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Investment strategy for blockchain technology in a shipping supply chain

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Abstract

In the post-COVID-19 pandemic era, how to promote blockchain technology to improve the efficiency of port customs clearance and logistics transparency has become a hot research question in the shipping industry. In this paper, we investigate the value of blockchain-based vertical cooperation led by a port or a shipping company in a one-to-two shipping service competition model. A status quo scenario and two different investment scenarios led by different stakeholders are constructed, and equilibrium solutions of the Stackelberg game in three scenarios are proposed. Meanwhile, consumer surplus and social welfare under different cooperation frameworks are discussed. We find that i) investment in blockchain technology can significantly increase the profits of shipping supply chain participants. ii) From the point of view of profit, when the investment efficiency of the port and the shipping company satisfies a certain relationship, there is a balanced strategy for both parties to invest in blockchain technology. iii) The more intense the competition for the services of shipping companies, the lower the level of blockchain technology to improve the logistics capabilities of the supply chain participants. iv) The port’s investment in blockchain technology brings more consumer surplus and social welfare. The abovementioned findings can provide managerial insights for ports and shipping companies and present decision support for the government to formulate blockchain technology promotion policies.

Keywords:
Blockchain technology, Logistics transparency, Customs clearance efficiency, Shipping supply chain, Stackelberg game

1. Introduction

As the mainstream mode of transportation, maritime transportation is currently responsible for more than 90% of the global cargo transportation each year (Yang, 2019; Wang et al., 2021). Through water transportation, a wide variety of finished and semifinished products can be traded across borders efficiently and cost-effectively (Liu et al., 2021; Chen et al., 2021). Especially with the deepening of economic globalization and the formation of the world factory, shipping has become more critical (Xin et al., 2021; Chen et al., 2020). Therefore, it is not surprising that the research enthusiasm of the academic community and the industry on operational management issues in the shipping field is gradually increasing.

The COVID-19 outbreak severely impacted the shipping industry and the shipping supply chain (i.e., the supply chain composed of shippers, shipping companies, and ports) at the end of 2019 (Xu et al., 2021; Tan et al., 2021). The multidimensional preventive measures of COVID-19 by ports and shipping companies in the post-COVID-19 pandemic era have reduced the operational efficiency of global ports, producing a series of historically rare phenomena (Gao et al., 2022). For example, several hub ports around the world are experiencing severe congestion, such as the Port of Yantian in China and the Port of Los Angeles and Port of Long Beach in the United States (Merk et al. 2022). Meanwhile, since the post-COVID-19 pandemic era, governments of different countries have different leniency and strictness in their epidemic prevention and control policies (Chen et al., 2021; Zhang et al., 2021). This has resulted in the inability to fully and completely control the COVID-19 epidemic worldwide. Therefore, the sporadic outbreak of the COVID-19 epidemic around the world has led to the risk of disruption to the global supply chain at any time, with a large number of orders being cancelled and the flow of goods unpredictable. Motivated by the abovementioned background, ports and shipping companies have to take advantage of digital technology to enhance their logistics transparency and traceability (Choi et al., 2019; Choi 2021). Hence, how to improve operational

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capabilities and digitalization for greater efficiency and transparency in the shipping supply chain has become a hot topic in academic and industry circles in the post-COVID-19 pandemic era.

To this end, blockchain technology has emerged in recent years to enable real-time tracking of cargo status (Sodhi and Tang, 2019), improve logistics transparency (Sodhi and Tang, 2019), and shorten customs clearance time (Wang et al., 2021). As a special data structure, blockchain has several advantages. First, it makes the decision-making process easier for the various participants in the shipping supply chain (Yang 2019). As the information of many participants is integrated and shared within the same digital platform, global shipping supply chain participants have realized that blockchain technology can improve the efficiency and security of the shipping supply chain (Chen et al., 2021). Second, it has the feature of distributed storage of encrypted data, making data tampering nearly impossible (Wang et al., 2019). A blockchain platform allows multiple stakeholders to access these trusted data with permission and without being affected by database corruption (Zhang et al., 2018). Therefore, blockchain technology can effectively connect shipping supply chains to improve traceability and transparency by providing timestamps to prove data exchange and visibility. Numerous ports and shipping companies have taken steps to utilize this technology. For example, blockchain technology provider DexFreight has announced a partnership with Port of Veracruz to actively promote efficiency in the transportation of cargo (Wang et al., 2021; Zhang et al., 2021). TradeLens is an open platform jointly developed by A.P. Moller - Maersk and IBM, dedicated to automating customs filing and clearance (Yang 2019; Xu et al., 2021).

However, behind such a convenient technology is the high cost of operation. For a typical supply chain, the average amount of data to manage per day will exceed 100 GB (Choi and Luo 2019). Information management costs can even account for as much as 20% of the total operating budget if the information system is not well managed (Wang et al., 2021). This means that although both ports and shipping companies have ample incentives to apply blockchain technology, how it is applied will determine their benefits. Meanwhile, as there are conflicts of interest between the participants in the shipping supply chain, an increasing number of ports and shipping companies are beginning to respond to the increasingly competitive market by forming alliances (Liu and Wang 2019; Zheng et al., 2021). Therefore, the benefits of participants under different forms of cooperation framework will bring significant differences. This motivates us to establish a shipping supply chain structure with a single oligopoly port (in the upstream) and two competing shipping companies (in the downstream) to discuss the effect of applying blockchain technology under different cooperation modes.

In other words, our paper focuses on the vertical cooperation between ports and shipping companies rather than the horizontal cooperation between ports. The research goal of our paper is to answer the following three research questions.

