The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/1066-2243.htm

Received 15 September 2020
Revised 8 December 2020
27 April 2021
Accepted 3 June 2021

Pricing and coordination of vaccine supply chain based on blockchain technology

Ruihuan Liu
Central South University, Changsha, China
Chunqiao Tan
Nanjing Audit University, Nanjing, China and
Central South University, Changsha, China, and
Chengwei Zhao
Central South University, Changsha, China

Abstract

Purpose – Vaccine safety is a major issue in the world. Blockchain technology is the right solution to this worldwide problem. The impact of introducing blockchain technology on the operational efficiency of the vaccine supply chain is unclear. Therefore, from the perspective of game theory, this paper aims to construct a vaccine supply chain model consisting of a vaccine manufacturer, a vaccine traceability service platform based on blockchain technology and a vaccination unit to discuss its pricing and coordination.

Design/methodology/approach – This study analyzes the pricing and coordination of the vaccine supply chain based on blockchain technology, compares the decision-making of fixed charge scenario and proportional charge scenario and reveals the impact of blockchain on the vaccine supply chain.

Findings – Results demonstrate that the revenue-sharing contract can coordinate the vaccine supply chain when the proportion of revenue sharing meets certain conditions. The fixed charge scenario is more beneficial to the vaccine supply chain than the proportional charge scenario. The introduction of blockchain technology increases the total profit, consumer surplus and social welfare of the vaccine supply chain. Therefore, the operational efficiency of the vaccine supply chain is improved.

Originality/value – This study not only provides important support for enterprises to adopt blockchain technology but also provides some guidance for decision-makers to implement scientific and feasible vaccine supply chain management schemes.

Keywords Blockchain technology, Vaccine supply chain, Vaccine traceability service platform, Game theory, Pricing, Coordination

Paper type Research paper

1. Introduction

Vaccination is the most economical and effective means for humans to prevent and control infectious diseases (Duijzer *et al.*, 2018; Adida *et al.*, 2013). Governments all over the world regard vaccination as the top priority of public health prevention services. In recent years, vaccine incidents have been erupting continuously, especially in China where many serious vaccine incidents have occurred, such as the illegal operation of vaccines in Shandong in March 2016, the illegal production of freeze-dried rabies vaccine for human use by Changchun Changsheng Biotechnology Co., Ltd. in July 2018 and the illegal vaccination of 9-valent cervical cancer vaccine in Boao, Hainan in April 2019, which had a great impact on the society and attracted great attention from the state. How to strengthen vaccine management, ensure the safety of vaccination and provide efficient services for the masses is a hot topic

We appreciate all the helpful and insightful comments by the Editors and the anonymous reviewers. This work is supported in part by the National Natural Science Foundation of China (Grant No. 71971218).

Internet Research
Vol. 31 No. 6, 2021
pp. 2096-2119

1066-2243
DOI 10.1108/INTR-09-2020-0508

concerned by the people and governments of all countries. With the continuous development of blockchain technology, its application in the vaccine supply chain has become a reality.

In the vaccine supply chain, vaccines are faced with various security risks such as changing the real source of reagents, certificates or processes (Apte and Petrovsky, 2016); changing quality documents, testing protocols and/or contracts; making false invoices; and not sharing information among systems (Haq and Esuka, 2018). Since every link in the drug supply chain plays a vital role in drug safety (Tseng *et al.*, 2018), improving the drug supply chain management is the most direct and comprehensive way to solve drug safety problems. The same is true for vaccines.

Nowadays, with the continuous development and practice of blockchain technology, its application scope is getting wider and wider. Blockchain technology has become an effective solution to the drugs (including vaccines) supply chain management and security problems (Haq and Esuka, 2018). For example, the US Food and Drug Administration started to use blockchain to track prescription drugs in March 2017. In May 2017, a group of companies led by pharmaceutical giants Genentech and Pfizer announced the MediLedger project, which aims to create a blockchain tool for managing the drug supply chain, so that pharmaceutical manufacturers, wholesalers, hospitals and other relevant institutions can use the blockchain to register all drug-related information and ensure its traceability to the maximum extent. On July 30, 2018, Henan Ziyun Cloud Computing Co., Ltd. officially released the vaccine traceability and anti-counterfeiting platform based on blockchain technology. Through this platform, we can ensure that the information of vaccine production, quality inspection, storage, delivery, circulation, vaccination and other aspects is true and effective and cannot be tampered with. At the same time, we can also make the data traceable, increase the cost of data fraud and make the use of vaccines safer.

All indications show that blockchain, as an emerging technology with strong development potential, has been applied in the vaccine supply chain, trying to escort the safe circulation of vaccines. However, the impact of the introduction of blockchain technology on the operational efficiency of the vaccine supply chain remains unknown. It is very important and necessary to study this problem. This paper attempts to explore this issue by constructing a game model of the vaccine supply chain based on blockchain technology.

Although blockchain technology has been introduced into the vaccine supply chain by enterprises or institutions to ensure the effectiveness and safety of vaccines, the existing research is very limited, and there are still many problems to be paid attention to and solved. Therefore, based on the current situation of the combination of the vaccine supply chain and blockchain technology platform/system, we build a game model to discuss the pricing and coordination of the vaccine supply chain supported by blockchain technology, analyze the impact of different charging strategies on the supply chain and provide some management enlightenment.

Specifically, we mainly discussed the following questions:

(1) How to achieve equilibrium in the vaccine supply chain in the basic model? What is the relationship between the equilibrium solution and the main parameters? What is the relationship between the total profit of the vaccine supply chain, the total consumer surplus and the social welfare under different decision-making situations (centralized and decentralized)?

(2) Can the widely used cost-sharing contract and revenue-sharing contract achieve the vaccine supply chain coordination based on blockchain technology? If yes, what are the conditions for achieving coordination?

(3) Compared with the fixed charge scenario of vaccine traceability service platform, what are the vaccine price, total profit of supply chain and total consumer surplus

under the proportional charge scenario? Which scenario is better for the vaccine supply chain?

Using game theory to analyze these problems, the main results are as follows. In the basic model, there are equilibrium solutions in both centralized and decentralized decision-making. Moreover, the total profit of the supply chain under the centralized decision-making is always no less than that under the decentralized decision-making, and the total consumer surplus and the social welfare under the centralized decision-making is always greater than that under the decentralized decision-making. In both cases, the optimal selling price of the vaccine is related to the service cost of the vaccine traceability service platform to unit vaccine. The cost-sharing contract cannot realize the coordination of the vaccine supply chain based on the blockchain technology. When the proportion of revenue sharing meets certain conditions, the revenue-sharing contract can coordinate the vaccine supply chain. Compared with the fixed charge scenario, the total profit of the supply chain obtained by adopting the proportional charge strategy in the vaccine traceability service platform is less, and the total consumer surplus and the social welfare is also lower. Therefore, the fixed charge scenario is more beneficial to the vaccine supply chain than the proportional charge scenario. But which scenario to choose depends on the vaccine traceability service platform based on blockchain.

This paper is the first one to analyze the pricing and coordination strategy of the vaccine supply chain based on blockchain technology and to deeply explore the value and impact of blockchain technology in the vaccine supply chain through the model. This study not only provides important support for enterprises to adopt blockchain technology from an economic perspective but also provides some guidance for decision-makers to implement a scientific and feasible vaccine supply chain management scheme. Simultaneously, the research results have some contribution to the future literature research.

2. Related literature

2.1 Safety management of vaccine supply chain

Vaccine safety concerns public health and national security. Vaccine safety management is the primary task in vaccine supply chain management. In the traditional vaccine management, vaccines are supervised by the government regulatory authorities (Chen *et al.*, 2015). In this case, the regulatory authorities test vaccines by random sampling to ensure their safety. However, the management of vaccine information is centralized. When companies find that vaccine information is harmful to themselves, they will tamper with it (Abeyratne and Monfared, 2016). Therefore, this method is not very effective in solving the vaccine safety problem. In addition, falsified vaccine information greatly increases the difficulty of traceability and accountability of fake vaccines by regulatory authorities. To reduce the risk of vaccine deterioration and failure, Dhandapani and Uthayakumar (2019) proposed an economic order quantity model based on mathematical principles to find the optimal vaccine replenishment time. However, this model has no effect on the vaccine deterioration caused by humans. With the development of information technology, some advanced technologies have been applied to the vaccine supply chain management. For example, in order to realize drug tracking, barcode scanning systems or radio frequency identification technology has been applied to the drug supply chain in a relatively mature way (Sarac *et al.*, 2010). However, drug counterfeiting still occurs. Some vaccine management problems, such as false records in production and closed information in circulation, still plague enterprises and public sectors. Once the problem vaccine enters the market, it will result in a serious threat to public health and cause great harm to society. Blockchain technology can solve these safety problems in the vaccine supply chain management. In this paper, the vaccine traceability service platform based on blockchain technology is introduced into the vaccine supply chain to discuss, which is completely different from the previous studies.

2.2 Pricing and coordination of vaccine supply chain

At present, some scholars have researched the vaccine supply chain model. Chick *et al.* (2008) first proposed a coordination model of influenza vaccine supply chain from the perspective of operation management and found that the designed cost-sharing contract could realize a global optimization of the supply chain. Arifoğlu *et al.* (2012) discussed the influence of consumption externality and yield uncertainty on the influenza vaccine supply chain. They found that the government could improve the effectiveness of the supply chain by intervening on the supply side or the demand side. Adida *et al.* (2013) studied the decision-making problem of the vaccine supply chain with uncertain supplier output and negative consumer network effect and pointed out that the government subsidy mechanism could improve vaccine coverage. Huang *et al.* (2015) explored the pricing and coordination of the vaccine supply chain under uncertain output and believed that the shortage penalty and cost-sharing contract could realize the perfect coordination of the influenza vaccine supply chain. Sun *et al.* (2019) discussed the risk problems in the vaccine supply chain and found that using Shapley value method, analytic network process and fuzzy comprehensive evaluation method can realize reasonable profit distribution between the vaccine manufacturer and the retailer. The above literature studied the vaccine supply chain from the perspective of model construction but did not involve the application of blockchain technology in the vaccine supply chain. This paper proposes to establish a model to study the pricing and coordination strategy of the vaccine supply chain under blockchain technology.

