is suitable for the real-world scenarios of blockchain technology development. Based on the characteristics of blockchain technology to enhance trust between supply chain members, different contracts are designed, and their corresponding coordinating effects are investigated.

3.2 Model assumptions

Blockchain technology brings real-time traceability (Helo and Shamsuzzoha, 2020), shortens delivery time (Kamble et al., 2020), improves transparency among supply chain members (Banerjee, 2018), and reduces the appearance of fake and inferior products (Azzi et al., 2019). With these advantages, the credit level of enterprises can be greatly improved, which then improves their competitiveness (Delloite, 2019). In this study, we assume the core enterprise as an upstream supplier and the SME as a downstream distributor. The products flow from the core enterprise to the SME and finally to customers. In this process, the degree of blockchain system development of the core enterprise and SME jointly determines the overall development effect of blockchain technology in the supply chain, so it has a joint impact on the market demand. For example, according to our interview with three managers of JD.COM auto parts supply chain department on August 17, 2022, JD.COM applied blockchain technology in the quality traceability service of auto parts supply chain. As the blockchain level of the supply chain member in different links varies, the interviewed managers indicated that the blockchain development level in the upstream and downstream of the supply chain jointly affects the final market demand. In addition, in this study, the decision-making information is symmetrical on both sides. On the one hand, the technology and information needed for blockchain development belong to public resources to both sides of the supply chain. Therefore, the development cost of blockchain technology is public information and transparent to both sides of the supply chain (Hayrutdinov et al., 2020; Yang et al., 2022). Moreover, as public information, the sales price of core enterprise is easy for the SME to obtain from the market, and this parameter is also shared. The production transaction price of the core enterprise and SME is shared as well. On the other hand, this paper studies the strategies to promote the development of blockchain technology, rather than the state of the enterprise after the development of blockchain technology. During development, both parties can share corresponding information on the basis of cooperation to achieve better decision-making effect. The application of blockchain technology can provide technical support for the information sharing of supply chain enterprises (Wu et al., 2022). We expand this research in Section 6.4. However, information symmetry

Table 1 Comparison of the existing studies with this study

Research object	Chao et al. (2009)	Huang et al. (2016)	Zhou et al. (2020)	Kumar Bhardwaj et al. (2021)	This paper
	Manufacturers and suppliers	The ternary structure of supplier-supplier-manufacturer	Two manufacturers and downstream factories	SME	A core enterprise and an SME
Is there a need for technical development or transformation	√	×	×	√	√
Whether to consider the synergy between the two parties	×	√	√	×	√
Whether to compare the synergistic effects of different contracts	√	×	×	×	√
Whether to apply the hybrid contract	×	×	×	×	√

after blockchain application is not the main research focus of this study, so the impact of information asymmetry is not considered in the basic assumptions.

With the improvement of the development level of the blockchain, the market's trust in the products in the supply chain increases accordingly, so the market demand increases, too. At the same time, owing to the different influences of the core enterprise and SME on the market, the development level of blockchain on both sides have varying demand promotion effects. Hence, according to the description of the demand function by Savaskan et al. (2004) and Wei et al. (2022), we assume that the market demand is $D = q_0 + \theta_1 m_1 + \theta_2 m_2$. Here, q_0 is the base market demand not affected by the blockchain, m_1 and m_2 represent the development degree of the blockchain system of the core enterprise and the SME, respectively, and θ_1 and θ_2 denote the impact coefficient of the core enterprise's and the SME's blockchain development level on market demand, respectively.

When the core enterprise joins the blockchain, it produces the corresponding development cost of blockchain technology. According to the theory of increasing marginal costs, considering that the development of blockchain technology requires a large amount of technical investment, the quadratic cost function is applied to capture the trend of the accelerated rise of related costs. Following Liu et al. (2017b), we assume that the core enterprise's development cost of blockchain is $\alpha m_1^2/2$, where α is the cost coefficient of the core enterprise's development of blockchain technology. Moreover, as the technical capabilities and capital reserves of the SME are relatively weak, the SME tends to rely on blockchain platforms of the core enterprise. Therefore, the impact of the SME's blockchain development level on the development cost of the core enterprise is omitted in this study. The development of blockchain technology requires substantial technical input, and the quadratic cost function can well represent the trend of the acceleration of related costs. Existing studies adopt the same service-level cost assumption (Jiang et al., 2016; Chakraborty et al., 2019). This paper focuses on collaborative blockchain development, which is independent of the developed blockchain operation, to solve the blockchain development problems and promote the development and application of blockchain. Blockchain operations is already researched (Li et al., 2020; Wang et al., 2021), so the operating cost of the application process of the blockchain is not considered in this model.

In the supply chain, the development level of blockchain technology of the core enterprise has a certain supporting influence on that of the SME (Ottati, 1996; Kumar Bhardwaj et al., 2021). When an SME builds its own blockchain nodes, the cost of developing blockchain technology is not only related to its own cost coefficient but also affected by the blockchain development level of the core enterprise. That is, the blockchain technology development level of the core enterprise can reduce the cost of blockchain development for the SME. Therefore, following Xie et al. (2016), the influence parameter of core enterprises on the blockchain development cost of the SME is β_2/m_1. Considering the joint influence of the blockchain development level of the two enterprises on the blockchain development cost of the SME, we assume that the SME's blockchain technology development cost is $\frac{1}{2}\beta_1 m_2^2 \frac{\beta_2}{m_1} = \frac{1}{2}\frac{\beta_1\beta_2}{m_1} m_2^2$, where β_1 is the cost coefficient for the SME to develop blockchain technology, and β_2/m_1 reflects the impact of the core enterprise on the blockchain development cost of the SME. For simplicity, by denoting $\beta = \beta_1\beta_2$, the blockchain development cost of the SME is $\beta m_2^2/2m_1$.

The credit valuation of the SME participating in the development of blockchain technology is defined as $km_1 + (a + m_2 b)$, where k is the influence coefficient of the core enterprise's blockchain development level on the credit value of the SME, and a and b represent the basic credit value and variable credit value, respectively (Moorthy and Png, 1992; Chen, 2001; Zhang et al., 2017). The core enterprise's blockchain development level has a certain promotion effect on the improvement of the SME's credit value. A unit change in the variable credit value generated by participation in the blockchain can be directly reflected in the credit revenue it later produces. That is, the more efforts the SME makes to build the blockchain, the more credit gains it obtains from supporting the blockchain.

The participation of the core enterprise in the development of blockchain technology can improve the credit value of the enterprise. Moreover, the improvement of the SME's credit value has a positive impact on the blockchain development of the core enterprise. Thus, obtaining real data and information and supervising the SME are advantageous for the core enterprise to improve its operational efficiency and profitability. We denote the positive impact of the SME's credit value as $w(a + m_2 b)$, where w is the positive influence coefficient of the SME's credit value on the core enterprise. The impact of the core enterprise's participation in blockchain collaboration on its own revenue is $K[m_1 + w(a + m_2 b)]$, where K is the impact coefficient of blockchain development on the credit value of the core enterprise (Liu et al., 2021b).

After participating in a blockchain, the SME can improve its credit level and enhance its data credibility (Wang and Hu, 2020). Here, the credit revenue generated to the SME by participating in the blockchain is denoted as $W[km_1 + (a + m_2 b)]$, where W represents the influence coefficient of the SME's credit value on its own credit revenue due to its participation in blockchain technology development.

Table 2 lists the parameters related to the model establishment.

Table 2 Meaning of model parameters

Notation	Description
p_1	Average unit marginal profit of the core enterprise participating in blockchain
p_2	Average unit marginal profit of the SME participating in blockchain
q_0	Base market demand without blockchain development
θ_1	Influence coefficient of the core enterprise participating in blockchain development on market demand
θ_2	Influence coefficient of the SME participating in blockchain development on market demand
m_1	Development level of blockchain of the core enterprise
m_2	Development level of blockchain of the SME
α	Influence coefficient of the core enterprise's own development cost
β_1	Influence coefficient of the SME's own development cost
β_2	Influence coefficient of the core enterprise on the development cost of the SME
K	Influence coefficient of the blockchain development of the core enterprise on its own credit value
W	Influence coefficient of the credit value of the SME on its own credit revenue
k	Influence coefficient of the blockchain development level of the core enterprise on the credit value of the SME
w	Influence coefficient of the credit value of the SME on the core enterprise's revenue
U^i	Total profit of the supply chain in model *i*
U^i_c	Profit of the core enterprise in model *i*
U^i_m	Profit of the SME in model *i*

3.3 Model setup

According to the analysis so far, we establish a basic Stackelberg game model to investigate optimal decisions of a core enterprise and an SME on their development levels of blockchain technology. The impact of adopting blockchain technology on their profits under centralized and decentralized decision-making mechanisms without coordination by supply chain contracts is analyzed in this subsection.