(1) Compared with traditional technology, will the use of blockchain technology bring more benefits to ports and shipping companies?

(2) By whom and in what form of cooperation should blockchain technology be applied?

(3) How will the application of this technology in the shipping supply chain affect consumer surplus and social welfare?

To answer the abovementioned three research questions, we construct three contrasting models (scenarios): (1) the model without blockchain alliance (scenario NB); (2) the model with a port-based blockchain alliance (scenario PB); and (3) the model with a carrier-based blockchain alliance (scenario CB). By comparing the profits of the two parties in scenarios NB, PB and CB, we can answer the research question (1). Then, we compare the changes in demand, freight rate, port service price, and total profit in different scenarios to answer the second research question. Finally, a discussion is presented to provide a detailed analysis of the impact of the application of blockchain technology on consumer surplus and social welfare to answer the last research question. Overall, the contribution of this paper includes two aspects. First, we discuss blockchain technology investment in the shipping supply chain in the post-COVID-19 pandemic era. The game behaviors and equilibrium strategies of various stakeholders in different cooperation models are proposed. Second, we present some managerial insights, which can provide decision-making references for the operations management of various stakeholders. Our major findings contain the following three aspects.

(1) The closer the service capabilities of the two shipping companies on the shipping supply chain are, the less obvious the blockchain technology will be in improving the overall logistics capabilities. Moreover, the lower the technology investment efficiency of the technology investor is, the greater the profit.

(2) Blockchain investment can bring more profits to the shipping supply chain participants. Under the premise that the investment efficiency of blockchain technology of the ports and the shipping company satisfies a certain relationship, it will be more profitable for the shipping company to invest in blockchain when its investment is less efficient. When the investment efficiency of the shipping company is high, the port’s blockchain investment will be more conducive to each shipping supply chain participant obtaining more profits. There is a balanced strategy for both parties to invest in blockchain technology.

(3) Compared with the scenario where no participant invests in blockchain, blockchain investment will reduce consumer surplus and social welfare. Both consumer surplus and social welfare are inversely related to investment efficiency. From the perspective of maximizing consumer surplus and social welfare, the port's investment in blockchain technology will bring more consumer surplus and social welfare, which can reduce the adverse effects caused by the transmission effect of rising service prices to a certain extent.

The rest of the paper is organized as follows. Section 2 briefly reviews the relevant literature to identify the research gap. Section 3 introduces the game model, event sequence, and notations used and constructs the game model. In Section 4, we investigate the different effects under three scenarios and discuss the equilibrium strategy for shipping supply chain participants. Section 5 compares consumer surplus and social welfare in different scenarios. Section 6 conducts several numerical experiments to verify the soundness of the proposed propositions. Finally, the conclusions, policy implementations and several future research directions are presented in Section 7.

2. Literature review

The research of this paper focuses on blockchain technology and coopetition relationships in the shipping supply chain. Therefore, the following two subsections summarize the related research from the abovementioned two aspects.

2.1. Research on blockchain technology for the shipping supply chain

As an emerging digital technology, blockchain technology has had a significant impact on different economic sectors and organizations since its inception (Ying et al., 2018). Several studies (Orji et al., 2020; Choi and Sginn 2022; Dutta et al., 2020) in the transportation sector have systematically summarized the application of blockchain technology. However, there is still a lack of research on the application of blockchain technology to shipping supply chains (Yang 2019). Zhou et al. (2020) identified the cost of information management and the lack of experienced partners as the most critical challenges in applying blockchain in the marine ecosystem in Singapore. In the shipping supply chain field, a systematic summary of the literature on the application of blockchain...
technology can be found in Balci and Surucu-Balci (2021). The authors affirmed that the application of blockchain technology in the shipping supply chain will have a revolutionary impact. Meanwhile, the authors also identified eight major impediments to the application of blockchain technology in the shipping supply chain by applying an interpretive structural modeling technique.

In recent years, scholars have conducted detailed analyses related to the effects generated by the application of blockchain in the shipping supply chain. For example, Kim and Shim (2018) concluded that the application of blockchain can effectively realize the paperlessness of various transaction documents and promote the formation of a low-carbon shipping supply chain. Zhang et al. (2018) and Jain et al. (2018) showed that blockchain technology brings together logistics partners on a global scale, thus improving maritime logistics transparency and customs clearance efficiency. Similarly, Yang (2019) found that digitization of various shipping documents can effectively improve customs clearance, and it is a significant advantage that will have a positive impact on the shipping supply chain. Pu and Jasmine Sui (2021) believed that paper-based transactions possess the problems of long time, high cost, and high data error rate. Therefore, blockchain technology in shipping supply chains will effectively improve the efficiency and security of shipping services. The same findings can be found in Papathanasiou et al. (2020). The authors also confirmed the advantages of blockchain technology in terms of security and efficiency in an empirical study of eight shipping companies in Greece. However, the authors also identified that enterprise resource planning transformations have discouraged shipping companies from developing blockchain information platforms.

2.2. Research on cooperation relationships in the shipping supply chain

In recent years, an increasing number of scholars have started to explore the cooperative relationship in the shipping supply chain. In an earlier study, Heaver et al. (2000) discussed the forms of cooperation between the European shipping supply chains. A representative literature review can be found in Lee and Song (2015). Currently, mainstream qualitative research contains several topics, such as port congestion (Shao et al., 2016), pricing decisions (Strandenes and Peter, 2000), incentive theory (Wang et al., 2017), liner (or carrier) alliances (Liu and Wang 2019; Fusillo 2003), storage space allocation (Yu and Qi 2013), and auction behavior (Triki et al., 2014). In quantitative research, Agarwal and Ergun (2010) discussed how two liner companies collaborate on network design in the context of a liner alliance. By designing a reasonable transaction price, the authors constructed a benefit distribution mechanism between the two companies. Inverse optimization theory was applied to calculate the optimal transaction price. Based on the theory proposed by Agarwal and Ergun (2010), Liu et al. (2021) further discussed an alliance shipping network design problem considering carbon tax and variable speed factors to respond to the increasingly severe environmental problem.