2.3 Blockchain technology

In 2008, Nakamoto introduced bitcoin (Nakamoto, 2008). Since then, "blockchain" has gradually entered people's field of vision and developed rapidly in recent years. Blockchain is a publicly accessible distributed database that never be changed or tampered with (Hofmann *et al.*, 2018; Saberi *et al.*, 2018). It can ensure the high integrity of all transactions on the block. By deploying a transparent consensus mechanism, blockchain can ensure the validity of the transactions executed (Bocek and Stiller, 2018) and eliminate the control role of third parties or intermediaries on the system. Since the information of all participants in the blockchain network is transparent, the malicious activities of participants are prevented.

At present, blockchain technology has been applied in many fields such as finance (Guo and Liang, 2016), logistics (Li *et al.*, 2019), agriculture (Kamilaris *et al.*, 2019) and food (Galvez *et al.*, 2018) and is expanding to other fields. Supply chain management is a promising application field of blockchain (Kamble *et al.*, 2019). Some scholars have analyzed the application and value of blockchain in supply chain management. Longo *et al.* (2019) showed through an experimental study that blockchain technology could not only overcome the problems of cooperation and trust in the supply chain, improve the overall performance of the supply chain, minimize the negative impact of information asymmetry on supply chain members but also prevent any improper behavior of enterprises, such as data fraud or low data accuracy. Liu and Li (2020) constructed a cross-border e-commerce supply chain framework based on blockchain to solve the traceability of products and transactions. Andoni *et al.* (2017) proposed to use decentralization and traceability of blockchain technology for controlling the energy supply. Min (2019) discussed how to use blockchain technology to enhance the flexibility of supply chain when risk and uncertainty increase. Wang *et al.* (2018) built a supply chain management system based on the blockchain to discuss the feasibility of applying blockchain technology in the vendor-managed inventory mode supply chain. Leng *et al.* (2018) studied the application of blockchain in the agricultural supply chain and proposed a dual chain structure of agricultural commercial resource blockchain. Choi (2019) analyzed the application of blockchain technology in the diamond supply chain. Choi *et al.* (2020) discussed the impact of introducing blockchain technology into the rental service platform on product information disclosure. The above research shows that blockchain has been applied in supply chain management. Different from the above studies, this paper focuses on the vaccine supply chain.

2.4 Blockchain technology and vaccine supply chain

With the expansion of blockchain applications and the increasingly prominent vaccine problems, some researchers are considering establishing transparent data transactions in the human medical industry to prevent counterfeit vaccines from entering the supply chain (Taylor *et al.*, 2019). Haq and Esuka (2018) proposed to build a vaccine supply chain system based on blockchain technology to improve vaccines safety. Thomason (2017) pointed out that when fake vaccines are prevalent, vaccinators can use blockchain to confirm whether the vaccines are true or not. At present, there have been literature studies on the blockchain-based vaccine supply chain system. Tseng *et al.* (2018) built a drug supply chain monitoring network through the G-coin blockchain system, which allowed all participants in the drug supply chain to participate in the supervision for preventing counterfeit drugs. Yong *et al.* (2020) developed a vaccine blockchain system based on blockchain and machine learning technology to solve the problems of expired vaccines and fraudulent vaccine record in the vaccine supply chain. Wu and Lin (2019) proposed a drug recall service system based on blockchain to improve system transparency and protect data integrity in drug recall.

It can be seen from the above research that most of the existing literature focus on the theoretical significance of blockchain in the vaccine supply chain and the construction of the vaccine supply chain system based on blockchain technology. In fact, in order to solve the vaccine problem, some enterprises have started to implement it. For example, JD Digits Intelligent Vaccine Management System has been put into operation since March 2019. In this paper, we discuss the application of blockchain in the vaccine supply chain. The pricing and coordination mechanism of the vaccine supply chain are investigated in detail after the introduction of the vaccine traceability service platform based on blockchain technology. The specific research content is different from the existing literature.

3. Basic model: fixed charge (FC) scenario

3.1 Problem description and model building

Consider a vaccine supply chain consisting of a vaccine manufacturer (M), a vaccination unit (U) (e.g., centers for disease control and prevention, epidemic prevention stations, hospitals setting up vaccination spots, etc.) and a vaccine traceability service platform based on blockchain technology (BVP). The M is responsible for vaccine production and sale. The U buys vaccines from the M and sells them to vaccinators at a certain price. The BVP is a service provider of blockchain technology. It uses blockchain technology to link the vaccine manufacturer, the vaccination unit, consumers and regulatory authorities to realize traceability data sharing, which is safe, reliable and win-win. Relying on the system, the vaccine manufacturer and the vaccination unit can trace the whole process information from vaccine production to vaccination, which effectively solve the problems of unreliable tracing and difficult channel control. It is simple and convenient for vaccinators to check the authenticity and production source of the vaccine for free through mobile devices.

In the blockchain-based vaccine supply chain, the M can assign a unique identification number to each vaccine, including its identification, storage temperature, shelf life and other parameter information. At each stage of the supply chain, participants can write vaccine circulation information into the blockchain by using identification codes. When an authorized node conducts a "transaction" with another node, the two nodes will reach a unified protocol and digital signature. Before vaccination, consumers can check the accurate information of vaccine flow through the blockchain platform.

Different from the traditional vaccine supply chain, smart contracts are signed between members in the blockchain-based vaccine supply chain. Smart contract is a new technology, which can automatically negotiate, fulfill and enforce the terms of the agreement in the blockchain environment. It is digital, stored in the blockchain and uses encrypted code to execute the protocol. From the signing of the contract to the end of the performance, there are blocks, which are connected in time stamp order to form a complete blockchain. In this paper, the manufacturer and the vaccination unit complete all transaction processes such as smart contract signing, execution and fund payment on the BVP, which ensures that all information and transactions in the supply chain are transparent, traceable and unchangeable and improves the safety and effectiveness of vaccines.

Assume that the unit production cost of the vaccine manufacturer is c_M, the wholesale price of the vaccine is w, the selling price of the vaccination unit is p, and the unit cost of vaccination service provided by the vaccination unit for consumers is c_U, where $p > w > c_M > 0$, $p - w > c_U > 0$. There are two common ways of making profit for the BVP. One is fixed charge (FC), that is, in a certain time interval, fixed fees are charged to M and U, which are F_{M} and F_{U}, respectively. The other is proportional charge (PC), that is, according to the income of the manufacturer and the vaccination unit at a certain time or period, the expenses are drawn by proportion φ_1 $(0 < \varphi_1 < 1)$ and φ_2 $(0 < \varphi_2 < 1)$, respectively. In this paper, the pricing and coordination strategies of the vaccine supply chain are analyzed by using the first charging method in the basic model. In the extended model, the pricing choice of supply chain members when charging by proportion is discussed and compared with the FC.

Suppose that in a given time period, the number of potential vaccinators from the U is n, and the perceived value of vaccinators to the vaccine is v, which follows the distribution of $f(v)$. According to the existing literature, in order to improve the operability of the analysis, in this paper, we assume that $f(v)$ obeys the uniform distribution on (0,1). The time and effort taken by vaccinators to find and test the vaccine before vaccination is t $(t > 0)$, and the unit negative effect was γ $(\gamma > 0)$. The vaccinators may have side effects by vaccination itself, which is indicated by θ $(\theta > 0)$. The positive effect of vaccine on the vaccinator is s $(s > 0)$. For example, through vaccination, the possibility of infection or illness of the vaccinator is reduced or avoided. Therefore, the consumer utility u of the vaccinator can be expressed as: $u = v - p - t\gamma - \theta + s$. When $u > 0$, vaccinators will choose to vaccinate. Therefore, the number of people who finally choose to vaccinate, that is, the vaccine demand function d is shown as follows:

$$d = n \int_{p+t\gamma+\theta-s}^{1} f(v)dv = n(1 - p - t\gamma - \theta + s). \tag{1}$$

It is noteworthy that vaccinators can log in to the vaccine traceability service platform based on blockchain technology to view all the information of the vaccine for free before vaccination, so as to ensure the safety and effectiveness of vaccination. It can be considered that the vaccines vaccinated by consumers under such circumstances are safe. Therefore, d is the number of effective vaccines of the vaccination unit. When the vaccinator finds that the vaccine to be vaccinated has expired, is ineffective or has other safety problems, he or she will not choose to vaccinate and will continue to search for and verify other vaccines until an effective vaccine is found. Assume that the proportion of vaccines identified as having problems is λ $(\lambda > 0)$, the number of vaccines with problems in the vaccination unit can be expressed as λd. Therefore, the total amount of vaccines purchased by the vaccination unit from the vaccine manufacturer is $d + \lambda d$.

According to the above description and assumptions, the profits of the M, the U and the BVP are as follows:

$$\Pi_M^{FC} = (w - c_M)(1 + \lambda)d - F_M, \tag{2}$$

$$\Pi_U^{FC} = (p - c_U)d - w(1 + \lambda)d - F_U, \tag{3}$$

$$\Pi_{BVP}^{FC} = F_M + F_U - c_s(1 + \lambda)d, \tag{4}$$

where c_s is the service cost of the vaccine traceability service platform to unit vaccine, $c_s > 0$.

Besides, we also discuss the total consumer surplus CS and social welfare SW in the market, which are expressed as follows, respectively:

$$CS^{FC} = n\int_{p+t\gamma+\theta-s}^{1} (v - p - t\gamma - \theta + s)f(v)dv = \frac{n}{2}(1 - p - t\gamma - \theta + s)^2, \tag{5}$$

$$SW^{FS} = \Pi_M^{FC} + \Pi_U^{FC} + \Pi_{BVP}^{FC} + CS^{FS}. \tag{6}$$

3.2 Centralized decision-making (C)

In centralized decision-making, each member of the supply chain makes decisions with the goal of maximizing the overall profit of the supply chain. According to equations (2)–(4), the total profit of the vaccine supply chain is

$$\Pi^{FC} = \Pi_M^{FC} + \Pi_U^{FC} + \Pi_{BVP}^{FC} = (p - c_U)d - (c_M + c_s)(1 + \lambda)d. \tag{7}$$

Proposition 1. In the case of centralized decision-making, there are:

(a) The optimal selling price of the vaccination unit is

$$p^{(FC-C)*} = \frac{1 - t\gamma - \theta + s + c_U + (1 + \lambda)(c_M + c_s)}{2}. \tag{8}$$

(b) The optimal profit of the vaccine supply chain is

$$\Pi^{(FC-C)*} = \frac{n}{4}(1 - t\gamma - \theta + s - c_U - (1 + \lambda)(c_M + c_s))^2. \tag{9}$$

(c) The consumer surplus is

$$CS^{(FC-C)*} = \frac{n}{8}(1 - t\gamma - \theta + s - c_U - (1 + \lambda)(c_M + c_s))^2. \tag{10}$$

(d) The social welfare is

$$SW^{(FC-C)*} = \frac{3n}{8}(1 - t\gamma - \theta + s - c_U - (1 + \lambda)(c_M + c_s))^2. \tag{11}$$

See Appendix A1 for the process of Proposition 1. Then, we discuss the influence of each parameter on the optimal solution.