3.3.1 Decentralized decision making

In practice, enterprises often make technology development decisions independently (Massimino et al., 2017). Here, the core enterprise is assumed to have a first-mover advantage in decision making. When both parties participate in the blockchain, their profit functions are as follows:

$$U_\mathrm{c} = p_1(q_0+\theta_1 m_1+\theta_2 m_2)+K[m_1+w(a+m_2 b)]-\frac{1}{2}\alpha m_1^2, \tag{1}$$

$$U_\mathrm{m} = p_2(q_0+\theta_1 m_1+\theta_2 m_2)+W[km_1+(a+m_2 b)]-\frac{1}{2}\frac{\beta}{m_1}m_2^2. \tag{2}$$

Here, $p_1(q_0+\theta_1 m_1+\theta_2 m_2)$ and $p_2(q_0+\theta_1 m_1+\theta_2 m_2)$ represent the base profit of the core enterprise and the SME, respectively. By backward induction (Liu et al., 2017a), we obtain their optimal blockchain development levels as shown below:

$$m_1^D = \frac{p_1\theta_1+K}{\alpha}+\frac{(p_1\theta_1+Kwb)(p_2\theta_2+Wb)}{\alpha\beta}, \tag{3}$$

$$m_2^D = \frac{p_2\theta_2+Wb}{\beta}m_1^D. \tag{4}$$

Then, the optimal profits of the core enterprise and the SME can be calculated as shown in Eqs. (5) and (6), respectively, and the supply chain profit is presented in Eq. (7):

$$U_\mathrm{c}^D = p_1 q_0+Kwa+\frac{1}{2}\alpha(m_1^D)^2, \tag{5}$$

$$U_\mathrm{m}^D = p_2 q_0+Wa+\left[p_2\theta_1+Wk+\frac{(p_2\theta_2+Wb)^2}{2\beta}\right]m_1^D, \tag{6}$$

$$U^D = pq_0+(Kw+W)a+\frac{1}{2}\alpha(m_1^D)^2 +\left[p_2\theta_1+Wk+\frac{(p_2\theta_2+Wb)^2}{2\beta}\right]m_1^D. \tag{7}$$

3.3.2 Centralized decision making

In this subsection, we consider the situation in which the core enterprise and the SME jointly determine their development levels of blockchain technology. Under this circumstance, the overall profit function of the supply chain is:

$$U^C = p(q_0+\theta_1 m_1+\theta_2 m_2)+K[m_1+w(a+m_2 b)] + W[km_1+(a+m_2 b)]-\frac{1}{2}\alpha m_1^2-\frac{1}{2}\frac{\beta}{m_1}m_2^2. \tag{8}$$

To maximize the supply chain profit, their optimal blockchain development levels can be calculated as provided below:

$$m_1^C = \frac{p\theta_1+K+Wk}{\alpha}+\frac{(p\theta_2+Kwb+Wb)^2}{2\alpha\beta}, \tag{9}$$

$$m_2^C = \frac{p\theta_2+Kwb+Wb}{\beta}m_1^C. \tag{10}$$

Calculating the Hessian matrix for $\pi(m_1, m_2)$ under (m_1^C, m_2^C) as shown in Eq. (11), we find that the first-order leading principal minor is negative, whereas the second-order principal minor is positive. Therefore, the matrix is negative, and the optimal solution obtained is a maximum value.

$$\boldsymbol{H} = \begin{bmatrix} \frac{\partial^2 U}{\partial m_1^2} & \frac{\partial^2 U}{\partial m_1 \partial m_2} \\ \frac{\partial^2 U}{\partial m_2 \partial m_1} & \frac{\partial^2 U}{\partial m_2^2} \end{bmatrix} = \begin{bmatrix} -\alpha-\beta\frac{m_2^2}{m_1^3} & \beta\frac{m_2}{m_1^2} \\ \beta\frac{m_2}{m_1^2} & -\frac{\beta}{m_1} \end{bmatrix}. \tag{11}$$

Hence, the total profit of the supply chain is:

$$U^C = pq_0+(Kw+W)a+\frac{1}{2}\alpha(m_1^C)^2. \tag{12}$$

Theorem 1: $U^C > U^D$, $m_1^C > m_1^D$, $m_2^C > m_2^D$.

Theorem 1 demonstrates that the total profit of a supply chain under centralization is always greater than that under decentralization. The development levels of blockchain of the core enterprise and the SME under centralization are also higher. This confirms that the decentralized system has room for improvement. The following attempts to design a supply chain contract to promote cooperation between the core enterprise and the SME improve their levels of blockchain development and thus improve the supply chain profit.

4 Supply chain contract coordination

4.1 CS contract

According to Theorem 1, the total profit of the supply chain and the development level of the blockchain under centralized decision making are greater than those under decentralized decision making. Therefore, a reasonable supply chain contract must be designed to coordinate and improve the development level of blockchain technology to improve the profit of the supply chain. The blockchain technology development studied in this paper belongs to technology investment, so it is not applicable to contract models directly aimed at sales such as wholesale price, repurchase, and quantity flexibility contracts. Moreover, according to existing studies, adding coordination parameters to contracts can improve the efficiency of contract coordination (Yan, 2015), but it also complicates contracts. Therefore, coordinating supply chain with appropriate parameters and achieving higher coordination efficiency are important reference standards for formulating supply chain contracts. CS and RS contracts are common supply chain contracts with fewer decision parameters and higher coordination efficiency (Yan, 2015; Yan and Zaric, 2016). CS and RS contracts play a key role in incentivizing product lifecycle sharing based on blockchain technology (Ran et al., 2020). Enterprises have different ideal application levels of digital technologies as well (blockchain, cloud computing, big data, etc.). Through the adjustment of CS and RS contracts, the application level of digital technology and supply chain performance are improved (Hayrutdinov et al., 2020). This paper thus introduces these two contracts to analyze the collaborative development of blockchain technology in the supply chain.

The collaborative development of blockchain technology is closely related to the development cost. The development cost then directly affects the willingness and results of enterprises to participate in blockchain development. Hence, we first design a contract to reduce the cost pressure for participants in blockchain development. As an effective approach to coordinating interests, CS contracts can stimulate supply chains with expensive development costs through CS. In the literature, CS contracts are widely applied in technology research and development (Chu and Sappington, 2009; Leng and Parlar, 2010) and supply chain collaboration (Ma et al., 2013). This section designs a CS contract to coordinate. In particular, a coefficient of CS, x, is first added in the model, where $x \in [0, 1)$. Then, the profit functions of the core enterprise and the SME are as follows:

$$U_{\mathrm{c}}^{CS} = p_1(q_0+\theta_1 m_1+\theta_2 m_2)+K[m_1+w(a+m_2 b)] -\frac{1}{2}\alpha m_1^2-\frac{1}{2}x\frac{\beta}{m_1}m_2^2, \tag{13}$$

$$U_{\mathrm{m}}^{CS} = p_2(q_0+\theta_1 m_1+\theta_2 m_2)+W[km_1+(a+m_2 b)] -\frac{1}{2}(1-x)\frac{\beta}{m_1}m_2^2. \tag{14}$$

Using backward induction, we can obtain the optimal blockchain development level of the core enterprise and the SME as shown below:

$$m_1^{CS}=m_1^D+\frac{x(p_2\theta_2+Wb)[2(1-x)(p_1\theta_2+Kwb)-(p_2\theta_2+Wb)]}{2(1-x)^2\alpha\beta}, \tag{15}$$

$$m_2^{CS} = \frac{p_2\theta_2 + Wb}{(1-x)\beta} m_1^{CS}. \tag{16}$$

The optimal profits of the core enterprise and the SME are provided in Eqs. (17) and (18), respectively, and the total profit of the supply chain is given in Eq. (19):

$$U_{\mathrm{c}}^{CS} = p_1 q_0 + Kwa + \frac{1}{2}\alpha (m_1^{CS})^2, \tag{17}$$

$$U_{\mathrm{m}}^{CS} = p_2 q_0 + Wa + \left[p_2\theta_1 + Wk + \frac{(p_2\theta_2 + Wb)^2}{2(1-x)\beta} \right] m_1^{CS}, \tag{18}$$

$$\begin{aligned} U^{CS} &= pq_0 + (Kw + W)a + \frac{1}{2}\alpha (m_1^{CS})^2 \\ &\quad + \left[p_2\theta_1 + Wk + \frac{(p_2\theta_2 + Wb)^2}{2(1-x)\beta} \right] m_1^{CS}. \end{aligned} \tag{19}$$

Finally, as the core enterprise is the leader, it can prioritize the decisions that are beneficial to it. We obtain $x^* = \dfrac{p_1\theta_2 + Kwb - (p_2\theta_2 + Wb)/2}{p_1\theta_2 + Kwb + (p_2\theta_2 + Wb)/2}$ to maximize the blockchain development level of the core enterprise, m_1^{CS}, and derive the following theorem.