Since the financial crisis, competition in the shipping industry has intensified. Therefore, cooperation between ports and shipping companies to integrate the shipping supply chain has become a new trend. In this context, academia began to use game theory to discuss the relationship between stakeholders. For example, Li and Zhang (2015) discussed vertical cooperation between a shipping company and two freight forwarders, while Alvarez-SanJaime et al. (2013) focused on the competition between shipping companies and land carriers. Studies related to port competition include Anderson et al. (2008), Ishii et al. (2013), and Wan et al. (2016). There are also studies focusing on liner alliances (Fusillo 2003; Liu and Wang 2019) and capacity competition (Kou and Luo 2016; Wang et al., 2021).

With the advent of the post-COVID-19 pandemic era, the need for digitization in the shipping supply chain has grown stronger. Recently, some of the studies have focused on the role of blockchain technology in the shipping supply chain. For example, Zhong et al. (2021) suggested that container liner companies apply blockchain technology to avoid price wars between shipping routes. By constructing a two-stage game model, the authors concluded that the shipping blockchain plays a key role in regulating freight rates. Wang et al. (2021) discussed the impact of the application of blockchain technology by two ports that have a competitive relationship on their own development. The authors found that competition between ports would put the game in a prisoner’s dilemma. By designing a ‘blockchain technology sharing + compensation’ collaboration mechanism, it is possible to break the dilemma between ports and achieve the Pareto optimum.

2.3. Research gap

By reviewing the abovementioned two streams of literature, we can identify two research gaps. First, most of the research related to shipping blockchain has focused on the role of blockchain and the current challenges in applying blockchain technology. There are relatively few studies that consider different supply chain participants competing (or cooperating) based on blockchain technology. To the best of our knowledge, only Zhong et al. (2021) and Wang et al. (2021) discussed the cooperation between ports and shipping companies horizontally. To fill this research gap, we discuss the cooperation between port and shipping companies based on blockchain technology by discussing a vertical shipping supply chain. Second, various studies conducted in the context of blockchain tend to focus on the assessment of the self-interests and decisions of the game players, ignoring the increase in consumer surplus and social value brought about by the technology. Obviously, transportation activities are a public service. The application of new technologies will have some impact on consumers and society. Therefore, we add a discussion of consumer surplus and social welfare to provide decision support for the government to assess the advantages of blockchain technology and develop a reasonable subsidy policy.

3. The model

Ports and shipping companies usually form a vertical complementary relationship in a shipping supply chain, and there is a cooperative game between shipping companies and ports (Liu and Wang 2019). In this paper, we consider a one-to-two shipping supply chain that is composed of an upstream oligopolistic port and two downstream competing shipping companies (as shown in Fig. 1). This structure has been discussed by numerous scholars (e.g., Liu and Wang (2019)). The two shipping companies (indexed by $i = 1, 2$) offer substitutable shipping services and set freight rates independently. The port provides the necessary berthing, pilotage, loading and unloading services for shipping companies and sets service prices. There is a Stackelberg game between the port and the two shipping companies, where the port is the

![Fig. 1. Structure of the shipping supply chain.](image-url)
core enterprise (leader) and two shipping companies are followers.

To explore the blockchain investment strategies of different supply chain participants under different cooperation models, we construct the following three scenarios, as shown in Fig. 2. They are (1) Scenario NB, where three participants make decisions independently; (2) Scenario PB, where the port is responsible for establishing the blockchain platform and collaborating with two other participants; and (3) Scenario CB, where a shipping company (i.e., shipping company 1) is responsible for establishing the platform and collaborating with two other participants.

Specifically, in Scenario NB, neither the port nor the two shipping companies invest in blockchain technology. The three participants seek to maximize their own interests. In scenario PB, two shipping companies work independently with the port and compete with each other. All participants aim to maximize their own interests. The port develops a blockchain platform to improve its customs clearance efficiency, while two shipping companies can improve their customs clearance efficiency or logistics transparency level. In regard to Scenario CB, the investor in the blockchain platform becomes shipping company 1. Port and shipping company 2 can improve their customs clearance efficiency or logistics transparency and need to pay the related costs.

For ease of reading, we list the notations commonly used in this paper below.

| Symbol | Description |
|--------|-------------|
| $s$    | Base market potential |
| $\bar{p}$ | The level of service competition between the two shipping companies |
| $w$    | Port service price set by port |
| $p_i$ | Freight rate set by shipping company $i$ |
| $q_i$  | The demand of shipping company $i$ |
| $a_i$  | The level of logistics transparency of shipping company $i$ |
| $c_i$  | The level of customs clearance efficiency of the port |
| $c_p$  | Port operation cost |
| $c_s$  | Shipping company operation cost |
| $e_i$  | Profit of shipping company $i$ |
| $e_p$  | Profit of port |
| $e_s$  | Profit of shipping supply chain |
| $CS$   | Consumer surplus |
| $SW$   | Social welfare |

Note that if NB, PB, or CB is added as a subscript, it indicates a solution in a specific scenario. Similarly, we use $p$, 1 (or $c_1$) and 2 (or $c_2$) as subscripts to denote the port, shipping company 1 and shipping company 2, respectively. For the optimal solution, we add an extra asterisk to the superscript.