Proposition 2. In the case of centralized decision-making, we have

(a) $\frac{\partial p^{(FC-C)*}}{\partial t} < 0, \quad \frac{\partial p^{(FC-C)*}}{\partial \lambda} > 0, \quad \frac{\partial p^{(FC-C)*}}{\partial c_s} > 0.$

(b) $\frac{\partial \Pi^{(FC-C)*}}{\partial t} < 0, \quad \frac{\partial \Pi^{(FC-C)*}}{\partial \lambda} < 0, \quad \frac{\partial \Pi^{(FC-C)*}}{\partial c_s} < 0.$

(c) $\frac{\partial CS^{(FC-C)*}}{\partial t} < 0, \quad \frac{\partial CS^{(FC-C)*}}{\partial \lambda} < 0, \quad \frac{\partial CS^{(FC-C)*}}{\partial c_s} < 0.$

(d) $\frac{\partial SW^{(FC-C)*}}{\partial t} < 0, \quad \frac{\partial SW^{(FC-C)*}}{\partial \lambda} < 0, \quad \frac{\partial SW^{(FC-C)*}}{\partial c_s} < 0.$

Proposition 2(a) shows that the optimal selling price of the vaccine is inversely proportional to t under centralized decision-making. This is because the larger t is, the more time and effort it takes for vaccinators to find and test the vaccine, and the greater the cost for consumers to vaccinate. To meet consumers' vaccination expectations, the optimal selling price of the vaccine will be reduced. $p^{(FC-C)*}$ is in direct proportion to λ and c_s. This is because the larger the λ (c_s) is, the greater the marginal cost of the vaccine supply chain is. To maximize the overall profit, the selling price will be increased. From Propositions 2(b) to (d), it can be seen that the optimal profit, total consumer surplus and social welfare of the vaccine supply chain under centralized decision-making are inversely proportional to t, λ and c_s. This shows that with the increase of t, λ and c_s, the optimal profit, total consumer surplus and social welfare of the vaccine supply chain decrease. In order to improve the total profit of the supply chain, increase the consumer surplus and social welfare, it can reduce the time and effort spent by the vaccinators in finding and testing vaccines, control the proportion of problem vaccines or reduce the unit service cost of the vaccine traceability service platform. Blockchain technology can meet these measures. The proof of Proposition 2 is shown in Appendix A2.

3.3 Decentralized decision-making (D)

In decentralized decision-making, each member of the supply chain chooses the pricing strategy with the ultimate goal of maximizing their own interests. In this paper, because the *BVP* is profitable according to its own charging standards (fixed charge or proportional charge) and does not participate in the pricing decisions of the vaccine manufacturer and the vaccination unit, the decentralized decision-making can be regarded as a Stackelberg game between the vaccine manufacturer and the vaccination unit. As the leader, the vaccine manufacturer first determines the wholesale price, then the vaccination unit as the follower determines the selling price according to the manufacturer's decision.

Proposition 3. In the case of decentralized decision-making, there are

(a) The optimal wholesale price of vaccine manufacturers is

$$w^{(FC-D)*} = \frac{1 - t\gamma - \theta + s - c_U + (1+\lambda)c_M}{2(1+\lambda)} \tag{12}$$

(b) The optimal selling price of the vaccination unit is

$$p^{(FC-D)*} = \frac{3(1 - t\gamma - \theta + s) + c_U + (1+\lambda)c_M}{4} \tag{13}$$

(c) The optimal profit of the vaccine manufacturer is

$$\Pi_M^{(FC-D)*} = \frac{n}{8}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)^2 - F_M. \tag{14}$$

(d) The optimal profit of the vaccination unit is

$$\Pi_U^{(FC-D)*} = \frac{n}{16}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)^2 - F_U. \tag{15}$$

(e) The profit of the vaccine traceability service platform is

$$\Pi_{BVP}^{(FC-D)*} = F_M + F_U - \frac{nc_s(1+\lambda)}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M). \tag{16}$$

(f) The profit of the vaccine supply chain is

$$\begin{aligned}\Pi^{(FC-D)*} =& \frac{n}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)\bigg(\frac{3}{4}(1 - t\gamma - \theta + s - c_U \\ & - (1+\lambda)c_M) - c_s(1+\lambda)\bigg).\end{aligned} \tag{17}$$

(g) The consumer surplus is

$$CS^{(FC-D)*} = \frac{n}{32}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)^2 \tag{18}$$

(h) The social welfare is

$$\begin{aligned}SW^{(FC-D)*} =& \frac{n}{32}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)(7(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M) \\ & - 8c_s(1+\lambda)).\end{aligned} \tag{19}$$

See Appendix A3 for the process of Proposition 3. Then, we explore the influence of each parameter on the optimal solution.

Proposition 4. In the case of decentralized decision-making, we have

(a) $\frac{\partial w^{(FC-D)*}}{\partial t} < 0, \frac{\partial w^{(FC-D)*}}{\partial \lambda} < 0, \frac{\partial p^{(FC-D)*}}{\partial t} < 0, \frac{\partial p^{(FC-D)*}}{\partial \lambda} > 0.$

(b) $\frac{\partial \Pi_M^{(FC-D)*}}{\partial t} < 0, \frac{\partial \Pi_M^{(FC-D)*}}{\partial \lambda} < 0, \frac{\partial \Pi_U^{(FC-D)*}}{\partial t} < 0, \frac{\partial \Pi_U^{(FC-D)*}}{\partial \lambda} < 0, \frac{\partial \Pi^{(FC-D)*}}{\partial t} < 0,$
$\frac{\partial \Pi^{(FC-C)*}}{\partial \lambda} < 0, \frac{\partial \Pi^{(FC-C)*}}{\partial c_s} < 0.$

(c) $\frac{\partial \Pi_{BVP}^{(FC-D)*}}{\partial t} > 0$, $\frac{\partial \Pi_{BVP}^{(FC-D)*}}{\partial c_S} < 0$, when $0 < \lambda < \frac{1-t\gamma-\theta+s-c_U-2c_M}{2c_M}$, $\frac{\partial \Pi_{BVP}^{(FC-D)*}}{\partial \lambda} < 0$, when $\lambda > \frac{1-t\gamma-\theta+s-c_U-2c_M}{2c_M}$, $\frac{\partial \Pi_{BVP}^{(FC-D)*}}{\partial \lambda} > 0$, when $\lambda = \frac{1-t\gamma-\theta+s-c_U-2c_M}{2c_M}$, $\frac{\partial \Pi_{BVP}^{(FC-D)*}}{\partial \lambda} = 0$.

(d) $\frac{\partial CS^{(FC-D)*}}{\partial t} < 0, \frac{\partial CS^{(FC-C)*}}{\partial \lambda} < 0.$

(e) $\frac{\partial SW^{(FC-C)*}}{\partial t} < 0, \frac{\partial SW^{(FC-C)*}}{\partial \lambda} < 0, \frac{\partial SW^{(FC-C)*}}{\partial c_s} < 0.$

Proposition 4(a) shows that $w^{(FC-D)*}$ and $p^{(FC-D)*}$ also decrease with the increase of t. This reason is that as t increases, the cost for consumers to buy the vaccine will increase, resulting in a decrease in the number of vaccinations. To stimulate the purchase, the vaccine manufacturer and the vaccination unit will adopt a price reduction strategy. With the increase of λ, $w^{(FC-D)*}$ decreases, while $p^{(FC-D)*}$ increases. The larger the λ is, the more problem vaccines are, and the greater the loss ($w\lambda d$) or cost (((1 + λ)w + c_U) d) of the vaccination unit is. On the one hand, in order to improve profit, the vaccination unit will set a higher selling price. On the other hand, the vaccination unit will reduce the number of vaccine doses ordered to reduce losses. To obtain higher profits, the vaccine manufacturer will reduce the wholesale price to attract the vaccination unit to order more vaccines. Proposition 4(b) shows that under the decentralized decision-making, $\Pi_M^{(FC-D)*}$ and $\Pi_U^{(FC-D)*}$ are only related to t and λ. With the increase of t and λ, $\Pi_M^{(FC-D)*}$ and $\Pi_U^{(FC-D)*}$ will decrease. The optimal profit of the vaccine supply chain is related to t, λ and c_s. With the increase of t, λ and c_s, the optimal profit of the vaccine supply chain will decrease. Proposition 4(c) shows that $\Pi_{BVP}^{(FC-D)*}$ at the optimal selling price is the increasing function of t and the decreasing function of c_s. Besides, the profit of the BVP is also related to λ. When $0 < \lambda < \frac{1-t\gamma-\theta+s-c_U-2c_M}{2c_M}$, $\Pi_{BVP}^{(FC-D)*}$ is the decreasing function of λ. When $\lambda > \frac{1-t\gamma-\theta+s-c_U-2c_M}{2c_M}$, $\Pi_{BVP}^{(FC-D)*}$ is the increasing function of λ. When $\lambda = \frac{1-t\gamma-\theta+s-c_U-2c_M}{2c_M}$, if there is only one variable λ, $\Pi_{BVP}^{(FC-D)*}$ is the lowest. Propositions 4(d) and (e) show that in the decentralized decision-making, the total consumer surplus decreases with the increase of t and λ, while the social welfare decreases with the increase of t, λ and c_s. The proof of Proposition 4 is shown in Appendix A4.

Proposition 5. Comparing the centralized decision-making with decentralized decision-making, we get

(a) If $c_s > \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$, $p^{(FC-C)*} > p^{(FC-D)*}$; if $0 < c_s < \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$, $p^{(FS-C)*} < p^{(FC-D)*}$; if $c_s = \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$, $p^{(FC-C)*} = p^{(FC-D)*}$.

(b) If $c_s = \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$, $\Pi^{(FC-C)*} = \Pi^{(FC-D)*}$; if $c_s \neq \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$, $\Pi^{(FS-C)*} > \Pi^{(FC-D)*}$.