Theorem 2: If $\max\left\{ \dfrac{p_1\theta_2 + Kwb - (p_2\theta_2 + Wb)/2}{p_1\theta_2 + Kwb + (p_2\theta_2 + Wb)/2}, 0 \right\} \geqslant x \geqslant 0$ or $p_1\theta_2 + Kwb > (p_2\theta_2 + Wb)/2$, $m_1^C > m_1^{CS} > m_1^D$, $m_2^C > m_2^{CS} > m_2^D$, $U_{\mathrm{c}}^{CS} > U_{\mathrm{c}}^D$, $U_{\mathrm{m}}^{CS} > U_{\mathrm{m}}^D$, $U^C \geqslant U^{CS} > U^D$.

Based on Theorem 2, compared with decentralization, a CS contract can improve the profit of each participant in the supply chain. The CS contract encourages the SME to improve its development level of blockchain and the overall benefits. However, although the CS contract improves the total profit of the supply chain, it does not achieve the optimal supply chain profit. In the case of the high development cost of blockchain, supply chain coordination can be realized under certain conditions by introducing a CS contract.

4.2 RS contract

Section 4.1 shows that the CS contract can coordinate the development of the supply chain blockchain, but it does not achieve the best coordination effect. An RS coordination contract is thus introduced in this section, in which the SME is encouraged to participate in blockchain technology development through RS. In the literature, RS contracts are widely used in cooperation problems (Palsule-Desai, 2013; Zhang and Zhou, 2016). From this perspective, this section introduces the RS contract in the model and discusses its coordination effect on the collaborative development of blockchain technology.

Similarly, by introducing the coefficient of RS, y ($y \in [0, 1)$), we allow the core enterprise to share its revenue gained from blockchain development with the SME. The profit functions of the core enterprise and the SME are presented in Eqs. (20) and (21), respectively:

$$\begin{aligned} U_{\mathrm{c}}^{RS} &= p_1 q_0 + (1-y)p_1(\theta_1 m_1 + \theta_2 m_2) \\ &\quad + K[m_1 + w(a + m_2 b)] - \frac{1}{2}\alpha m_1^2, \end{aligned} \tag{20}$$

$$\begin{aligned} U_{\mathrm{m}}^{RS} &= p_2(q_0 + \theta_1 m_1 + \theta_2 m_2) + yp_1(\theta_1 m_1 + \theta_2 m_2) \\ &\quad + W[km_1 + (a + m_2 b)] - \frac{1}{2}\frac{\beta}{m_1} m_2^2. \end{aligned} \tag{21}$$

By backward induction, we obtain the optimal blockchain development levels of the core enterprise and the SME, respectively, as shown below:

$$\begin{aligned} m_1^{RS} &= \frac{1}{\alpha}\left[(1-y)p_1\left(\theta_1 + \theta_2 \frac{(p_2 + yp_1)\theta_2 + Wb}{\beta} \right) \right. \\ &\quad \left. + K + Kwb \frac{(p_2 + yp_1)\theta_2 + Wb}{\beta} \right], \end{aligned} \tag{22}$$

$$m_2^{RS} = \frac{(p_2 + yp_1)\theta_2 + Wb}{\beta} m_1^{RS}. \tag{23}$$

Then, the optimal profit of the core enterprise and the SME and the profit of the supply chain can be given, respectively, as:

$$U_{\mathrm{c}}^{RS} = p_1 q_0 + Kwa + \frac{1}{2}\alpha (m_1^{RS})^2, \tag{24}$$

$$\begin{aligned} U_{\mathrm{m}}^{RS} &= p_2 q_0 + Wa \\ &\quad + \left[(yp_1 + p_2)(\theta_1 + \theta_2 A) + Wk + A - \frac{1}{2}A^2\beta \right] m_1^{RS}, \end{aligned} \tag{25}$$

$$\begin{aligned} U^{RS} &= pq_0 + (Kw + W)a + \frac{1}{2}\alpha (m_1^{RS})^2 \\ &\quad + \left[(yp_1 + p_2)(\theta_1 + \theta_2 A) + Wk + A - \frac{1}{2}A^2\beta \right] m_1^{RS}, \end{aligned} \tag{26}$$

where $A = \dfrac{(p_2 + yp_1)\theta_2 + Wb}{\beta}$. By maximizing the blockchain development level of the core enterprise m_1^{RS}, the optimal RS coefficient is obtained, where $y^* = \dfrac{p_1\theta_2^2 + Kwb\theta_2 - p_2\theta_2^2 - Wb\theta_2 - \beta\theta_1}{p_1\theta_2(\theta_1 + \theta_2)}$.

Theorem 3: If $\max\left\{ \dfrac{p_1\theta_2^2 + Kwb\theta_2 - p_2\theta_2^2 - Wb\theta_2 - \beta\theta_1}{p_1\theta_2(\theta_1 + \theta_2)}, 0 \right\} \geqslant y \geqslant 0$ or $p_1\theta_2^2 + Kwb\theta_2 > p_2\theta_2^2 + Wb\theta_2 + \beta\theta_1$, $m_1^C > m_1^{RS} > m_1^D$, $m_2^C > m_2^{RS} > m_2^D$, $U_{\mathrm{c}}^{RS} > U_{\mathrm{c}}^D$, $U_{\mathrm{m}}^{RS} > U_{\mathrm{m}}^D$, $U^C \geqslant U^{RS} > U^D$.

According to Theorem 3, compared with decentralization, the RS contract can improve the profit of each participant and the total profit of the supply chain.

Moreover, as the core enterprise shares part of the revenue with the SME, which encourages the SME to participate in blockchain development, the SME performs more actively to improve the blockchain development level to improve overall efficiency.

Theorem 4: When $p_1\theta_2 + Kwb > (p_2\theta_2 + Wb)/2$, $m_1^{CS} > m_1^{RS} > m_1^{D}$, $m_2^{CS} > m_2^{RS} > m_2^{D}$, $U^C > U^{CS} > U^{RS} > U^D$.

According to Theorem 4, with the RS contract, the overall profit of the supply chain and the blockchain development levels of the core enterprise and the SME are greater than that with decentralized decision making when $p_1\theta_2 + Kwb > (p_2\theta_2 + Wb)/2$, but the effect is generally lower than that with the CS contract. This is because the cost of developing the blockchain is too high, and the RS obtained is not enough to encourage the SME to expend sufficient effort to participate in the blockchain. This finding is similar to the results obtained by Cachon and Lariviere (2005), in which the RS contract is not always effective in the supply chain, especially when the chain depends on the efforts of expensive retailers. By contrast, the CS contract fundamentally reduces the burden of the SME from the very beginning. Therefore, enterprises are more motivated to develop blockchain, thus improving supply chain revenue.

4.3 Hybrid CS-RS contract

From the above analysis, both CS and RS contracts can achieve supply chain coordination to a certain extent. Still, they do not achieve the best coordination compared with that under centralized decision making. Existing studies find that the combination of CS contract and RS contract can achieve better coordination effect (Yan, 2015). In this section, a hybrid CS-RS contract is proposed and introduced in the model to coordinate and optimize the supply chain so as to achieve optimal supply chain coordination. Under this hybrid CS-RS contract, the core enterprise first shares the development cost of the SME. At the same time, the SME needs to share some of the profit gained from participating in the blockchain with the core enterprise to ensure that the core enterprise actively participates in the blockchain. After gaining profit, the core enterprise shares part of the sales profit gained from participating in the blockchain with the SME to ensure that the SME still has the motivation to develop the blockchain while making concessions on sales revenue. The revenue gained from developing the blockchain is related to their efforts, encouraging both participants to participate in the blockchain actively.