3.1. Demand model

We assumed that the demand function is jointly determined by the freight rate and service quality. Since we focus on the improvement of customs clearance efficiency and logistics transparency by blockchain technology, the service quality of ports and shipping companies is defined as the customs clearance efficiency $c_i$ and logistics transparency $a_i$ ($i \in \{1, 2\}$). The demand function of each shipping company is linearly related to self-price, cross-price, self-quality and cross-quality and competitors’ service quality (Liu and Wang 2019). This assumption is also widely found in other studies of supply chain systems, such as Huang et al. (2012), Liu and Wang (2019) and Lu et al. (2011). Let $\alpha > 0$ be the base market potential; $\eta_i > 0$ represent the price elasticity coefficient of shipping company $i$; $\beta_i > 0$ denote the logistics transparency demand elasticity coefficient of shipping company $i$; $p_i$ represent the basic freight rates of shipping company $i$; and $\eta_i$ and $\eta_{3-i}$ denote the self- and cross-price elasticity coefficients of shipping company $i$, respectively. Finally, $\beta_i$ and $\beta_{3-i}$ represent the self- and cross-price elasticity of logistics transparency of shipping company $i$, respectively. Based on the above notations, we have the following demand function.

$$q_i = \alpha - \eta_i p_i + \eta_i p_{3-i} + \beta_i a_i + \beta_i a_{3-i} + t \quad \forall i \in \{1, 2\}$$  (1)

The above function is constructed to match reality. In general, the freight rate consists of a basic price and an additional price. Some shippers expect to pay a higher additional price to obtain an improved quality of service to meet their high demand for cargo information traceability. When high-value cargo is stranded somewhere because of the COVID-19 outbreak, the shipper’s supply chain is likely to be disrupted by the lack of timely access to relevant logistics information, which may be a fatal blow to the shipper. Therefore, we use logistics transparency (service quality) to characterize the additional price.

In the actual shipping market, the demand of shipping companies is more affected by their own service capabilities than the impact brought by competitors (Wang et al., 2017). Therefore, parameters $\eta_i$ and $\beta_i$ can be normalized to 1, and $\eta_2$ be 0 (Feng and Lu 2013; Liu and Wang 2019; Yue and Liu 2006). Thus, we can further set $\beta_2 = \beta_1 = 1$ in Equation (1) to help us focus our discussion on the changes in logistics transparency of shipping companies (Raju and Roy 2000). Based on the above-mentioned discussion, the demand function can be rewritten as Equation (2). When there are no supply chain participants investing in blockchain technology, the demand function can be reduced to Equation (3).

$$q_i = \alpha - p_i + a_i - \beta a_{3-i} + t \quad \forall i \in \{1, 2\}$$  (2)

$$q_i = \alpha - p_i \quad \forall i \in \{1, 2\}$$  (3)

3.2. Service cost

The port and the two shipping companies are independent economies, and they all need to pay for daily operating costs and service costs (e.g., wages of the employees) (Liu et al., 2021; Gao et al., 2022). Blockchain technology is a typical service, and the costs derived from it (e.g., wages of the employees) (Liu et al., 2021; Gao et al., 2022). Therefore, parameters $\eta_i$ and $\beta_i$ can be normalized to 1, and $\eta_2$ be 0 (Feng and Lu 2013; Liu and Wang 2019; Yue and Liu 2006). Thus, we can further set $\beta_2 = \beta_1 = 1$ in Equation (1) to help us focus our discussion on the changes in logistics transparency of shipping companies (Raju and Roy 2000). Based on the above-mentioned discussion, the demand function can be rewritten as Equation (2). When there are no supply chain participants investing in blockchain technology, the demand function can be reduced to Equation (3).

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$$q_i = \alpha - p_i \quad \forall i \in \{1, 2\}$$  (3)

Fig. 2. Three typical scenarios.
database, and the platform builder can allow licensors to access trusted data and control the degree of openness (Pu and Jasmine Siu, 2021).

In general, there is a marginal diminishing returns effect on service quality improvement (Tsay and Agrawal 2000; Xin et al., 2022). Therefore, we set the blockchain technology investment cost for shipping company 1 as $\frac{1}{2}x_{1}^{2}a_{1}$, where $x_{1}$ denotes the investment efficiency of blockchain technology and $a_{1}$ represents the blockchain technology investment level. One can see that the higher $x_{1}$ is, the higher the investment required under the same blockchain technology level. Similarly, the investment cost for the port can be written as $\frac{1}{2}x_{p}^{2}t^{2}$. Finally, we let the port’s service price to the shipping company be $w$, the port’s operating cost be $c_{p}$, and the shipping company’s operating cost be $c_{i}$.

3.3. Event sequence

(1) In scenario NB, the decision-making sequence is shown as follows. First, the port determines its own optimal service price $w$ by predicting the freight rate $p_{i}$ set by shipping companies 1 and 2. Then, two shipping companies determine their own optimal freight rates $p_{1}$ and $p_{2}$, respectively. In the first stage, the port’s goal is to maximize its own interests, and its profit is shown in Equation (5).

$$\pi^{NB} = (w - c_{p})(q_{1} + q_{2})$$  \hspace{1cm} (5)

Proposition 1. The second derivative of $\pi^{NB}$ with respect to $w$ is negative.

In the second stage, two shipping companies aim to maximize their own interests $\pi^{NB}$ by determining the optimal freight rates $p_{1}$ and $p_{2}$, which can be stated as Equation (6).

$$\pi^{NB} = (p_{i} - w - c_{i})q_{i}.$$  \hspace{1cm} (6)

Proposition 2. The second derivative of $\pi^{NB}$ with respect to $p_{i}$ is negative.