(c) $CS^{(FC-C)*} > CS^{(FC-D)*}$.

(d) $SW^{(FC-C)*} > SW^{(FC-D)*}$.

Proposition 5(a) shows that when c_s is high enough ($c_s > \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$), the optimal selling price of the vaccination unit in the centralized decision-making is higher than that in decentralized decision-making. This reason is that the cost of the whole supply chain increases when c_s is high. To improve the profit of the supply chain, the optimal selling price under the centralized decision-making may exceed that under the decentralized decision-making. When c_s is low enough ($0 < c_s < \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$), the optimal selling price of the vaccination unit in the centralized decision-making is less than that in the decentralized decision-making. This reason is shown as follows. On the one hand, when c_s is low, the cost of the whole supply chain is low. In order to increase the vaccine ordering quantity, the selling price will be lower (in the case of centralized decision-making). On the other hand, in the case of decentralized decision-making, the vaccination unit aims at maximizing their own interests. In order to increase profits, it will choose a higher vaccine selling price. When $c_s = \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$, in these two situations, the optimal selling price is equal. From Proposition 5(b), it can be seen that the total profit of the vaccine supply chain is the same in the centralized decision-making and decentralized decision-making when $c_s = \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$. When $c_s \neq \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$, the optimal profit of the supply chain in the centralized decision-making is greater than that in the decentralized decision-making. It can be seen from Propositions 5(c) and (d) that the total consumer surplus and social welfare under centralized decision-making are greater than ones under decentralized decision-making. As a third party, the vaccine traceability service platform does not participate in the supply chain decision-making, and can increase its own profit by increasing the fixed cost F_M or (and) F_U, which has no influence on the profits of the supply chain, the total consumer surplus and social welfare. Therefore, in order to improve the overall profit of the supply chain, increase the consumer surplus and social welfare, the vaccine manufacturer and the vaccination unit can improve their profit distribution by seeking some cooperation. See Appendix A5 for the process of Proposition 5.

4. Benefit coordination mechanism of the vaccine supply chain

In order to improve the profit of the vaccine manufacturer and the vaccination unit, make the overall profit of the vaccine supply chain under the decentralized decision-making reach the level of the centralized decision-making, and increase the consumer surplus and the social welfare, it is necessary to coordinate the vaccine supply chain through certain contracts. Among all the contracts, cost-sharing contract and revenue-sharing contract are most commonly used in the supply chain. Therefore, in this section, we try to discuss the interest coordination of the proposed model through the two contracts.

4.1 Cost-sharing contract (S)

Under the blockchain technology, the problem vaccine ($(1+\lambda)d$) cannot be vaccinated by consumers, which causes the cost of the vaccination unit to increase. In the vaccine supply chain, the cost-sharing contract means that the vaccine manufacturer (the leader) will bear part of the cost of the problem vaccine for the vaccination unit (the follower) besides bearing his or her own production cost. Assuming that the cost-sharing ratio is η $(0 = \eta \leq 1)$, the profits of the vaccine manufacturer and the vaccination unit can be expressed as follows:

$$\Pi_M^{(FC-S)} = (w - c_M)(1+\lambda)d - \eta w \lambda d - F_M, \tag{20}$$

$$\Pi_U^{(FC-S)} = (p - c_U - w)d - (1-\eta) w \lambda d - F_U. \tag{21}$$

We solve the problem by backward induction. Combining equations (1) and (21), the optimal selling price of the vaccination unit is obtained as follows:

$$p^{(FC-S)*} = \frac{1 - t\gamma - \theta + s + c_U + (1 + (1-\eta_1)\lambda)w}{2}. \tag{22}$$

Substituting equation (22) into equation (20), the optimal wholesale price of the vaccine manufacturer under the cost-sharing contract is obtained as follows:

$$w^{(FC-S)*} = \frac{1 - t\gamma - \theta + s - c_U + (1+\lambda)c_M}{2(1 + (1-\eta_1)\lambda)}. \tag{23}$$

Substituting equation (23) into equation (22), we have

$$p^{(FC-S)*} = \frac{3(1 - t\gamma - \theta + s) + c_U + (1+\lambda)c_M}{4}. \tag{24}$$

Proposition 6. Under the cost-sharing contract, we have

(a) $w^{(FC-S)*} > w^{(FC-D)*}, p^{(FC-S)*} = p^{(FC-D)*}$.

(b) $\Pi_M^{(FC-S)*} = \Pi_M^{(FC-D)*}, \Pi_U^{(FC-S)*} = \Pi_U^{(FC-D)*}, \Pi_{BVP}^{(FC-S)*} = \Pi_{BVP}^{(FC-D)*}, \Pi^{(FC-S)*} = \Pi^{(FC-D)*}$, $CS^{(FC-S)*} = CS^{(FC-D)*}, SW^{(FC-S)*} = SW^{(FC-D)*}$.

Proposition 6(a) shows that compared with the decentralized decision-making, the optimal wholesale price of the vaccine manufacturer increases under the cost-sharing contract. The result is obvious, because the cost of the vaccine manufacturer increases. However, the optimal selling price of the vaccination unit under the cost-sharing contract is the same as the decentralized decision-making. From Proposition 6(b), we can see that under the cost-sharing contract, the profit of the vaccine manufacturer, the profit of the vaccination unit, the profit of the vaccine traceability service platform, the total profit of the vaccine supply chain, the total consumer surplus and the social welfare are the same as those in the decentralized decision situation. Therefore, the cost-sharing contract cannot improve the profit of the vaccine supply chain and total consumer surplus. The proof of Proposition 6 is shown in Appendix A6.

4.2 Revenue-sharing contract (R)

Under the revenue-sharing contract, the vaccine manufacturer sells vaccines to the vaccination unit at a wholesale price below the cost ($w < c_M$). In order to make up for the loss of the vaccine manufacturer, the vaccination unit shares part of its selling revenue with the vaccine manufacturer, so as to ensure that the income level of both parties is higher than that of the decentralized decision-making and achieve the best performance of the supply chain. Assuming that the revenue-sharing ratio of the vaccination unit is ϕ ($0 = \phi \leq 1$). The profits of the vaccine manufacturer and the vaccination unit can be expressed as follows:

$$\Pi_M^{(FC-R)} = (w - c_M)(1+\lambda)d + \phi p d - F_M, \tag{25}$$

$$\Pi_U^{(FC-R)} = ((1-\phi)p - c_U - (1+\lambda)w)d - F_U. \tag{26}$$

Since $\frac{\partial^2 \Pi_U^{(FC-R)}}{\partial p^2} = -2(1-\phi)n < 0$, $\Pi_U^{(FC-R)}$ reveals that it is a concave function in p.

When $\frac{\partial \Pi_U^{(FC-R)}}{\partial p} = 0$, the vaccination unit obtains the optimal selling price, which is

$$p^{(FC-R)*} = \frac{(1-\phi)(1-t\gamma-\theta+s) + c_U + (1+\lambda)w}{2(1-\phi)}. \tag{27}$$

Let $p^{(FC-R)*} = p^{(FC-C)*}$. Therefore, the wholesale price of the vaccine manufacturer under the revenue-sharing contract is

$$w^{(FC-R)} = \frac{(1-\phi)(1+\lambda)(c_M+c_s) - \phi c_U}{1+\lambda}. \tag{28}$$

Proposition 7. Under the revenue-sharing contract, if and only if $0 < c_s \leq \frac{1-t\gamma-\theta+s-c_U-(1+\lambda)c_M}{2(1+\lambda)}$ and $\frac{(1-t\gamma-\theta+s-c_U-(1+\lambda)c_M-2(1+\lambda)c_s)^2}{2(1-t\gamma-\theta+s-c_U-(1+\lambda)(c_M+c_s))^2} \leq \phi \leq \frac{(3(1-t\gamma-\theta+s-c_U-(1+\lambda)c_M)-2(1+\lambda)c_s)(1-t\gamma-\theta+s-c_U-(1+\lambda)c_M-2(1+\lambda)c_s)}{4(1-t\gamma-\theta+s-c_U-(1+\lambda)(c_M+c_s))^2}$, there are: $\Pi_M^{(FC-R)*} \geq \Pi_M^{(FC-D)*}$, $\Pi_U^{(FC-R)*} \geq \Pi_U^{(FC-D)*}$, $\Pi^{(FC-R)*} = \Pi^{(FC-C)*}$, $CS^{(FC-R)*} = CS^{(FC-C)*}$, $SW^{(FC-R)*} = SW^{(FC-C)*}$.

It can be seen from Proposition 7 that when c_s and φ meet certain conditions, the optimal profits of the vaccine manufacturer and the vaccination unit under revenue-sharing contract are greater than that under decentralized decision-making, and the total profit, total consumer surplus and social welfare of the vaccine supply chain reach the centralized decision-making level. The profit of the BVP can be improved by increasing fixed fee F_M or (and) F_U. The proof of Proposition 7 is shown in Appendix A7.

5. Extended model: proportional charge (*PC*) scenario

In this section, we will discuss the pricing and profit of the vaccine supply chain when the blockchain technology based on the vaccine traceability service platform, adopts the proportional charge method and compares it with the fixed charge scenario. That is to say, at a certain time or a certain time period, the vaccine traceability service platform based on blockchain technology extracts fees in proportion of φ_1 ($0 < \varphi_1 < 1$) and φ_2 ($0 < \varphi_2 < 1$) according to the income of the manufacturer and the vaccination unit. To facilitate the calculation, we assume that $\varphi_1 = \varphi_2 = \varphi$. Therefore, in the extended model, the profits of the vaccine manufacturer, the vaccination unit and the vaccine traceability service platform based on blockchain technology are as follows:

$$\Pi_M^{PC} = (1-\varphi)w(1+\lambda)d - c_M(1+\lambda)d, \tag{29}$$

$$\Pi_U^{PC} = (1-\varphi)pd - w(1+\lambda)d - c_U d, \tag{30}$$

$$\Pi_{BVP}^{PC} = \varphi w(1+\lambda)d + \varphi pd - c_s(1+\lambda)d. \tag{31}$$

Proposition 8. In the extended model, there are

(a) The optimal wholesale price for the vaccine manufacturers is:

$$w^{PC*} = \frac{(1-t\gamma-\theta+s)(1-\varphi)^2 - c_U(1-\varphi) + c_M(1+\lambda)}{2(1+\lambda)(1-\varphi)}. \tag{32}$$

(b) The optimal selling price of the vaccination unit is:

$$p^{PC*} = \frac{3(1-t\gamma-\theta+s)(1-\varphi)^2 + c_U(1-\varphi) + c_M(1+\lambda)}{4(1-\varphi)^2}. \tag{33}$$

Proposition 8 gives the optimal solution of the supply chain's selling price, total profit and total consumer surplus when the vaccine traceability service platform based on blockchain technology implements the profit model of charging by proportion. See Appendix A8 for the specific certification process. Next, we discuss the influence of each parameter on the optimal solution.