Specifically, by introducing the coefficient of CS, $u \in [0, 1)$, sales profit sharing coefficient, $v \in [0, 1)$, and coefficient of RS, $t \in [0, 1)$, the profit function of the core enterprise and the SME is given, respectively, as follows:

$$\begin{aligned}U_{\mathrm{c}}^{CR} &= p_1q_0 + K[m_1 + w(a + m_2b)] \\ &\quad + (1-t)\left[(p_1 + vp_2)(\theta_1m_1 + \theta_2m_2) - \frac{1}{2}\alpha m_1^2 - \frac{1}{2}u\frac{\beta}{m_1}m_2^2\right],\end{aligned} \tag{27}$$

$$\begin{aligned}U_{\mathrm{m}}^{CR} &= p_2q_0 + (1-v)p_2(\theta_1m_1 + \theta_2m_2) \\ &\quad + W[km_1 + (a + m_2b)] - \frac{1}{2}(1-u)\frac{\beta}{m_1}m_2^2 \\ &\quad + t\left[(p_1 + vp_2)(\theta_1m_1 + \theta_2m_2) - \frac{1}{2}\alpha m_1^2 - \frac{1}{2}u\frac{\beta}{m_1}m_2^2\right].\end{aligned} \tag{28}$$

Using backward induction, we obtain the optimal blockchain development levels of the core enterprise m_1^{CR} and the SME m_2^{CR}. To achieve full coordination under centralized decision making, we set $m_1^{CR} = m_1^{C}$, $m_2^{CR} = m_2^{C}$. Subsequently, we can obtain the following:

$$v^* = \frac{p_1\theta_1 + p_2\theta_2 - p_1\theta_2 + wk}{p_2\theta_2} + \frac{Kt}{p_2\theta_2(t-1)}, \tag{29}$$

$$u^* = \frac{(t-1)(v^*p_2\theta_2 + p_1\theta_2) - Kwb}{B(t-1)}, \tag{30}$$

where $B = p\theta_2 + Kwb + Wb$. The optimal profits for the core enterprise and the SME are obtained, as shown below:

$$U_{\mathrm{c}}^{CR} = p_1q_0 + t(U^C - pq_0), \tag{31}$$

$$U_{\mathrm{m}}^{CR} = p_2q_0 + (1-t)(U^C - pq_0). \tag{32}$$

Theorem 5: When $v = v^*$, $u = u^*$, and $\frac{U_{\mathrm{m}}^{D} - p_2q_0}{U^C - pq_0} \leqslant t \leqslant 1 - \frac{U_{\mathrm{c}}^{D} - p_1q_0}{U^C - pq_0}$, $m_1^{CR} = m_1^{C}$, $m_2^{CR} = m_2^{C}$, $U^{CR} = U^C$, $U_{\mathrm{c}}^{CR} > U_{\mathrm{c}}^{D}$, $U_{\mathrm{m}}^{CR} \geqslant U_{\mathrm{m}}^{D}$.

Under the above conditions, the CS-RS contract can achieve the highest development levels for the two enterprises. Moreover, the total profit of the supply chain reaches the optimal level in centralized decision making, and the profits of both the core enterprise and the SME are greater than those obtained under the CS contract. Their increased profits depend on the proportion to be shared. In general, under the CS-RS contract, both participants can be motivated to develop blockchain technology actively, thus increasing their profit and maximizing the supply chain profit.

Theorem 6: If and only if $\max\left\{\frac{U_{\mathrm{m}}^{D} - p_2q_0}{U^C - pq_0}, Z_1\right\} \leqslant t \leqslant \min\left\{1 - \frac{U_{\mathrm{c}}^{D} - p_1q_0}{U^C - pq_0}, Z_2, Z_3\right\}$, can the CS-RS contract achieve full coordination, in which we have $Z_1 = \frac{(p + p_1)(\theta_2 - \theta_1)}{K - [p\theta_1 + p_1(\theta_1 - \theta_2) + wk]}$, $Z_2 = \frac{p_1\theta_2 - p\theta_1 - wk}{p_1\theta_2 - p\theta_1 - wk - K}$, and $Z_3 = \frac{wk - p(\theta_2 - \theta_1)}{K - [p(\theta_2 - \theta_1) - wk]}$.

In the collaborative development model of blockchain technology, the core enterprise needs to scientifically adjust the contract to ensure that the proportion of CS, RS, and sales profit sharing is within a reasonable range to encourage both participants to improve the development level and realize the optimal coordination of the supply chain.

5 Numerical simulation

In this section, we use MATLAB 2018a to carry out numerical analysis on the abovementioned models: The centralized decision-making model, decentralized decision-making model, CS contract model, RS contract model, and newly proposed CS-RS contract model. The results obtained from the five models in terms of the development level of blockchain technology and profits of both parties are compared to verify the derived theorems.

5.1 Parameter setting

The parameter setting follows the basic assumptions of price and cost from Qu et al. (2016). According to the characteristics of the model in this paper, the parameter settings are shown in Table 3.

5.2 Comparison between decentralization and centralization

Considering the impact of participating in the blockchain on the credit evaluation of the supply chain, we analyze the change in the development level of blockchain in each model with the change in variable credit value b through numerical simulation. Figures 1 and 2 show, respectively, the development level of blockchain technology and profits of the core enterprise (abbreviated as C) and the SME under decentralized and centralized decision making.

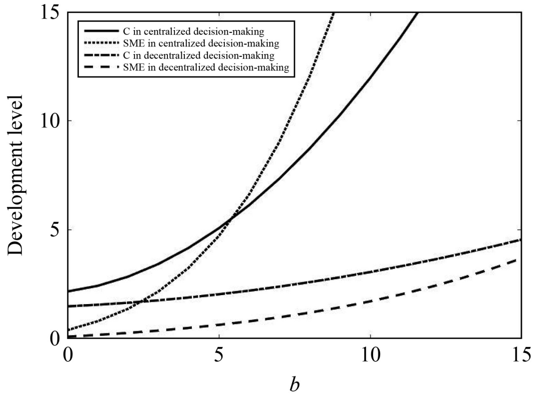

Fig. 1 Development levels m_1 and m_2 in decentralized and centralized decision-making models.

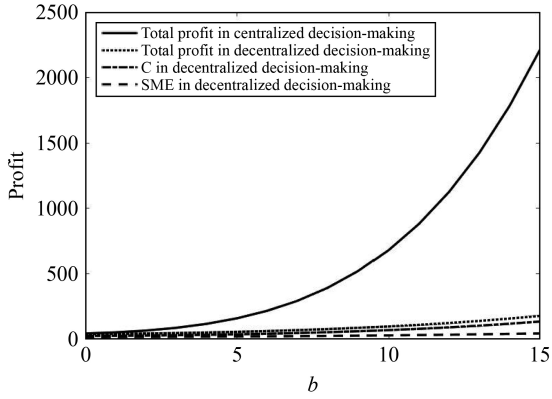

Fig. 2 Profits U in decentralized and centralized decision making.

Figure 1 shows the changes in the development level of blockchain technology of the core enterprise and the SME with the change of the credit coefficient under decentralized and centralized decision making. With the improvement of the variable coefficient of credit, all levels increase, and the development level of the core enterprise and SME under centralized decision making are higher than those under decentralized decision making. Furthermore, whether it is a core enterprise or SME, the blockchain development level in centralized decision making is always higher than that in decentralized decision making, so there is great room for optimization of the blockchain development level. A reasonable contract model can be designed to motivate the core enterprise and SME to improve the blockchain development level, which is consistent with the finding summarized in Section 3.

Figure 2 shows the profit changes of the core enterprise, SME, and overall supply chain as a function of the credit coefficient under decentralized and centralized decision making. All profits increase with b. Moreover, the total profit of the supply chain under centralized decision making is always greater than that under decentralized decision making. The supply chain profit gap under the two decision-making models gradually increases, indicating that the supply chain has a gap for optimization under decentralized decision making, especially when the variable credit level is high. It also indicates that an appropriately designed contract can improve the overall

Table 3 Numerical simulation parameter setting

Parameter	p_1	p_2	q_0	θ_1	θ_2	K	k	W	w	a	α	β
Value	12	6	0	1.5	1	5	1	1	3	0	16	100

profit of the supply chain.

5.3 Comparison between traditional CS and RS contracts

This section compares the development level and profit of the core enterprise and SME under CS and RS contracts, respectively. When $b = 10$, there is a room for improvement in the total profit value of the supply chain and the development level of the blockchain. To make the results more obvious, we set $b = 10$ in this section. The RS contract achieves partial coordination if $0 \leqslant x \leqslant \frac{p_1\theta_2 + Kwb - (p_2\theta_2 + Wb)/2}{p_1\theta_2 + Kwb + (p_2\theta_2 + Wb)/2}$, and the CS contract attains partial coordination if $0 \leqslant y \leqslant \frac{p_1\theta_2^2 + Kwb\theta_2 - p_2\theta_2^2 - Wb\theta_2 - \beta\theta_1}{p_1\theta_2(\theta_1 + \theta_2)}$. Under the parameter setting in this paper, we can compare the effect of coordination between the CS and RS contracts, as shown in Figs. 3 and 4.

In Fig. 3, the blockchain development levels of the core enterprise and the SME under the CS contract are greater than that under the RS contract, which is consistent with our conclusion in Section 4.2. Moreover, with the improvement of sharing coefficient, the blockchain development level of the SME under the CS contract increases quickly. For the SME, the cost factor may be the key to the blockchain technology development level. If the cost problem is solved, it vigorously promotes the development of the SME in the field of blockchain technology. It may be because the SME can directly reduce its investment in cost and obtain direct capital savings under the CS contract, thereby stimulating its motivation to develop blockchain technology. However, under the RS contract, the SME needs to invest heavily before obtaining the corresponding revenue shared by the core enterprise, which is relatively uncertain. In addition, whether it is a core enterprise or SME, the blockchain development level under the CS contract is better than that under the RS contract. The core enterprise has more advantages in blockchain technology development than the SME does in participating in blockchain technology and can guide and help the SME develop blockchain technology. This is consistent with the original contract design intention that the core enterprise shares the blockchain technology development costs of the SME or shares part of its revenue with the SME to encourage the SME to develop blockchain technology.