(2) In scenario PB, the decision-making sequence is as follows: first, the port determines its own optimal service price $w$ and blockchain technology investment level $t$ by predicting the freight rate $p_{i}$ of shipping companies 1 and 2 and the level of logistics transparency $a_{i}$. Second, two shipping companies determine their own optimal freight rate $p_{i}$ and the level of logistics transparency $a_{i}$ they want to improve. In the first stage, the objective of the port is to maximize its own interests, which can be stated as Equation (7).

$$\pi^{PB} = (w - c_{p})(q_{1} + q_{2}) - \frac{1}{2}x_{p}^{2}t^{2} + \frac{1}{2}x_{p}^{2}(a_{1}^{2} + a_{2}^{2})$$  \hspace{1cm} (7)

Proposition 3. If $x_{p} > \frac{1}{2}(5 - 2\beta)$, $\pi^{PB}$ is a differentiable concave function with respect to $w$ and $t$.

In the second stage, both shipping companies 1 and 2 aim to maximize their own interests, and their profit can be written as Equations (8) and (9), respectively.

$$\pi_{1}^{CB} = (p_{1} - w - c_{1})q_{1} - \frac{1}{2}x_{p}^{2}a_{1}^{2}$$  \hspace{1cm} (8)

$$\pi_{2}^{CB} = (p_{2} - w - c_{2})q_{2} - \frac{1}{2}x_{p}^{2}a_{2}^{2}$$  \hspace{1cm} (9)

Proposition 4. If $x_{p} > \frac{1}{2}$, $\pi^{CB}$ is a differentiable concave function with respect to $p_{i}$ and $a_{i}$.

(3) In Scenario CB, the decision-making sequence is as follows: First, the port determines its own optimal service price $w$ and the optimal level of customs clearance efficiency $t$ improvement by predicting the freight rate $p_{i}$ of shipping companies 1 and 2 and their respective level of logistics service transparency $a_{i}$. Then, two shipping companies determine their own optimal freight rate $p_{i}$ and logistics service transparency $a_{i}$. In the first stage, the objective of the port is to maximize its own interests, which can be written as Equation (10).

$$\pi^{CB} = (w - c_{p})(q_{1} + q_{2}) - \frac{1}{2}x_{p}^{2}t^{2}$$  \hspace{1cm} (10)

Proposition 5. If $x_{p} > \frac{1}{2}$, $\pi^{CB}$ is a differentiable concave function with respect to $p_{i}$ and $a_{i}$.

In the second stage, both shipping companies 1 and 2 aim to maximize their own interests, and their profit can be written as Equations (11) and (12).

$$\pi_{1}^{CB} = (p_{1} - w - c_{1})q_{1} - \frac{1}{2}x_{p}^{2}a_{1}^{2} + \frac{1}{2}x_{p}^{2}t^{2}$$  \hspace{1cm} (11)

$$\pi_{2}^{CB} = (p_{2} - w - c_{2})q_{2} - \frac{1}{2}x_{p}^{2}a_{2}^{2}$$  \hspace{1cm} (12)

Proposition 6. If $x_{p} > \frac{1}{2}$, $\pi^{CB}$ is a differentiable concave function with respect to $p_{i}$ and $a_{i}$.

According to the reverse solution of the Stackelberg game, the optimal solutions of the decision variable and profit in the three scenarios are summarized in Table 1. Based on these results, we discuss the optimal solutions in different scenarios in the subsequent sections and analyze the managerial insights of the shipping supply chain with respect to the following question: ‘Which form of blockchain collaboration is more beneficial?’

4. Model analysis

The main purpose of this section is to analyze the effect of blockchain technology participation in shipping supply chain cooperation under different scenarios and to discuss the equilibrium strategies of different participants.

4.1. Blockchain technology cooperation effect analysis

In this section, the analysis is mainly carried out from four aspects: cost effect, input level effect, economic effect, and market effect. These effects can be used to illustrate the impact of changes in blockchain technology investment on service cost and profit.

4.1.1. Cost effect

Proposition 7. Comparing the service price of ports in different scenarios, it can be concluded that:

(i) When the port invests in the blockchain, comparing the port service cost, we can obtain the following: If $\frac{1}{x_{p}}(5 - 2\beta) < y_{p} < 1$, then $w^{FR} < w^{PB}$.

(ii) When shipping company 1 invests in blockchain, comparing port service prices, we can obtain the following: If $x_{p} > \frac{1}{2}$, then $w^{FR} < w^{CB}$.

Proposition 7 shows that the blockchain investment by different participants in the shipping supply chain will have a direct impact on the port’s service price. When blockchain technology enters the shipping
supply chain and investment efficiency meets a certain level, the port service price is higher than when there is no blockchain technology (regardless of who the investor is). This conclusion is in line with expectations. Regardless of whether the port is an investor, when applying blockchain technology, it needs to pay costs to improve its own customs clearance efficiency (only the payment objects are different).

### 4.1.2. Investment effect

**Proposition 8.** *Comparing the blockchain technology investment levels of different blockchain investment entities, we can conclude the following.*

(i) In scenario PB, the impact of blockchain investment efficiency on the efficiency level of port customs clearance and the logistics transparency of the shipping company is $\alpha_{\text{PB}}^{\text{PB}} < 0$; $\alpha_{\text{SNB}}^{\text{PB}} < 0$.

(ii) In scenario CB, the impact of blockchain investment efficiency on the efficiency level of port customs clearance and the logistics transparency of the shipping company is $\alpha_{\text{PB}}^{\text{SNB}} < 0$; $\alpha_{\text{SNB}}^{\text{PB}} < 0$.