Proposition 9. In the extended model, there are

(a) $\frac{\partial w^{PC*}}{\partial t} < 0, \frac{\partial w^{PC*}}{\partial \lambda} < 0, \frac{\partial w^{PC*}}{\partial \varphi} < 0.$

(b) $\frac{\partial p^{PC*}}{\partial t} < 0, \frac{\partial p^{PC*}}{\partial \lambda} > 0, \frac{\partial w^{PC*}}{\partial \varphi} > 0.$

Proposition 9 shows that w^{PC*} is inversely proportional to t and λ. p^{PC*} is inversely proportional to t and directly proportional to λ. See Proposition 4 for specific reasons. However, with the increase of φ, the optimal wholesale price for the vaccine manufacturer w^{PC*} decreases and the optimal selling price for the vaccination unit p^{PC*} increases. This is because the larger the φ is, the higher the cost that the vaccine manufacturer and the vaccination unit pay to the vaccine traceability service platform, and the greater their profits loss. In order to increase profits, the vaccine manufacturer will choose to lower the wholesale price to attract the vaccination unit to order more vaccines, and the vaccination unit will set a higher selling price. The proof of Proposition 9 is shown in Appendix A9.

Proposition 10. Comparing the fixed charge (FC) scenario with the proportional charge (PC) scenario, we get

(a) $w^{(FC-D)*} > w^{PC*}$.

(b) $p^{(FC-D)*} < p^{PC*}$.

(c) $\Pi^{(FC-D)*} > \Pi^{PC*}$.

(d) $CS^{(FC-D)*} > CS^{PC*}$.

(e) $SW^{(FC-D)*} > SW^{PC*}$.

Proposition 10(a) shows that the optimal wholesale price of the vaccine manufacturer in the fixed charge scenario is greater than that in the proportional charge scenario. This is because, under the proportional charge scenario, the higher the income of the vaccine manufacturer is, the higher the cost paid to the vaccine traceability platform based on blockchain technology. In order to reduce the cost, the vaccine manufacturer will lower the wholesale price. In addition, under the fixed charge scenario, the fee charged by the vaccine traceability service platform to the vaccine manufacturer is fixed. In order to improve its income, the vaccine manufacturer will raise the wholesale price at this time. Proposition 10(b) shows that the optimal selling price of the vaccination unit in the fixed charge scenario is lower than that in the proportional charge scenario. This may be because, while other conditions remain unchanged, the vaccination unit pays higher fees to the vaccine traceability service platform in the case of fixed charge. In order to ensure its interests, the vaccination unit will raise the selling price in the case of proportional charge. Propositions 10(c)–(e) show that the optimal total profit, total consumer surplus and social welfare of the vaccine supply chain under the fixed charge scenario are greater than those under the proportional charge scenario, respectively. Therefore, from the perspective of the vaccine supply chain as a whole, the fixed charge scenario has more advantages than the proportional charge scenario. But which mode to use depends on the vaccine traceability service platform based on blockchain technology. In addition, the extended model can realize profit coordination through a model similar to the contract signed in Section 3. We will not go into details here. The proof of Proposition 10 is shown in Appendix A10.

6. The roles of blockchain technology

In the previous sections, we analyzed the pricing and coordination of the vaccine supply chain based on blockchain technology by building a model. Next, we try to discuss the role of blockchain technology in the vaccine supply chain through the above analysis.

Proposition 11. In the blockchain technology based on the vaccine supply chain, it not only saves the time and effort taken by the vaccinator to find and test the vaccine before vaccination (t) but also reduces the proportion of the problematic vaccines in the supply chain (λ). Thus, the profit, total consumer surplus and social welfare of the vaccine supply chain increase. The operational efficiency of the vaccine supply chain is improved.

Proposition 11 illustrates the role of blockchain technology in the vaccine supply chain. First, it is obvious that using blockchain technology in the vaccine supply chain can save t. Before using blockchain technology, the vaccine information inquired by the vaccinators through the vaccine tracing platform is basically one-sided, incomplete and lack of timeliness. To ensure the safety of the vaccine, the vaccinators sometimes need to verify and evaluate the vaccine through various channels (e.g. browsing a large number of historical websites, telephone consultation with merchants), which requires more t. Moreover, due to the existence of false information, it is not completely certain whether the vaccines can be vaccinated. The introduction of blockchain technology ensures the accuracy and validity of the vaccine information. The vaccinators can log on to the vaccine traceability service platform directly and inquire all information about vaccines without using other channels. Therefore, t decreases.

Second, using blockchain technology in the vaccine supply chain can reduce λ. Since the information on the blockchain cannot be tampered with, if any link is found to have problems, the relevant institutions will punish the directly responsible businessmen to avoid the possibility of speculation at each stage. Facing this transparent supply chain environment, the supply chain members must ensure that the information on the platform is true and effective, so that they can exist in the supply chain for a long time. Therefore, λ decreases. In addition, it eliminates the distrust among the supply chain members and increases the possibility of their cooperation. It is worth noting that in the vaccine supply chain based on blockchain technology, λ will not drop to 0. This is caused by some external force majeure factors. Even if the information in each link is correct, it is not absolutely certain that the vaccine can be inoculated at last. When the vaccinator finds that the vaccine to be vaccinated has expired, is invalid or has other safety problems, he or she will not choose to vaccinate.

Finally, using blockchain technology can increase the profit, total consumer surplus and social welfare of the vaccine supply chain. From Propositions 2 and 4, we can find that when t or λ decreases, the profit, total consumer surplus and social welfare of the supply chain will increase.

To sum up, we come to the conclusion that the application of blockchain technology in the vaccine supply chain can improve the operational efficiency of the supply chain.

7. Conclusion

In recent years, with the outbreak of vaccine incidents, vaccine safety has become a hot topic in the world. Research shows that improving the vaccine supply chain management is the most direct and effective way to solve vaccine safety problems. However, the existing research on the vaccine supply chain does not solve the problem of vaccine safety. At present, the application of blockchain technology in the field of supply chain management is deepening gradually. Blockchain technology has the characteristics of decentralization, traceability and nontampering and has become an effective solution to solve the vaccine safety problems in the vaccine supply chain. In the vaccine supply chain, blockchain technology plays an important role based on a platform and provides services for members of the supply chain. However, after the introduction of the vaccine traceability service platform based on blockchain technology, the operational efficiency of the vaccine supply chain remains to be discussed. Based on this, we built a vaccine supply chain economic game model consisting of a vaccine manufacturer, a vaccine traceability service platform based on blockchain technology and a vaccination unit.

In the basic model (fixed charge scenario), we analyze the optimal pricing strategy, the optimal total profit, the total consumer surplus and the social welfare of the vaccine supply chain under centralized and decentralized decision-making. Sensitivity analysis is conducted to understand the influence of main parameters, especially these related to blockchain technology, on the vaccine supply chain optimization strategy. Then, we discuss whether two common contracts, cost-sharing contract and revenue-sharing contract, can achieve the coordination of the vaccine supply chain. In the extended model, we discuss the optimal solution of the vaccine supply chain under the proportional charge scenario and compare it with the fixed charge scenario.

By solving the problems raised in Section 1, we mainly get the following important insights and management implications:

(1) In the basic model, there are equilibrium strategies under the centralized and decentralized decision-making. Moreover, the total profit of the supply chain under the centralized decision-making is always no less than that under the decentralized decision-making, and the total consumer surplus and the social welfare under the centralized decision-making are always greater than ones under the decentralized decision-making. In both cases, the optimal selling price of the vaccine is related to the service cost of the vaccine traceability service platform to unit vaccine.

(2) The cost-sharing contract cannot realize the coordination of the vaccine supply chain based on the blockchain technology. When the proportion of revenue-sharing meets certain conditions, the revenue-sharing contract can coordinate the vaccine supply chain based on blockchain technology. Therefore, in the vaccine supply chain, the vaccine manufacturer and the vaccination unit can sign appropriate revenue-sharing contracts to improve the profits of each member and the vaccine supply chain.

(3) Compared with the fixed charge scenario, the total profit of the supply chain obtained by adopting the proportional charge strategy in the vaccine traceability service platform is less, and the total consumer surplus and the social welfare are also lower. Therefore, on the whole, the fixed charge scenario is more beneficial to the vaccine supply chain than the proportional charge scenario. However, the specific scenario model depends on the vaccine traceability service platform based on blockchain technology.

(4) After the introduction of blockchain technology, vaccinators can decide whether to vaccinate directly through the platform without using other channels. Therefore, the time and effort spent by vaccinators in finding and testing vaccines decreases. In addition, facing this transparent supply chain environment, the supply chain members must ensure that the information on the platform is true and effective, so that they can exist in the supply chain for a long time. Therefore, the proportion of problem vaccines decreases. At the same time, the profit of the vaccine supply chain, the total consumer surplus and the social welfare increased, which shows that the operation efficiency of the vaccine supply chain has been improved.

References

Abeyratne, S.A. and Monfared, R.P. (2016), "Blockchain ready manufacturing supply chain using distributed ledger", *International Journal of Research in Engineering and Technology*, Vol. 5 No. 9, pp. 1-10.

Adida, E., Dey, D. and Mamani, H. (2013), "Operational issues and network effects in vaccine markets", *European Journal of Operational Research*, Vol. 231 No. 2, pp. 414-427.

Andoni, M., Robu, V. and Flynn, D. (2017), "Crypto-control your own energy supply", *Nature*, Vol. 584 No. 7666, p. 158.

Apte, S. and Petrovsky, N. (2016), "Will blockchain technology revolutionize excipient supply chain management?", *Journal of Excipients and Food Chemicals*, Vol. 7 No. 3, pp. 76-78.

Arifoğlu, K., Deo, S. and Iravani, S.M.R. (2012), "Consumption externality and yield uncertainty in the influenza vaccine supply chain: interventions in demand and supply sides", *Management Science*, Vol. 58 No. 6, pp. 1072-1091.