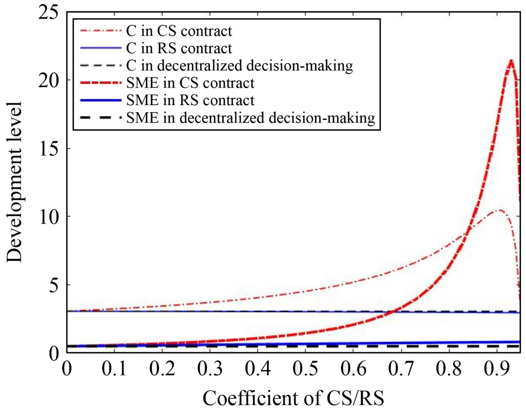

Fig. 3 Development levels m_1 and m_2 under CS and RS contracts as well as decentralized decision making.

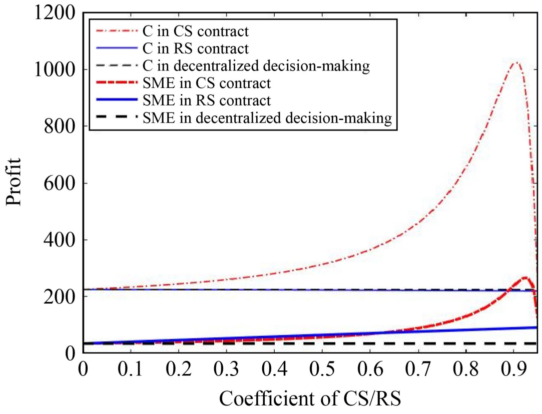

Fig. 4 Profits U_c and U_m under CS and RS contracts as well as decentralized decision making.

As shown in Fig. 4, for the core enterprise and SME, the profit under the CS contract is generally greater than that under the RS contract. This outcome may be related to the fact that the blockchain development level of both enterprises under the CS contract is better than that under the RS contract. For the core enterprise, the profit obtained by participating in blockchain increases first and then decreases with the increase of the distribution coefficient of the CS and RS contracts, which is consistent with our previous conclusions.

As shown in Fig. 5, under the CS contract, the total profit of the supply chain increases significantly with the increase of the sharing coefficient, indicating that the CS contract improves not only the enthusiasm of the SME to participate in blockchain technology but also the total

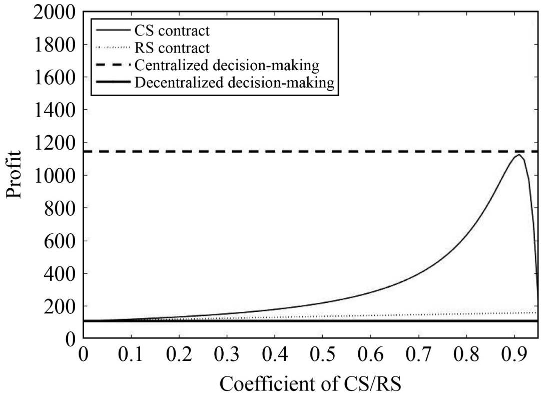

Fig. 5 Profits U under decentralized decision making, centralized decision making, CS contract, and RS contract.

profit of the supply chain. However, under the RS contract, with the increase in the RS coefficient, the total profit of the supply chain does not increase significantly. This may because, under the RS contract, the SME does not receive enough motivation to develop blockchain technology. RS is the revenue obtained under the premise of technology development. However, the cost problem can still hinder blockchain technology development. With the RS contract though, the core enterprise's enthusiasm for developing blockchain technology may be reduced due to a direct loss of revenue, resulting in the total coordination effect of the supply chain not being significant. In addition, as seen from the figure, with the increase of the CS coefficient, the overall profit of the supply chain increases first and then decreases. A new contract model can be designed to combine the two contracts to maximize the total profit of the supply chain.

5.4 Hybrid CS-RS contract

Theorem 5 demonstrates that the proposed CS-RS contract can realize the optimal coordination of the supply chain under certain conditions. We draw the applicable scope of the CS-RS contract, as shown in Fig. 6.

The scope of application in Fig. 6 reflects the ratio of RS, t, to achieve the optimal coordination of the supply chain and the range of the SME's variable credit value under the newly proposed CS-RS contract between the core enterprise and SME. Within this scope, the supply chain achieves optimal coordination. The solid line specifies the lower bound $\max\left(\frac{U_{\mathrm{m}}^{D}-p_2q_0}{U^{C}-pq_0}, Z_1\right)$, which ensures that the profit of the core enterprise under the CS-RS contract is better than that under decentralized decision making. The dotted line represents the upper bound $\min\left\{1-\frac{U_{\mathrm{c}}^{D}-p_1q_0}{U^{C}-pq_0}, Z_2, Z_3\right\}$, ensuring that the profit of the SME under the CS-RS contract is superior to that under decentralized decision making. Contract coordination can be achieved within the scope shown in the figure.

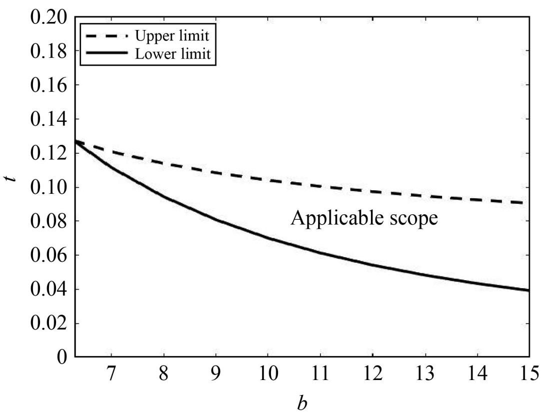

Fig. 6 Optimal adjustment range of hybrid CS-RS contract.

6 Model expansion

6.1 Blockchain technology development under uncertain demand

This section considers the impact of the risk aversion degree of risk-averse enterprises on blockchain technology development in the case of demand uncertainty. For enterprises, participating in blockchain technology development not only gains credit benefits and increases sales but also has certain technology development risks. These risks may reduce the enthusiasm of enterprises to participate in blockchain technology development. Blockchain technology development is subject to operational management risks and technology adaptation risks caused by technological change (Parks et al., 2015). Among various risk measurement methods, the mean-variance (MV) model has become one of the most common methods in supply chain risk management due to its intuitive and easy-to-calculate advantages. Many previous studies discuss supply chain contracts, supply chain coordination, and other operational issues based on the MV model (Wei and Choi, 2010; Cui et al., 2016; Choi et al., 2019). We also adopt the MV model to measure the degree of risk aversion. According to the following expression, the expected profit of the risk-averse SME is $\mathrm{E}(\prod_{\mathrm{m}}^{r})=\mathrm{E}(U_{\mathrm{m}}^{r})-\frac{r}{2}\mathrm{Var}(U_{\mathrm{m}}^{r})$, where r represents the degree of risk aversion. Based on the CS-RS model, this section considers the impact of the risk aversion factor on blockchain technology development in the case of uncertain demand.

In this section, demand uncertainty is considered based on the demand function $D=q_0+\theta_1m_1+\theta_2m_2$. Assuming that the basic market demand $\tilde{q}_0=q_0+\varepsilon$ is uncertain, where $\varepsilon(0,\sigma^2)$ is a random variable about market demand (Cui et al., 2016). Therefore, the demand function considering demand uncertainty is $D=\tilde{q}_0+\theta_1m_1+\theta_2m_2$.

In addition, blockchain transactions are irreversible, highly inflexible, and restrictive in nature (Pereira et al., 2019). Smart contracts in blockchain can be modified, and the cost of modifying or improving contracts increases linearly (Davidson et al., 2018), thereby increasing the cost due to security and uncertainty from the technical level (Pereira et al., 2019). In the case of demand uncertainty, the enterprise involved in blockchain technology development and application may incur additional technical complexity costs due to smart contract modifications. In this section, we define it as $C_i^r=\gamma_im_i$, where γ_i $(\gamma_i>0)$ represents the impact of a contract modification on the cost of technical complexity at different blockchain development levels under uncertain requirements. The calculation process is shown in **Appendix A**, and Theorem 7 is obtained.

Theorem 7: Under the centralized decision making, the blockchain development level and profits of the core enterprise and the SME considering the uncertain demand are lower compared with that without considering the uncertainties. The differences between the two scenarios depend on the degree of risk aversion and demand volatility. The higher the risk aversion degree is, the greater the demand volatility is, and the lower the profit will be under uncertain demand.