(iii) Comparing the improvement of logistics transparency of the shipping company, we can obtain:

(a) $\alpha_{\text{PB}}^{\text{SNB}} < 0$, $\alpha_{\text{SNB}}^{\text{PB}} < 0$.

(b) $\frac{1}{2}(5 - 2\beta) < \theta_{P} < 1$, $\frac{1}{2}(1 - 4\theta_{P}) < \gamma_{2} < 1$, $\alpha_{\text{PB}}^{\text{SNB}} > a_{\text{SNB}}^{\text{PB}}$.

(c) $\frac{1}{2}(5 - 2\beta) < \theta_{P} < 1$, $\frac{2\beta}{1 - 4\theta_{P}} < \gamma_{2} < \frac{1}{4}(-1 + 4\theta_{P})$, $\alpha_{\text{SNB}}^{\text{PB}} < a_{\text{SNB}}^{\text{PB}}$.

(iv) Comparing the customs clearance efficiency of the port, we can obtain:

(a) $\alpha_{\text{PB}}^{\text{SNB}} < 0$, $\alpha_{\text{SNB}}^{\text{PB}} < 0$.

(b) $\frac{1}{2}(5 - 2\beta) < \theta_{P} < 1$, $\frac{1}{2}(1 - 4\theta_{P}) < \gamma_{2} < 1$, $t_{\text{PB}}^{\text{SNB}} > t_{\text{SNB}}^{\text{PB}}$.

(c) $\frac{1}{2}(5 - 2\beta) < \theta_{P} < 1$, $\frac{2\beta}{1 - 4\theta_{P}} < \gamma_{2} < \frac{1}{4}(-1 + 4\theta_{P})$, $t_{\text{SNB}}^{\text{PB}} < t_{\text{SNB}}^{\text{PB}}$.

**Proposition 8** shows that the level of investment in blockchain technology is related to investment efficiency. Regardless of which participant makes the investment, the level of investment in blockchain technology decreases with the increase in investment efficiency. Specifically, whether the investor is a port or a shipping company, the improvement of customs clearance efficiency and logistics transparency are decreasing with the increase of investment efficiency. When the investment efficiency of the shipping company meets a certain range, the improvement of the logistics capacity brought by the blockchain investment of the shipping company will be higher than the effect brought by the port investment. The reason for this may be that in the port-dominated shipping supply chain, shipping companies follow the port’s investment behavior to make decisions. When a shipping company invests in blockchain technology, it will increase its investment according to its own investment status.

### 4.1.3. Economic effect

**Proposition 9.** *Comparing the optimal profits of each stakeholder in different scenarios, it can be concluded that:*

(i) Considering the profit of shipping company 1, we can obtain $\pi_{1}^{\text{PB}} > \pi_{1}^{\text{SNB}}$, $\pi_{1}^{\text{PB}} > \pi_{1}^{\text{CB}}$.

(ii) Considering the profit of shipping company 2, we can obtain $\pi_{2}^{\text{PB}} > \pi_{2}^{\text{SNB}}$, $\pi_{2}^{\text{PB}} > \pi_{2}^{\text{CB}}$.

(iii) From the perspective of port profit, the following relationships can be obtained: $\pi_{P}^{\text{PB}} > \pi_{P}^{\text{SNB}}$, $\pi_{P}^{\text{PB}} > \pi_{P}^{\text{CB}}$.

(iv) From the perspective of the profit of the shipping supply chain, the following relationships can be obtained: $\pi_{2}^{\text{PB}} > \pi_{2}^{\text{SNB}}$, $\pi_{2}^{\text{PB}} > \pi_{2}^{\text{CB}}$.

(v) If $\gamma_{2} > \frac{1}{12} M_{P}$, then $\pi_{P}^{\text{SNB}} < \pi_{P}^{\text{PB}}$; If $\gamma_{2} < \frac{1}{12} M_{P}$, then $\pi_{P}^{\text{SNB}} > \pi_{P}^{\text{PB}}$; If $\gamma_{2} > M_{P}$, then $\pi_{P}^{\text{CB}} > \pi_{P}^{\text{PB}}$; If $\gamma_{2} < M_{P}$, then $\pi_{P}^{\text{CB}} < \pi_{P}^{\text{PB}}$.

**Proposition 9** shows that the economic benefits brought by different investors are also different. From **Proposition 7(i)** to **Proposition 7(iii)**, one can see that under the premise that different entities meet the constraints, the profits of each stakeholder are higher than when there is no blockchain technology, whether the investor is a port or a shipping company. This shows that the improvement of customs clearance efficiency brought by blockchain investment to the port and the improvement of logistics clarity of shipping companies have been effectively transformed into the benefits of various entities, creating more profits for them.
In addition, combined with Proposition 8, one can find that an increase in the investment efficiency of blockchain technology reduces the level of investment, which helps investors increase their profit. This means that the efficient technology investment efficiency has driven the low-speed growth of the logistics level of the entire shipping supply chain and the high growth of the overall profit. According to Proposition 9, we can obtain the optimal investment strategy of each supply chain participant, as shown in Table 2. According to Table 2, we can further plot Fig. 3. Here, Fig. 3(a) to Fig. 3(b) present the optimal strategy choices for investment in port and shipping companies’ blockchain technology, respectively.