Bocek, T. and Stiller, B. (2018), "Smart contracts–blockchains in the wings", in Linnhoff-Popien, C., Schneider, R. and Zaddach, M. (Eds), *Digital Marketplaces Unleashed*, Springer, Berlin, Heidelberg, pp. 169-184.

Chen, R.T., Shimabukuro, T.T., Martin, D.B., Zuber, P.L., Weibel, D.M. and Sturkenboom, M. (2015), "Enhancing vaccine safety capacity globally: a lifecycle perspective", *Vaccine*, Vol. 33 No. 4, pp. D46-D54.

Chick, S.E., Mamani, H. and Simchi-Levi, D. (2008), "Supply chain coordination and influenza vaccination", *Operations Research*, Vol. 56 No. 6, pp. 1493-1506.

Choi, T.M. (2019), "Blockchain-technology-supported platforms for diamond authentication and certification in luxury supply chains", *Transportation Research E: Logistics and Transportation Review*, Vol. 128, pp. 17-29.

Choi, T.M., Feng, L. and Li, R. (2020), "Information disclosure structure in supply chains with rental service platforms in the blockchain technology era", *International Journal of Production Economics*, Vol. 221, pp. 1-14.

Dhandapani, J. and Uthayakumar, R. (2019), "An EOQ model for a high cost and most wanted vaccine considering the expiration period", *The Journal of Analysis*, Vol. 27 No. 1, pp. 55-73.

Duijzer, L.E., van Jaarsveld, W. and Dekker, R. (2018), "Literature review: the vaccine supply chain", *European Journal of Operational Research*, Vol. 268 No. 1, pp. 174-192.

Galvez, J.F., Mejuto, J.C. and Simal-Gandara, J. (2018), "Future challenges on the use of blockchain for food traceability analysis", *Trends in Analytical Chemistry*, Vol. 107, pp. 222-232.

Guo, Y. and Liang, C. (2016), "Blockchain application and outlook in the banking industry", *Financial Innovation*, Vol. 2 No. 1, p. 24.

Haq, I. and Esuka, O.M. (2018), "Blockchain technology in pharmaceutical industry to prevent counterfeit drugs", *International Journal of Computer Applications*, Vol. 180 No. 25, pp. 8-12.

Hofmann, E., Strewe, U.M. and Bosia, N. (2018), "Conclusion—what can we learn from blockchain-driven supply chain finance?", *Supply Chain Finance and Blockchain Technology*, Springer, Cham, pp. 89-91.

Huang, Y.L., Yang, C. and Jiang, S.J. (2015), "Influenza vaccine supply chain coordination with reordering opportunities under partial information", *Operations Research and Management Science*, Vol. 24 No. 1, pp. 40-56.

Kamble, S., Gunasekaran, A. and Arha, H. (2019), "Understanding the blockchain technology adoption in supply chains-Indian context", *International Journal of Production Research*, Vol. 57 No. 7, pp. 2009-2033.

Kamilaris, A., Fonts, A. and Prenafeta-Boldύ, F.X. (2019), "The rise of blockchain technology in agriculture and food supply chains", *Trends in Food Science and Technology*, Vol. 91, pp. 640-652.

Leng, K., Bi, Y., Jing, L., Fu, H.C. and Van Nieuwenhuyse, I. (2018), "Research on agricultural supply chain system with double chain architecture based on blockchain technology", *Future Generation Computer Systems*, Vol. 86, pp. 641-649.

Li, M., Shen, L. and Huang, G.Q. (2019), "Blockchain-enabled workflow operating system for logistics resources sharing in E-commerce logistics real estate service", *Computers and Industrial Engineering*, Vol. 135, pp. 950-969.

Liu, Z. and Li, Z. (2020), "A blockchain-based framework of cross-border e-commerce supply chain", *International Journal of Information Management*, Vol. 52, pp. 1-18.

Longo, F., Nicoletti, L., Padovano, A., d'Atri, G. and Forte, M. (2019), "Blockchain-enabled supply chain: an experimental study", *Computers and Industrial Engineering*, Vol. 136, pp. 57-69.

Min, H. (2019), "Blockchain technology for enhancing supply chain resilience", *Business Horizons*, Vol. 62 No. 1, pp. 35-45.

Nakamoto, S. (2008), "Bitcoin: a peer-to-peer electronic cash system", available at: http://bitcoin.org/bitcoin.pdf (accessed 21 August 2008).

Saberi, S., Kouhizadeh, M. and Sarkis, J. (2018), "Blockchain technology: a panacea or pariah for resources conservation and recycling?", *Resources, Conservation and Recycling*, Vol. 130, pp. 80-81.

Sarac, A., Absi, N. and Dauzère-Pérès, S. (2010), "A literature review on the impact of RFID technologies on supply chain management", *International Journal of Production Economics*, Vol. 128 No. 1, pp. 77-95.

Sun, Y., Chen, X. and Luo, Y. (2019), "Profit allocation method in influenza vaccine supply chain by risk compensation", *2019 IEEE 6th International Conference on Industrial Engineering and Applications*, IEEE,Tokyo, Japan, pp. 511-515.

Taylor, E., Banyard, A.C., Bourhy, H., Cliquet, F., Ertl, H., Fehlner-Gardiner, C., Horton, D.L., Mani, R.S., Müller, T., Rupprecht, C.E., Schnell, M.J., Del Rio Vilas, R. and Fooks, A.R. (2019), "Avoiding preventable deaths: the scourge of counterfeit rabies vaccines", *Vaccine*, Vol. 37 No. 17, pp. 2285-2287.

Thomason, J. (2017), "Blockchain: an accelerator for women and children's health?", *Global Health Journal*, Vol. 1 No. 1, pp. 3-10.

Tseng, J.H., Liao, Y.C., Chong, B. and Liao, S.W. (2018), "Governance on the drug supply chain via Gcoin blockchain", *International Journal of Environmental Research and Public Health*, Vol. 15 No. 6, pp. 1055-1062.

Wang, J., Liu, J. and Zheng, L. (2018), "Construction of VMI mode supply chain management system based on block chain", in Vaidya, J. and Li, J. (Eds), *International Conference on Algorithms and Architectures for Parallel Processing*, Springer, Cham, pp. 611-616.

Wu, X. and Lin, Y. (2019), "Blockchain recall management in pharmaceutical industry", *Procedia CIRP*, Vol. 83, pp. 590-595.

Yong, B., Shen, J., Liu, X., Li, F., Chen, H. and Zhou, Q. (2020), "An intelligent blockchain-based system for safe vaccine supply and supervision", *International Journal of Information Management*, Vol. 52, pp. 1-12.

Appendix

A1

By equations (1) and (7), we can see that the second derivative of p is $\frac{\partial^2 \Pi^{FC}}{\partial p^2} = -2n < 0$, which shows that Π^{FC} is a strictly concave function of p. We get $\frac{\partial \Pi^{FC}}{\partial p} = n(1 - 2p - t\gamma \ -\theta + s \ + c_U \ + (1+\lambda)(c_M + c_s)) = 0$. So, the optimal selling price of the vaccination unit is:

$$p^{(FC-C)*} = \frac{1 - t\gamma - \theta + s + c_U + (1+\lambda)(c_M + c_s)}{2}.$$

By substituting it into equations (5) ~ (7) respectively, we get:

$$CS^{(FC-C)*} = \frac{n}{8}(1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s))^2,$$

$$SW^{(FC-C)*} = \frac{3n}{8}(1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s))^2,$$

$$\Pi^{(FC-C)*} = \frac{n}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s))^2.$$

A2.

Calculating the first derivative of t, λ and c_s respectively for equation (8), we obtain that $\frac{\partial p^{(FC-C)*}}{\partial t} = -\frac{\gamma}{2}$, $\frac{\partial p^{(FC-C)*}}{\partial \lambda} = \frac{c_M + c_s}{2}$, $\frac{\partial p^{(FC-C)*}}{\partial c_s} = \frac{1+\lambda}{2}$. Because $\gamma > 0, c_M > 0, c_s > 0, \lambda > 0$, so $\frac{\partial p^{(FC-C)*}}{\partial t} < 0$, $\frac{\partial p^{(FC-C)*}}{\partial \lambda} > 0$, $\frac{\partial p^{(FC-C)*}}{\partial c_s} > 0$.

Calculating the first derivative of t, λ and c_s for equation (9), respectively, we get:

$$\frac{\partial \Pi^{(FC-C)*}}{\partial t} = -\frac{n}{2}(1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s))\gamma,$$

$$\frac{\partial \Pi^{(FC-C)*}}{\partial \lambda} = -\frac{n}{2}(1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s))(c_M + c_s),$$

$$\frac{\partial \Pi^{(FC-C)*}}{\partial c_s} = -\frac{n}{2}(1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s))(c_M + c_s).$$

Substituting equation (8) into equation (1), the number of consumers finally vaccinated is:

$$d^{(FC-C)*} = \frac{n}{2}(1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s)).$$

Because $d > 0$, we get that $1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s) > 0$. So $\frac{\partial \Pi^{(FC-C)*}}{\partial t} < 0$, $\frac{\partial \Pi^{(FC-C)*}}{\partial \lambda} < 0$, $\frac{\partial \Pi^{(FC-C)*}}{\partial c_s} < 0$.

Similarly, calculating the first derivative of t, λ and cs for equations (10) and (11), respectively, we obtain that $\frac{\partial CS^{(FC-C)*}}{\partial t} < 0$, $\frac{\partial CS^{(FC-C)*}}{\partial \lambda} < 0$, $\frac{\partial CS^{(FC-C)*}}{\partial c_s} < 0$, $\frac{\partial SW^{(FC-C)*}}{\partial t} < 0$, $\frac{\partial SW^{(FC-C)*}}{\partial \lambda} < 0$, $\frac{\partial SW^{(FC-C)*}}{\partial c_s} < 0$.

A3.