We use MATLAB 2018a for numerical analysis and compare the extended model with the level and profit of blockchain development without considering the demand uncertainty to verify Theorem 7. Table 4 describes the parameters.

The numerical simulation results are shown in Figs. 7 and 8. Combined with the calculation results, we find that the enterprise profit is affected by variable credit value considering the uncertain demand. In the case of demand uncertainty, the blockchain development levels of the core enterprise and the SME are reduced, and the supply chain profit declines. Therefore, the optimal blockchain development level may be affected by the consideration of the actual demand uncertainty. This has guiding significance for enterprises to participate in blockchain technology development. For the core enterprise, guarantying the supply chain demand stability is conducive to the development and application of blockchain technology, thus further maintaining the credibility and stability of the supply chain. For the SME, the enterprise should recognize the weaknesses in the supply chain, actively participate in the blockchain technology development, improve their credit level, and maintain the stability of the supply chain so as to form a virtuous cycle.

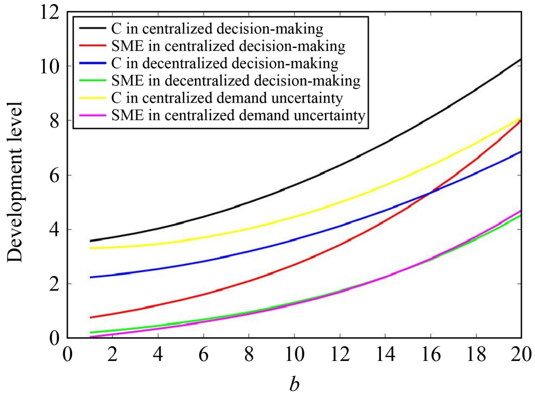

Fig. 7 Development levels m_1 and m_2 in three cases.

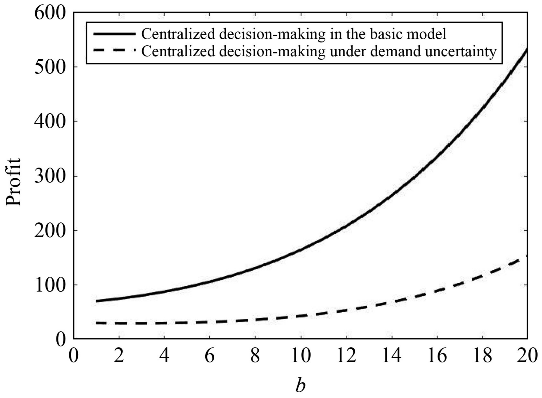

Fig. 8 Supply chain profits U comparison.

6.2 Blockchain technology development under the TPT contract

To further analyze the comparative effect between the CS-RS contract designed in this study and the single supply chain contract, we introduce TPT contract in this section to conduct a comparative analysis on the coordination effect with the CS-RS contract. As a supply chain contract effectively improves the coordination efficiency of supply chain, when coordinating the development of blockchain technology, the core enterprise pays the SME a fixed fee L to encourage it to develop blockchain technology. At the same time, the core enterprise adjusts the wholesale price of products according to the sales situation to obtain higher profits. The increased unit wholesale price is represented by c, and the calculation process is shown in **Appendix B**.

Similarly, MATLAB 2018a is used for numerical analysis to compare the blockchain development levels and supply chain profits of the TPT contract and CS-RS contract. The parameters are the same as shown in Table 3.

The numerical simulation results are shown in Figs. 9 and 10. The calculation results reveal that the optimal levels of blockchain technology development of the core enterprise and the SME are independent of fixed cost L, but are related to the unit increased wholesale price c. When $c = c^*$, the blockchain development level of core enterprise reaches the highest. By comparing the blockchain development level of core enterprise and the overall benefits of supply chain, we find that the coordination effect of CS-RS contract is better than that of TPT contract.

6.3 Blockchain technology development under the influence of minimum blockchain development level

In specific supply chain situations, the minimum blockchain development level of core enterprise or SME determines the market demand. Therefore, this section considers the blockchain development situation where the minimum blockchain development level in the supply

Table 4 Numerical simulation parameter setting

Parameter	p_1	p_2	q_0	θ_1	θ_2	K	k	W	w	a	α	β	γ_1	γ_2	r	σ
Value	12	6	0	1.5	1	3	1.5	2	1	1	10	100	8	20	1	0.1

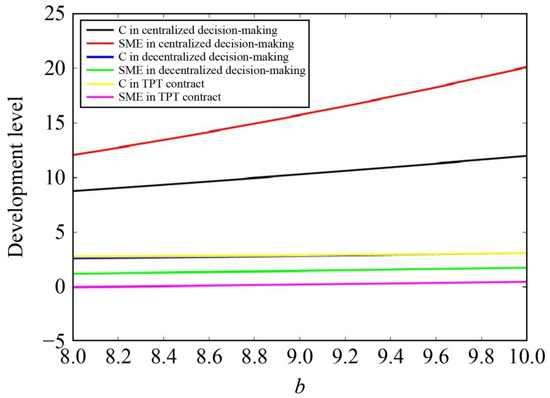

Fig. 9 Development levels m_1 and m_2 in three cases.

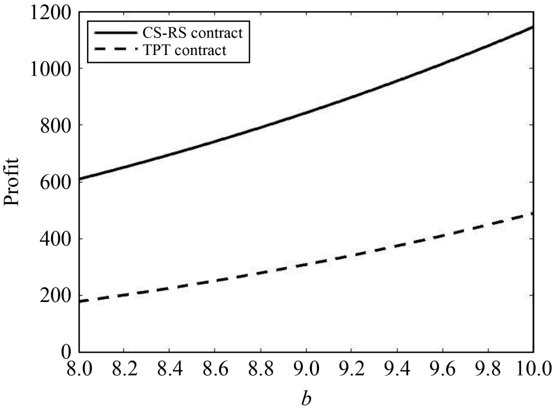

Fig. 10 Supply chain profits U comparison.

chain determines the market demand. Generally, the blockchain development level of the core enterprise has a greater impact on market demand, so this section assumes that $\theta_1 > \theta_2$, and the profit function of the supply chain under centralized decision making is as follows:

$$U^{Cm} = p(q_0 + \theta_2 \min(m_1, m_2)) + K[m_1 + w(a + m_2 b)] + W[km_1 + (a + m_2 b)] - \frac{1}{2}\alpha m_1^2 - \frac{1}{2}\frac{\beta}{m_1}m_2^2. \tag{33}$$

When $m_1 \geqslant m_2$, the utility function of supply chain under centralized decision making is as follows:

$$U^{Cm_2} = p(q_0 + \theta_2 m_2) + K[m_1 + w(a + m_2 b)] + W[km_1 + (a + m_2 b)] - \frac{1}{2}\alpha m_1^2 - \frac{1}{2}\frac{\beta}{m_1}m_2^2. \tag{34}$$

The blockchain development levels of core enterprise and SME is as follows:

$$m_1^{Cm_2} = \frac{K + Wk}{\alpha} + \frac{(p\theta_2 + Kwb + Wb)^2}{2\alpha\beta}, \tag{35}$$

$$m_2^{Cm_2} = m_1^{Cm_2}\frac{p\theta_2 + Kwb + Wb}{\beta}, \tag{36}$$

where $p\theta_2 + Kwb + Wb \leqslant \beta$. The total profit of the supply chain is as follows:

$$U^{Cm_2} = pq_0 + (Kw + W)a + \frac{1}{2}\alpha(m_1^{Cm_2})^2. \tag{37}$$

Through comparative analysis, we find that $m_1^{Cm_2} < m_1^C$, $m_2^{Cm_2} < m_2^C$, $U^{Cm_2} < U^C$.

When $m_1 < m_2$, the utility function of supply chain under centralized decision making is as follows:

$$U^{Cm_1} = p(q_0 + \theta_2 m_1) + K[m_1 + w(a + m_2 b)] + W[km_1 + (a + m_2 b)] - \frac{1}{2}\alpha m_1^2 - \frac{1}{2}\frac{\beta}{m_1}m_2^2. \tag{38}$$

The blockchain development levels of core enterprise and SME is as follows:

$$m_1^{Cm_1} = \frac{p\theta_2 + K + Wk}{\alpha} + \frac{(Kwb + Wb)^2}{2\alpha\beta}, \tag{39}$$

$$m_2^{Cm_1} = m_1^{Cm_1}\frac{Kwb + Wb}{\beta}, \tag{40}$$

where $Kwb + Wb > \beta$. Then, the total profit of the supply chain is as follows:

$$U^{Cm_1} = pq_0 + (Kw + W)a + \frac{1}{2}\alpha(m_1^{Cm_1})^2. \tag{41}$$

Through comparative analysis, we find that $m_1^{Cm_1} < m_1^C$, $m_2^{Cm_1} < m_2^C$, $U^{Cm_1} < U^C$.