Through Proposition 9(v) and combined with Table 3 and Fig. 2, we can conclude that for the port and two shipping companies, different optimal selection strategies will be generated according to different investment efficiencies of blockchain technology. In Fig. 2(a), Area I represents the situation where \( x_{ci}^{PB} < x_{ci}^{CB} \), while Area II denotes the situation where \( x_{ci}^{PB} > x_{ci}^{CB} \). Meanwhile, the area of Area I is significantly larger than that of Area II. Similarly, in Fig. 2(b), Area I represents the situation where \( x_{ci}^{CB} < x_{ci}^{PB} \), and Area II denotes the situation where \( x_{ci}^{CB} > x_{ci}^{PB} \). We note that the area of Area I is also larger than the area of Area II. This indicates that the port’s blockchain investment is better than the shipping company 1’s blockchain investment, which is more beneficial to their profit.

There may be two reasons for this phenomenon. First, whether a port or a shipping company invests in blockchain technology, the port, as the leader of the game in the system, always has the priority to make decisions. The decision-making of the shipping company should follow the port. Therefore, there may be a certain difference in investment efficiency. Second, the port is in an oligopolistic position upstream of the shipping supply chain and has no competitors. When shipping company 1 makes blockchain investment decisions, it must consider the pressure from the competition from shipping company 2. This will also greatly reduce the profit growth effect of a shipping company investing in blockchain.

4.1.4. Market effect

**Proposition 10.** **Comparing the freight rate and market demands of shipping companies in different scenarios,** it can be concluded that:

(i) Comparing the freight rates of different shipping companies, we can obtain:

(a) \( p_{ci}^{PB} > p_{ci}^{CB}, p_{ci}^{CB} > p_{ci}^{PB}, p_{ci}^{PB} < p_{ci}^{CB} \).

(b) If \( \frac{1}{5}(5 - 2\beta) < \tau_p < 1 \) and \( \frac{3\beta - 2\gamma + 2\gamma p}{\frac{3\beta - 2\gamma + 2\gamma p}{\gamma p} - \frac{2\gamma}{\gamma p}} < \gamma_c < 1 \), then \( p_{ci}^{CB} > \frac{p_{ci}^{PB}}{\gamma_c} \).

(c) If \( \frac{1}{5}(5 - 2\beta) < \tau_p < 1 \) and \( \frac{2\gamma}{\gamma p} < \gamma_c < \frac{3\beta - 2\gamma + 2\gamma p}{\frac{3\beta - 2\gamma + 2\gamma p}{\gamma p} - \frac{2\gamma}{\gamma p}} \), then \( p_{ci}^{CB} > \frac{p_{ci}^{PB}}{\gamma_c} \).

(ii) Comparing the market demand, we can obtain:

(a) \( q_{ci}^{PB} > q_{ci}^{CB}, q_{ci}^{CB} > q_{ci}^{PB}, q_{ci}^{PB} < q_{ci}^{CB} \).

(b) If \( \frac{1}{5}(5 - 2\beta) < \tau_p < 1 \) and \( \frac{3\beta - 2\gamma p}{\frac{3\beta - 2\gamma p}{\gamma p} - \frac{2\gamma}{\gamma p}} < \gamma_c < 1 \), then \( q_{ci}^{CB} > q_{ci}^{PB} \).

(c) If \( \frac{1}{5}(5 - 2\beta) < \tau_p < 1 \) and \( \frac{2\gamma}{\gamma p} < \gamma_c < \frac{3\beta - 2\gamma p}{\frac{3\beta - 2\gamma p}{\gamma p} - \frac{2\gamma}{\gamma p}} \), then \( q_{ci}^{CB} > q_{ci}^{PB} \).

**Proposition 10** shows that the investment in blockchain technology by the port and shipping company 1 will increase the freight rate and market demand of shipping companies compared with the scenario without blockchain technology. The abovementioned findings confirm that investment in blockchain technology has brought about a double increase in the service costs and demand of stakeholders, thereby driving the growth of their respective profits.

### 4.2. Analysis of equilibrium strategy

Further analysis of Proposition 9 leads to Proposition 11.

**Proposition 11.** **There is an equilibrium strategy for investment by blockchain investment entities.**

Through further analysis of the conclusion of Proposition 11, the equilibrium strategy of blockchain technology investment in the shipping supply chain can be obtained (as shown in Table 3 and Fig. 4). We find that the equilibrium strategy of Area I is to invest in blockchain technology by the port. The equilibrium strategy of Area III is to invest in blockchain technology by shipping company 1. Within the effective interval of investment efficiency, there are three equilibrium states, corresponding to Areas I, II and III in Fig. 3. With the changes in the relationship between port investment efficiency and shipping company investment efficiency, the equilibrium strategy of investment is gradually transitioning and changing from port investment to shipping company investment.

### 5. Impact on consumer surplus and social welfare

This section further discusses the impact on shippers of different blockchain investment modes in the shipping supply chain.

#### 5.1. The impact of blockchain technology investment on consumer surplus

Referring to Kök et al. (2018), we first define the calculation method of consumer surplus CS as Equation (13).

\[
CS = \int_{p^*}^{p_{\text{max}}} Q(p) dp
\]  

(13)

where \( p^* \) denotes the optimal freight rate (or service price) set by the shipping company (or port); \( p_{\text{max}} \) represents the maximum freight rate (or service price) defined in the demand function; and \( Q(p) \) is the demand function.

Based on Equation (13), the consumer surplus in each scenario can be calculated by the following equations, and Proposition 12 can be obtained.

\[
CS_{\text{König}} = \frac{1}{32} (c_i + c_p - a)^3
\]

(14)

\[
CS_{\text{König}} = \frac{(-a + c_o + c_i)^3}{2(-5 + 2\beta + 4\gamma c_p)}
\]

(15)

\[
CS_{\text{CB}} = \frac{(-a + c_o + c_i)^3}{8(-2 + \beta + 2\gamma_c)}
\]

(16)

**Proposition 12.** **Consumer surplus is inversely proportional to blockchain technology investment efficiency.**

(i) \( \frac{dCS_{\text{König}}}{dp} = \frac{dCS_{\text{König}}}{dp} = 0, \frac{dCS_{\text{CB}}}{dp} < 0, \frac{dCS_{\text{CB}}}{dp} < 0.\)
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Fig. 3. The optimal strategy choice for blockchain investment in ports and shipping companies (β = 0.6).