The inverse order method is used to solve the optimal solution. Firstly, combining equation (1) with equation (3), we obtain the second derivative of p is $\frac{\partial^2 \Pi_U^{FC}}{\partial p^2} = -2n < 0$, which shows that Π_U^{FS} is a strictly concave function of p. We get $\frac{\partial \Pi_U^{FC}}{\partial p} = n(1 - 2p - t\gamma - \theta + s + c_U + (1+\lambda)w) = 0$. So $p^{(FC-C)*}(w) = \frac{1 - t\gamma - \theta + s + c_U + (1+\lambda)w}{2}$. Then, putting it into equation (2), we obtain $\Pi_M^{FC}(p^{(FC-C)*}(w)) = \frac{n}{2}(w - c_M)(1+\lambda)(1 - t\gamma - \theta + s + c_U + (1+\lambda)w) - F_M$. Checking the structural properties of $\Pi_M^{FC}(p^{(FC-C)*}(w))$ reveals that it is a concave function in w. When $\frac{\partial \Pi_M^{FC}(p^{(FC-C)*}(w))}{\partial w} = 0$, we obtained the optimal wholesale price of the vaccine manufacturer is $w^{(FC-D)*} = \frac{1 - t\gamma - \theta + s - c_U + (1+\lambda)c_M}{2(1+\lambda)}$. So, the optimal selling price of the vaccination unit is $p^{(FC-D)*} = \frac{3(1 - t\gamma - \theta + s) + c_U + (1+\lambda)c_M}{4}$. Substitute $p^{(FC-D)*}$ and $w^{(FC-D)*}$ into equations (2) ~ (6), respectively, we have:

$$\Pi_M^{(FC-D)*} = \frac{n}{8}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)^2 - F_M,$$

$$\Pi_U^{(FC-D)*} = \frac{n}{16}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)^2 - F_U,$$

$$\Pi_{BVP}^{(FC-D)*} = F_M + F_U - \frac{nc_s(1+\lambda)}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M),$$

$$\Pi^{(FC-D)*} = \frac{n}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)(\frac{3}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M) - c_s(1+\lambda)),$$

$$CS^{(FC-D)*} = \frac{n}{32}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)^2,$$

$$SW^{(FC-D)*} = \frac{n}{32}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)(7(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M) - 8c_s(1+\lambda)).$$

A4.

Calculating the first derivative of t, λ for equation (12), respectively, we obtain that $\frac{\partial w^{(FC-D)*}}{\partial t} = -\frac{\gamma}{2(1+\lambda)}$, $\frac{\partial w^{(FC-D)*}}{\partial \lambda} = -\frac{1-t\gamma-\theta+s-c_U}{2(1+\lambda)^2}$. Because $\gamma > 0$, $1-t\gamma-\theta+s-c_U > 0$, $\lambda > 0$, so $\frac{\partial w^{(FC-D)*}}{\partial t} < 0$, $\frac{\partial w^{(FC-D)*}}{\partial \lambda} < 0$.

Calculating the first derivative of t, λ for equation (13), respectively, we obtain that $\frac{\partial p^{(FC-D)*}}{\partial t} = -\frac{3\gamma}{4}$, $\frac{\partial p^{(FC-D)*}}{\partial \lambda} = \frac{c_M}{4}$. Because $\gamma > 0$, $c_M > 0$, so $\frac{\partial p^{(FC-D)*}}{\partial t} < 0$, $\frac{\partial p^{(FC-D)*}}{\partial \lambda} > 0$.

Calculating the first derivative of t, λ for equation (14), respectively, we obtain that $\frac{\partial \Pi_M^{(FC-D)*}}{\partial t} = -\frac{n}{4}(1- t\gamma-\theta+s-c_U-(1+\lambda)c_M)\gamma$, $\frac{\partial \Pi_M^{(FC-D)*}}{\partial \lambda} = -\frac{n}{4}(1-t\gamma-\theta+s-c_U-(1+\lambda)c_M)c_M$. Because $n > 0$, $\gamma > 0$, $c_M > 0$, $1-t\gamma-\theta+s-c_U-(1+\lambda)c_M > 0$, so, $\frac{\partial \Pi_M^{(FC-D)*}}{\partial t} < 0$, $\frac{\partial \Pi_M^{(FC-D)*}}{\partial \lambda} < 0$. Similarly, calculating the first derivative of t, λ for equations (15) and (18), respectively, we obtain that $\frac{\partial \Pi_U^{(FC-D)*}}{\partial t} < 0$, $\frac{\partial \Pi_U^{(FC-D)*}}{\partial \lambda} < 0$, $\frac{\partial CS^{(FC-D)*}}{\partial t} < 0$, $\frac{\partial CS^{(FC-C)*}}{\partial \lambda} < 0$. Calculating the first derivative of t, λ and cs for equation (19), respectively, we obtain that $\frac{\partial SW^{(FC-C)*}}{\partial t} < 0$, $\frac{\partial SW^{(FC-C)*}}{\partial \lambda} < 0$, $\frac{\partial SW^{(FC-C)*}}{\partial c_s} < 0$.

Calculating the first derivative of t, λ and cs for equation (16), respectively, we get:

$$\frac{\partial \Pi_{BVP}(p^{(FC-D)*})}{\partial t} = \frac{n}{4}c_S(1+\lambda)\gamma,$$

$$\frac{\partial \Pi_{BVP}(p^{(FC-D)*})}{\partial c_S} = \frac{n}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)(1+\lambda),$$

$$\frac{\partial \Pi_{BVP}(p^{(FC-D)*})}{\partial \lambda} = -\frac{n}{4}(1 - t\gamma - \theta + s - c_U - 2(1+\lambda)c_M)c_S.$$

Since $n > 0$, $\gamma > 0$, $c_s > 0$, $1-t\gamma-\theta+s-c_U-(1+\lambda)c_M > 0$, $\lambda > 0$, so $\frac{\partial \Pi_{BVP}(p^{(FC-D)*})}{\partial t} > 0$, $\frac{\partial \Pi_{BVP}(p^{(FC-D)*})}{\partial c_S} < 0$.

But we do not know whether the expression $1-t\gamma-\theta+s-c_U-2(1+\lambda)c_M$ is positive or negative, so, when $1-t\gamma-\theta+s-c_U-2(1+\lambda)c_M > 0$, that is $0 < \lambda < \frac{1-t\gamma-\theta+s-c_U-2c_M}{2c_M}$, $\frac{\partial \Pi_{BVP}(p^{(FC-D)*})}{\partial \lambda} < 0$; when $1-t\gamma-\theta+s-c_U-2(1+\lambda)c_M < 0$, that is $\lambda > \frac{1-t\gamma-\theta+s-c_U-2c_M}{2c_M}$, $\frac{\partial \Pi_{BVP}(p^{(FC-D)*})}{\partial \lambda} > 0$; when $1-t\gamma-\theta+s-c_U-2(1+\lambda)c_M = 0$, that is $\lambda = \frac{1-t\gamma-\theta+s-c_U-2c_M}{2c_M}$, $\frac{\partial \Pi_{BVP}(p^{(FC-D)*})}{\partial \lambda} = 0$.

Calculating the first derivative of t, λ and cs for equation (17), respectively, we can get:

$$\frac{\partial \Pi^{(FC-D)*}}{\partial t} = -\frac{n\gamma}{4}(\frac{3}{2}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M) - c_s(1+\lambda)),$$

$$\frac{\partial \Pi^{(FC-D)*}}{\partial \lambda} = -\frac{n}{4}c_M(\frac{3}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M) - c_s(1+\lambda)) - \frac{n}{4}(\frac{3}{4}c_M + c_s)(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M),$$

$$\frac{\partial \Pi^{(FC-D)*}}{\partial c_s} = -\frac{n}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M)(1+\lambda).$$

Because $n > 0$, $\gamma > 0$, $\frac{3}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M) - c_s(1+\lambda) > 0$, $1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M > 0$, $c_M > 0$, $c_s > 0$, so $\frac{\partial \Pi^{(FC-D)*}}{\partial t} < 0$, $\frac{\partial \Pi^{(FC-C)*}}{\partial \lambda} < 0$, $\frac{\partial \Pi^{(FC-C)*}}{\partial c_s} < 0$.

A5.

By comparing equations (8) and (13), it is shown that:

$$p^{(FC-C)*} - p^{(FC-D)*} = -\frac{1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M - 2c_s(1+\lambda)}{4}.$$

If $1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M - 2c_s(1+\lambda) > 0$ $\left(c_s > \frac{1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M}{2(1+\lambda)}\right)$, $p^{(FC-C)*} > p^{(FC-D)*}$; if $1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M - 2c_s(1+\lambda) < 0$ $\left(0 < c_s < \frac{1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M}{2(1+\lambda)}\right)$, $p^{(FC-C)*} < p^{(FC-D)*}$; if $1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M - 2c_s(1+\lambda) = 0$ $\left(c_s = \frac{1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M}{2(1+\lambda)}\right)$, $p^{(FC-C)*} = p^{(FC-D)*}$.

By comparing equations (9) and (17), it is shown that:

$$\Pi^{(FC-C)*} - \Pi^{(FC-D)*} = \frac{n}{16}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M - 2c_s(1+\lambda))^2.$$

So, if $c_s = \frac{1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M}{2(1+\lambda)}$, $\Pi^{(FC-C)*} = \Pi^{(FC-D)*}$; if $c_s \neq \frac{1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M}{2(1+\lambda)}$, $\Pi^{(FC-C)*} > \Pi^{(FC-D)*}$.

By comparing equations (10) and (18), it is shown that:

$$CS^{(FC-C)*} - CS^{(FC-D)*}$$
$$= \frac{n}{8}\left(\frac{5}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M) - c_s(1+\lambda)\right)\left(\frac{3}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M) - c_s(1+\lambda)\right).$$

Because $n > 0$, $\frac{5}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M > 0$, $\frac{3}{4}(1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M) - c_s(1+\lambda) > 0$, so $CS^{(FC-C)*} > CS^{(FC-D)*}$.

By comparing equations (11) and (19), we have:

$$SW^{(FC-C)*} - SW^{(FC-D)*} = (\Pi^{(FC-C)*} + CS^{(FC-C)*}) - (\Pi^{(FC-D)*} + CS^{(FC-D)*}).$$

Because $\Pi^{(FC-C)*} > \Pi^{(FC-D)*}$ and $CS^{(FC-C)*} > CS^{(FC-D)*}$, obviously $SW^{(FC-C)*} > SW^{(FC-D)*}$.

A6.

By comparing equations (12) and (23), we have:

$$w^{(FC-S)*} - w^{(FC-D)*} = \frac{1 - t\gamma - \theta + s - c_U + (1+\lambda)c_M}{2(1 + (1-\eta_1)\lambda)} - \frac{1 - t\gamma - \theta + s - c_U + (1+\lambda)c_M}{2(1+\lambda)}.$$

Because $1 - t\gamma - \theta + s - c_U + (1+\lambda)c_M > 0$, $1 + (1-\eta)\lambda < 1 + \lambda$, so $w^{(FC-S)*} - w^{(FC-D)*} > 0$.