In conclusion, we consider the case where only the minimum blockchain development level of the core enterprise and SME in the supply chain determines market demand in this section. Regardless of whether the blockchain development level of the core enterprise is greater or lower than that of the SME, the optimal blockchain development level is lower than the corresponding optimal development level of the basic assumption under centralized decision making. The overall supply chain utility is also lower than the optimal supply chain utility in the basic assumption under centralized decision making. The optimal coordination effect of CS-RS contract is to realize the optimal blockchain development level under centralized decision making. Therefore, when the market demand is subject to the minimum blockchain development level of the core enterprise and SME, the optimal coordination effect of the CS-RS contract is also weaker than that under basic assumptions. That is, when market demand is only affected by the minimum blockchain development level in the supply chain, the optimal blockchain development level and supply chain utility of enterprises in the supply chain are reduced.

6.4 Blockchain technology development under information asymmetry

Information asymmetry is one of the important reasons for the financing difficulties of SMEs (Yoshino and Taghizadeh-Hesary, 2019). The application of blockchain technology can promote the dissemination of trusted information in the supply chain and help enterprises solve the problem of information asymmetry (Liu et al., 2021a). This section considers the benefits of developing blockchain technology for SME in terms of asymmetric information. Based on the basic assumption, the development of blockchain technology improves the information asymmetry of SME and brings additional benefits ωm_2 to SME, where ω represents the coefficient of impact of blockchain technology on information asymmetry. The utility function of supply chain under centralized decision making is as follows:

$$U^{Ca} = p(q_0 + \theta_1 m_1 + \theta_2 m_2) + K[m_1 + w(a + m_2 b)] + W[km_1 + (a + m_2 b)] + \omega m_2 - \frac{1}{2}\alpha m_1^2 - \frac{1}{2}\frac{\beta}{m_1} m_2^2. \tag{42}$$

To maximize the supply chain profit, the optimal blockchain development levels can be calculated as provided below:

$$m_1^{Ca} = \frac{p\theta_1 + K + Wk}{\alpha} + \frac{(p\theta_2 + Kwb + Wb + \omega)^2}{2\alpha\beta}, \tag{43}$$

$$m_2^{Ca} = m_1^{Ca}\frac{p\theta_2 + Kwb + Wb + \omega}{\beta}. \tag{44}$$

The total profit of the supply chain is as follows:

$$U^{Ca} = pq_0 + (Kw + W)a + \frac{1}{2}\alpha(m_1^{Ca})^2. \tag{45}$$

Through comparative analysis, we find that $m_1^{Ca} > m_1^C$, $m_2^{Ca} > m_2^C$, $U^{Ca} > U^C$. Considering the information asymmetry, the development of blockchain brings additional benefits to the SME. At this time, the optimal blockchain development levels of both core enterprise and SME are improved as well as the overall utility of supply chain. Similarly, the CS-RS contract can adjust the coordinated development between enterprises to achieve the optimal development level under centralized decision making. Therefore, the coordination effect of CS-RS contract under information asymmetry is superior to that under basic assumptions. That is, when considering the impact of information asymmetry on SME, the optimal blockchain development level and supply chain utility of enterprises in the supply chain can be improved.

7 Discussion

The COVID-19 pandemic has brought new challenges to enterprises, especially SMEs. However, it has also incentivized them to adopt blockchain technology for digital transformation in the post-pandemic era to improve supply chain resilience. This paper designs a Stackelberg game model to describe the collaborative development of blockchain technology between a core enterprise and an SME. Considering the credit benefits brought by blockchain technology, we calculate the coordination scope under CS and RS contracts to improve the development level of blockchain technology and supply chain profits and compare and evaluate the coordination effect of the two contracts. In addition, we propose a hybrid CR-RS contract to improve the coordination effect on the whole supply chain. The findings of this study are summarized below. In the post-pandemic era, the collaborative development of blockchain technology can help core enterprise and SME in the supply chain actively develop high-level blockchain and improve the profits of the supply chain. In the post-epidemic era, enterprises can use blockchain technology to track the delivery, conduct real-time data retrieval and data management, and provide support for enterprises to gain market competitive advantages (Khan et al., 2022). Blockchain technology can also track the spread of the epidemic and protect the privacy information of infected people based on anonymity. Blockchain provides technical support for enterprises to improve supply chain efficiency after the epidemic (Liu et al., 2022a).

First, for the development of blockchain technology, the CS and RS contracts can achieve a certain degree of coordination under specific conditions to improve their blockchain development levels and profits. This paper extends the research on CS and RS contracts to the field of collaborative blockchain technology development. It confirms the significance of adopting supply chain contracts to coordinate the joint development of blockchain technology.

Second, the CS contract is superior to the RS contract for a wider range of parameters, and the coordination efficiency is higher. This paper compares and analyzes the coordination effect of CS and RS contracts, which provides a better understanding of the collaborative development of blockchain technology under contract coordination. This result reveals the advantages of the CS contract in blockchain technology development. Broadly, it confirms the advantages of a CS contract in technology research and development-driven innovation (Song et al., 2019).

Third, the proposed hybrid CS-RS contract can improve the blockchain development level between the core enterprise and the SME, realize the optimal blockchain technology development level under the centralized decision making, and allow the supply chain to achieve perfect coordination under certain conditions. In theory, this paper complements the contract research in collaborative blockchain technology development, puts forward a theoretical basis for the blockchain technology development and innovation, and provides a new research idea for the high cost of technology development. It contributes to the study on contract theory and provides contract coordination with a new contract form.

Finally, the impact of risk factors brought by demand uncertainty can reduce the optimal blockchain development levels of the core enterprise and SME and the overall profits of the supply chain. The risk factor complements the impact of demand uncertainty on blockchain development and application (Pereira et al., 2019) and provides a new research direction for the operation management research of blockchain technology.

8 Conclusions and future work

8.1 Main conclusions

The spread of COVID-19 has significantly affected the global supply chain network. It has also forced enterprises to improve their supply chain resilience and adopt blockchain technology. In this context, this paper studies the collaborative development of blockchain technology in supply chains. Specifically, this paper develops a Stackelberg game model to investigate the collaborative development of blockchain technology between a core enterprise and an SME through supply chain contracts. It then discusses the impact of different supply chain contracts on the collaborative development of blockchain technology. A hybrid CS-RS contract is designed to optimize the collaborative development level and supply chain profit.

The main conclusions of this study are as follows. First, compared with decentralized decision making, centralized decision making can help enterprises obtain higher profit. The blockchain development level and enterprise profit under centralized decision making can achieve the optimal coordination among supply chain enterprises. Second, under certain conditions, the CS and RS contracts have a coordination effect on the collaborative development of blockchain technology, and the coordination effect of CS contract is better. However, neither of them can achieve the optimal coordination of supply chain under centralized decision making. Finally, the hybrid CS-RS contract proposed in this study can coordinate the blockchain development of the core enterprise and SME, make the blockchain development level of the core enterprise reach the optimal level under centralization, and realize the maximal supply chain profit. In addition, when the demand is uncertain, the development level and supply chain profit of blockchain under the coordination of a hybrid contract decrease. When the market demand is subject to the minimum blockchain development level in the supply chain, the blockchain technology development level and supply chain utility of core enterprise and SME also decrease. However, when considering the impact of information asymmetry on the SME, the blockchain development level and supply chain utility of core enterprise and SME are improved. These can provide insights into blockchain technology development research and practical application.

8.2 Management inspiration

The results obtained in this study provide several managerial insights. First, setting a reasonable cost or revenue distribution ratio can coordinate the collaborative development of blockchain technology under certain conditions. Still, neither can achieve perfect coordination of the supply chain. In reality, the use of the CS and RS contracts requires full awareness of their coordination effects and shortcomings.

Second, under the CS contract, the overall profits of the supply chain, core enterprise, and SME cannot reach the optimum simultaneously. Under the CS contract, when the core enterprise and SME pursue their own profit optimization unilaterally, the supply chain profit decreases.

Third, when the core enterprise and SME need to develop blockchain technology, neither a CS nor an RS contract can achieve supply chain coordination, which shows that the CS or RS contract alone is ineffective to promote the adoption of blockchain technology in the supply chain. Therefore, the SME should also cooperate with the core enterprise in blockchain development and supply chain coordination.

Finally, for the collaborative development of blockchain technology, the hybrid CS-RS contract can achieve perfect coordination. On the one hand, the core enterprise bears part of the costs and uses its own capital and technological advantages to support the blockchain technology development of the SME. On the other hand, the SME shares its revenue and incentivizes the core enterprise. The core enterprise should also share the benefits obtained from the development of blockchain technology. An optimized and coordinated supply chain helps establish a long-term, stable, and trustworthy partnership between the two participants. Specifically, the development and application of blockchain technology can help firms recover more quickly and maintain supply chain resilience in the post-pandemic era. Blockchain technology can help SMEs acquire supply chain information, provide credibility guarantees, and improve supply chain stability.