By comparing equations (13) and (24), it is shown that $p^{(FC-S)*} = p^{(FC-D)*}$.

Putting equations (23) and (24) into equations (20), (21), (4), (5), (6) and (7), respectively, we get that $\Pi_M^{(FC-S)*} = \Pi_M^{(FC-D)*}$, $\Pi_U^{(FC-S)*} = \Pi_U^{(FC-D)*}$, $\Pi_{BVP}^{(FC-S)*} = \Pi_{BVP}^{(FC-D)*}$, $\Pi^{(FC-S)*} = \Pi^{(FC-D)*}$, $CS^{(FC-S)*} = CS^{(FC-D)*}$, $SW^{(FC-S)*} = SW^{(FC-D)*}$.

A7.

Putting equations (8) and (28) into equations (25), (26), (5), (6) and (7), respectively, we get that:

$$\Pi_M^{(FC-R)*} = \frac{n}{4}(\varphi(1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s)) + 2c_s(1+\lambda))(1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s)) - F_M,$$

$$\Pi_U^{(FC-R)*} = \frac{n}{4}(1-\varphi)(1 - t\gamma - \theta + s - c_U - (1+\lambda)(c_M + c_s))^2 - F_U,$$

$$\Pi^{(FC-R)*} = \Pi^{(FC-C)*}, \quad CS^{(FC-R)*} = CS^{(FC-C)*}, \quad SW^{(FC-R)*} = SW^{(FC-C)*}.$$

Let $A = 1 - t\gamma - \theta + s - c_U - (1+\lambda)c_M$, $B = (1+\lambda)c_s$.

Checking $\Pi_M^{(FC-R)*}$ and $\Pi_M^{(FC-D)*}$, $\Pi_U^{(FC-R)*}$ and $\Pi_U^{(FC-D)*}$, we find that:

$$\Pi_M^{(FC-R)*} - \Pi_M^{(FC-D)*} = \frac{n}{4}(\varphi(A-B) + 2B)(A-B) - \frac{A^2}{8},$$

$$\Pi_U^{(FC-R)*} - \Pi_U^{(FC-D)*} = \frac{n}{4}(1-\varphi)(A-B)^2 - \frac{A^2}{16}.$$

Under the revenue-sharing contract, it should be guaranteed that $\Pi_M^{(FC-R)*} \geq \Pi_M^{(FC-D)*}$, $\Pi_U^{(FC-R)*} \geq \Pi_U^{(FC-D)*}$. So c_s and φ should meet $0 < c_s \leq \frac{A}{2(1+\lambda)}$, $\frac{(A-2B)^2}{2(A-B)^2} \leq \phi \leq \frac{(3A-2B)(A-2B)}{4(A-B)^2}$.

A8.

Firstly, combining equation (1) with equation (30), we obtain the second derivative of p is $\frac{\partial^2 \Pi_U^{PC}}{\partial p^2} = -2n(1-\phi) < 0$, which shows that Π_U^{PC} is a strictly concave function of p. We get $\frac{\partial \Pi_U^{PC}}{\partial p} = n((1 - 2p - t\gamma - \theta + s)(1-\phi) + c_U + (1+\lambda)w) = 0$. So $p^{PC*}(w) = \frac{(1 - t\gamma - \theta + s)(1-\phi) + c_U + (1+\lambda)w}{2(1-\phi)}$.

Then, putting it into equation (29), we obtain that:

$$\Pi_M^{PC}(p^{PC*}(w)) = \frac{n}{2(1-\phi)}(w(1-\phi) - c_M)(1+\lambda)((1 - t\gamma - \theta + s)(1-\phi) - c_U - (1+\lambda)w) - F_M.$$

Checking the structural properties of $\Pi_M^{PC}(p^{PC*}(w))$ reveals that it is a concave function in w. When $\frac{\partial \Pi_M^{PC}(p^{PC*}(w))}{\partial w} = 0$, we obtained the optimal wholesale price of the vaccine manufacturer is:

$$w^{PC*} = \frac{(1 - t\gamma - \theta + s)(1-\phi)^2 - c_U(1-\phi) + (1+\lambda)c_M}{2(1+\lambda)(1-\phi)}.$$

So, the optimal selling price of the vaccination unit is:

$$p^{PC*} = \frac{3(1 - t\gamma - \theta + s)(1-\phi)^2 + c_U(1-\phi) + (1+\lambda)c_M}{4(1-\phi)^2}.$$

A9.

Putting equation (33) into equation (1), we can get the demand that ultimately choose to be vaccinated is:

$$d^{PC*} = \frac{(1 - t\gamma - \theta + s)(1-\phi)^2 - (1-\phi)c_U - (1+\lambda)c_M}{4(1-\phi)^2}.$$

Calculating the first derivative of t, λ for equation (32), respectively, we obtain $\frac{\partial w^{PC*}}{\partial t}=-\frac{\gamma(1-\phi)}{2(1+\lambda)}$, $\frac{\partial w^{PC*}}{\partial \lambda}=-\frac{(1-t\gamma-\theta+s)(1-\phi)-c_U}{2(1+\lambda)^2}$, $\frac{\partial w^{PC*}}{\partial \phi}=-\frac{(1-t\gamma-\theta+s)(1-\phi)^2-(1+\lambda)c_M}{2(1+\lambda)(1-\phi)^2}$. Because $\gamma>0, \lambda>0, 1-\varphi>0, d^{PC*}>0$, we know $(1-t\gamma-\theta+s)(1-\phi)-c_U>0$, $(1-t\gamma-\theta+s)(1-\phi)^2-(1+\lambda)c_M>0$. Therefore, $\frac{\partial w^{PC*}}{\partial t}<0$, $\frac{\partial w^{PC*}}{\partial \lambda}<0$, $\frac{\partial w^{PC*}}{\partial \phi}<0$.

Calculating the first derivative of t, λ for equation (33), respectively, we obtain $\frac{\partial p^{PC*}}{\partial t}=-\frac{3\gamma}{4}$, $\frac{\partial p^{PC*}}{\partial \lambda}=\frac{c_M}{4(1-\phi)^2}$, $\frac{\partial p^{PC*}}{\partial \phi}=\frac{c_U(1-\phi)+2c_M(1+\lambda)}{4(1-\phi)^3}$. Because $\gamma>0$, cM >0, $1-\varphi>0$, so $\frac{\partial p^{PC*}}{\partial t}<0$, $\frac{\partial p^{PC*}}{\partial \lambda}>0$, $\frac{\partial p^{PC*}}{\partial \phi}>0$.

A10.

By comparing equations (12) and (32), we have:

$$w^{(FC-D)*}-w^{PC*}=\frac{\phi((1-t\gamma-\theta+s)(1-\phi)-(1+\lambda)c_M)}{2(1-\phi)(1+\lambda)}.$$

Since $(1-t\gamma-\theta+s)(1-\phi)^2-(1+\lambda)c_M>0$, $1-\varphi>0$, so $(1-t\gamma-\theta+s)(1-\phi)-(1+\lambda)c_M>0$. We get $w^{(FC-D)*}>w^{PC*}$ when $0<c_M<\frac{(1-tr-\theta+s)(1-\phi)}{1+\lambda}$.

By comparing equations (13) and (33), we have:

$$p^{(FC-D)*}-p^{PC*}=-\frac{c_U\phi(1-\phi)+(1+\lambda)c_M(1-(1-\phi)^2)}{4(1-\phi)^2}.$$

Since $0<\varphi<1$, $0<1-\varphi<1$, $1-(1-\phi)^2>0$, so $p^{(FC-D)*}-p^{PC*}<0$, that is, $p^{(FC-D)*}<p^{PC*}$.

By comparing $\Pi^{(FC-D)*}$ and Π^{PC*}, we have:

$$\begin{aligned}&\Pi^{(FC-D)*}-\Pi^{PC*}\\&=\left(p^{(FC-D)*}-c_U-(c_M+c_s)(1+\lambda)\right)\left(1-t\gamma-\theta+s-p^{(FC-D)*}\right)n-\left(p^{PC*}-c_U-(c_M+c_s)(1+\lambda)\right)\left(1-t\gamma-\theta+s-p^{PC*}\right)n\\&=n\left(p^{(FC-D)*}-p^{PC*}\right)\left(1-t\gamma-\theta+s-p^{(FC-D)*}+p^{PC*}+c_U+(c_M+c_s)(1+\lambda)\right)\end{aligned}$$

Since $p^{(FC-D)*}<p^{PC*}$, so, $p^{(FC-D)*}-p^{PC*}<0$, $1-t\gamma-\theta+s-p^{(FC-D)*}+p^{PC*}+c_U\ +(c_M+c_s)(1+\lambda)>0$. We get $\Pi^{(FC-D)*}>\Pi^{PC*}$.

By comparing $CS^{(FC-D)*}$ and CS^{PC*}, we have:

$$CS^{(FC-D)*}-CS^{PC*}=\frac{n}{2}\left(1-p^{(FC-D)*}-t\gamma-\theta+s\right)^2-\frac{n}{2}\left(1-p^{PC*}-t\gamma-\theta+s\right)^2.$$

Because $p^{(FC-D)*}<p^{PC*}$, so $1-p^{(FC-D)*}-t\gamma-\theta+s>1-p^{PC*}-t\gamma-\theta+s$. We get $CS^{(FC-D)*}>CS^{PC*}$.

By comparing $SW^{(FC-D)*}$ and SW^{PC*}, we have:

$$\begin{aligned}SW^{(FC-D)*}-SW^{PC*}&=\left(p^{(FC-D)*}-c_U-(c_M+c_s)(1+\lambda)\right)\left(1-t\gamma-\theta+s-p^{(FC-D)*}\right)n+\frac{n}{2}\left(1-p^{(FC-D)*}-t\gamma-\theta+s\right)^2\\&-\left(p^{PC*}-c_U-(c_M+c_s)(1+\lambda)\right)\left(1-t\gamma-\theta+s-p^{PC*}\right)n-\frac{n}{2}\left(1-p^{PC*}-t\gamma-\theta+s\right)^2.\end{aligned}$$

Because $p^{(FC-D)*}<p^{PC*}$, we get $SW^{(FC-D)*}>SW^{PC*}$.

Corresponding author

Chunqiao Tan can be contacted at: chunqiaot@sina.com