In addition, demand uncertainty can affect the blockchain technology development level and supply chain profit, and enterprises need to consider the impact of risk factors during blockchain development.

8.3 Limitations and future work

This paper studies the collaborative development of blockchain technology based on supply chain contract models in the post-pandemic era. Our analysis and results provide insights for enterprises to improve their supply chain resilience in the post-pandemic era. However, the paper has several limitations. In modeling blockchain technology development, this paper only considers the development cost of blockchain technology. Hence, research on marketing and implementation costs in blockchain technology development may be examined in future research. In addition, this paper focuses on analyzing the impact of blockchain technology on the credit of the SME. The credit evaluation of the core enterprise may be further discussed and analyzed in future research.

Appendix A

Since the mean of ε is 0, and the variance is σ^2, according to the variance calculation formula, we can obtain $\mathrm{Var}(U_{\mathrm{m}}^{r}) = p_2^2\sigma^2$, and $\mathrm{Var}(U_{\mathrm{c}}^{r}) = p_1^2\sigma^2$. Under centralized decision making, the profit function of the supply chain with uncertain demand when participating in the blockchain is:

$$\begin{aligned} U^{Cr} = {} & p(\tilde{q}_0 + \theta_1 m_1 + \theta_2 m_2) + K[m_1 + w(a + m_2 b)] \\ & + W[km_1 + (a + m_2 b)] - \frac{1}{2}\alpha m_1^2 - \frac{1}{2}\frac{\beta}{m_1} m_2^2 \\ & - \gamma_1 m_1 - \gamma_2 m_2 - \frac{r}{2} p_1^2 \sigma^2 - \frac{r}{2} p_2^2 \sigma^2. \end{aligned} \tag{A1}$$

According to the reverse solution method, the blockchain development levels of the core enterprise and the SME are as follows:

$$m_1^{Cr} = \frac{p\theta_1 + K + Wk}{\alpha} + \frac{(p\theta_2 + Kwb + Wb - \gamma_2)^2 - \gamma_1}{2\alpha\beta}, \tag{A2}$$

$$m_2^{Cr} = \frac{p\theta_2 + Kwb + Wb - \gamma_2}{\beta} m_1^{Cr}. \tag{A3}$$

Obviously, it can be seen from the comparison with the blockchain development levels of the core enterprise and the SME under centralized decision making without considering the uncertainty of demand, $m_1^{Cr} < m_1^{C}$, $m_2^{Cr} < m_2^{C}$, and thus $U^{Cr} < U^{C}$.

Considering the supply chain with uncertain demand using the CS-RS contract to coordinate, according to the variance calculation formula, the profit of the SME with uncertain demand is shown as:

$$\begin{aligned} U_{\mathrm{m}}^{CRr} = {} & p_2 \tilde{q}_0 + (1 - v) p_2 (\theta_1 m_1 + \theta_2 m_2) \\ & + W[km_1 + (a + m_2 b)] - \frac{1}{2}(1 - u)\frac{\beta}{m_1} m_2^2 \\ & + t\left[(p_1 + vp_2)(\theta_1 m_1 + \theta_2 m_2) - \frac{1}{2}\alpha m_1^2 - \frac{1}{2} u \frac{\beta}{m_1} m_2^2\right] \\ & - \frac{r}{2} p_2^2 \sigma^2 - \gamma_2 m_2. \end{aligned} \tag{A4}$$

Therefore, the expected profit of the SME is shown as:

$$\begin{aligned} \mathrm{E}\left(\prod\nolimits_{\mathrm{m}}^{CRr}\right) = {} & p_2 q_0 + (1 - v) p_2 (\theta_1 m_1 + \theta_2 m_2) \\ & + W[km_1 + (a + m_2 b)] - \frac{1}{2}(1 - u)\frac{\beta}{m_1} m_2^2 \\ & + t\left[(p_1 + vp_2)(\theta_1 m_1 + \theta_2 m_2) - \frac{1}{2}\alpha m_1^2 - \frac{1}{2} u \frac{\beta}{m_1} m_2^2\right] \\ & - \frac{r}{2} p_2^2 \sigma^2 - \gamma_2 m_2. \end{aligned} \tag{A5}$$

Similarly, the expected profit of the core enterprise can be calculated as shown:

$$\begin{aligned} & \mathrm{E}\left(\prod\nolimits_{\mathrm{c}}^{CRr}\right) \\ & = p_1 q_0 + K[m_1 + w(a + m_2 b)] \\ & \quad + (1 - t)\left[(p_1 + vp_2)(\theta_1 m_1 + \theta_2 m_2) - \frac{1}{2}\alpha m_1^2 - \frac{1}{2} u \frac{\beta}{m_1} m_2^2\right] \\ & \quad - \frac{r}{2} p_1^2 \sigma^2 - \gamma_1 m_1. \end{aligned} \tag{A6}$$

According to the reverse solution method, we make $m_1^{CRr} = m_1^{Cr}$, $m_2^{CRr} = m_2^{Cr}$, then we can obtain the expected profits of the core enterprise and the SME by considering the risk factor:

$$U_{\mathrm{c}}^{CRr} = p_1 q_0 + t(U^{Cr} - pq_0) - \frac{r}{2} p_1^2 \sigma^2 - \gamma_1 m_1^{Cr}, \tag{A7}$$

$$U_{\mathrm{m}}^{CRr} = p_2 q_0 + (1 - t)(U^{Cr} - pq_0) - \frac{r}{2} p_2^2 \sigma^2 - \gamma_2 m_2^{Cr}. \tag{A8}$$

Obviously, the profit of the core enterprise and the SME under the coordination of the CS-RS contract considering the demand uncertainty is lower than that without considering the demand uncertainty, namely, $U^{CRr} < U^{CR}$.

Appendix B

The profit functions of the core enterprise and the SME are:

$$\begin{aligned} U_{\mathrm{c}}^{TPT} = {} & (p_1 + c)(q_0 + \theta_1 m_1 + \theta_2 m_2) \\ & + K[m_1 + w(a + m_2 b)] - \frac{1}{2}\alpha m_1^2 - L, \end{aligned} \tag{B1}$$

$$\begin{aligned} U_{\mathrm{m}}^{TPT} = {} & (p_2 - c)(q_0 + \theta_1 m_1 + \theta_2 m_2) \\ & + W[km_1 + (a + m_2 b)] - \frac{1}{2}\frac{\beta}{m_1} m_2^2 + L. \end{aligned} \tag{B2}$$

Using backward induction, we can obtain the optimal blockchain development levels of the core enterprise and the SME:

$$m_1^{TPT} = m_1^D + \frac{\beta\theta_1 + c\theta_2(p_2\theta_2 + Wb - p_1\theta_2 - Kwb - c\theta_2)}{\alpha\beta}, \tag{B3}$$

$$m_2^{TPT} = \frac{(p_2 - c)\theta_2 + Wb}{\beta} m_1^{TPT}. \tag{B4}$$

Then, the optimal profits of the core enterprise and the SME are provided as:

$$U_{\mathrm{c}}^{TPT} = (p_1 + c)q_0 + Kwa - \frac{1}{2}\alpha(m_1^{TPT})^2 - L, \tag{B5}$$

$$\begin{aligned} U_{\mathrm{m}}^{TPT} = {} & (p_2 - c)q_0 + Wa + (p_2 - c)\theta_1 + Wk \\ & + \frac{[(p_2 - c)\theta_2 + Wb]^2}{2\beta} m_1^{TPT} + L. \end{aligned} \tag{B6}$$

We obtain $c^* = [(p_2\theta_2 + Wb - p_1\theta_2 - Kwb)\theta_2 + \beta\theta_1]/2\theta_2^2$ to maximize the blockchain development level of the core enterprise m_1^{TPT}. Then, the optimal profit of the supply chain is:

$$\begin{aligned} U^{TPT} = {} & pq_0 + (Kw + W)a - \frac{1}{2}\alpha(m_1^{TPT})^2 + (p_2 - c)\theta_1 \\ & + Wk + \frac{[(p_2 - c)\theta_2 + Wb]^2}{2\beta} m_1^{TPT}. \end{aligned} \tag{B7}$$

When $p_2\theta_2 + Wb - p_1\theta_2 - Kwb > -\beta\theta_1/\theta_2$ and $p_2\theta_2 + Wb + p_1\theta_2 + Kwb > \beta\theta_1/\theta_2$, $m_1^C > m_1^{TPT}$, $m_2^C > m_2^{TPT}$, $U^{CR} = U^C > U^{TPT}$.

Compared with the TPT contract, the CS-RS contract has better coordination result.

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