(ii) If \( \frac{1}{2} (5 - 2\beta) < \gamma_p < 1 \) and \( -\frac{2\beta + 2\gamma_p}{5 - 2\beta} < \gamma_c < 1 \), then \( CS^{PB} > CS^{CB} \).

(iii) If \( \frac{1}{2} (5 - 2\beta) < \gamma_p < 1 \) and \( \frac{4\beta}{5 - 2\beta} < \gamma_c < 1 \), then \( CS^{PB} < CS^{CB} \).

Through Proposition 12, we can conclude that the growth of investment efficiency of blockchain technology in any scenario will reduce consumer surplus. In addition, when the investment efficiency of the investment entity is within a certain range, the consumer surplus brought by port investment will largely exceed the consumer surplus when the shipping company 1 invests in blockchain technology. Port’s investment in blockchain technology will reduce the reduction in consumer surplus to a certain extent compared to the investment made by the shipping company 1.

5.2. The impact of blockchain technology investment on social welfare

In this section, we further explore the impact of investing in blockchain technology in the shipping supply chain on social welfare. Social welfare \( SW \) can be calculated by Equation (17) (Niu et al. 2019). Thus, Proposition 13 can be obtained:

\[
SW = \pi_c + CS + a_1 + a_2 + t \tag{17}
\]

Based on Equation (17), the social welfare under the three scenarios is calculated as follows:

\[
SW^{PB} = \frac{1}{32} \left( -\alpha + c_a + c_r \right)^2 + 12 \left( -\alpha + c_a + c_r \right) \gamma_p \gamma_c
\]

\[
SW^{CB} = \frac{(a_c - c_p)(-40 + 4\beta(4 + a_c - (c_p + c_r)\gamma_p) + \gamma_p(-12\alpha + 4(8 + 3c_p + 3c_r) - 13(-\alpha + c_c + c_r)\gamma_p))}{2(-\beta + 4\gamma_p)^2}
\]

\[
SW^{CB} = \frac{(a_c - c_p)(-32 + 4\beta(4 + a_c - (c_p + c_r)\gamma_p) + \gamma_p(32 - 5\alpha + 5c_p + 5c_r - 13(-\alpha + c_c + c_r)\gamma_p))}{8(-2 + 2\gamma_p)^2}
\]

Proposition 13. Comparing social welfare in various scenarios, the following conclusions can be drawn:

\[
\frac{\partial SW^{PB}}{\partial \gamma_p} = \frac{\partial SW^{CB}}{\partial \gamma_p} = 0, \quad \frac{\partial SW^{PB}}{\partial \gamma_c} < 0, \quad \frac{\partial SW^{CB}}{\partial \gamma_c} > 0.
\]

From Proposition 13, one can find that any supply chain participant investing in blockchain technology will make social welfare decrease with the improvement of investment efficiency. This conclusion is consistent with the conclusion of Proposition 12. As a component of social welfare, consumer surplus also affects the change in social welfare.

Combining Proposition 12 and Proposition 13, we find that investment in blockchain technology reduces consumer surplus and social welfare. This may be related to the increase in prices brought about by investment. According to Proposition 6 and Proposition 9, the investment of blockchain technology will increase the service price of the port and the freight rate of the shipping company. Price has a certain ‘pass-through effect’. When investment is generated, expenses are superimposed layer by layer, and consumer surplus and social welfare will decrease. Compared with investment by a shipping company, blockchain investment in port will generate more consumer surplus and social welfare.

6. Numerical analysis

To verify the soundness of the abovementioned propositions, we further conduct several numerical experiments in this section. Numerical simulation is used to explore the impact of blockchain investment efficiency and service competition on various parameters and stake-
holder benefits. The parameters are set as $\alpha = 10$, $c_p = 3$, and $c_c = 4$ (Liu and Wang 2019; Wang et al., 2021).

6.1. Analysis of results

We use Fig. 5(a) and Fig. 5(b) to illustrate the changes in port service prices in scenarios PB and CB. Meanwhile, Fig. 5(c) to Fig. 5(d) show the changes in the freight rate of shipping companies in scenarios PB and CB, respectively. Comparing Fig. 5(a) to Fig. 5(d), one can find that when shipping company 1 invests in blockchain, the upper limit of port service price is higher. When the port invests in blockchain technology, two shipping companies can reach a higher freight rate ceiling. When investment efficiency remains unchanged, regardless of who the investor is, the port service price will decrease as the competition between two shipping companies increases. This shows that the more similar the capabilities of the two shipping companies are, the greater they can invest in blockchain technology, which can reduce the service cost of the investor. When the service competition between the two shipping companies remains unchanged, no matter which shipping company invests, the freight rate of both will decrease with the growth of the investor’s investment efficiency. This means that the improvement of investment efficiency by the investor is conducive to reducing the service price and freight rate for both port and shipping company 1.

Fig. 6(a) to Fig. 6(d) further show the impact of blockchain investment on the logistics capabilities of supply chain participants. Specifically, Fig. 6(a) to Fig. 6(b) illustrate the changes in the logistics transparency of shipping company 1 in scenarios PB and CB. Meanwhile, Fig. 6(c) to Fig. 6(d) exhibit the changes in port customs clearance efficiency in scenarios PB and CB. Based on the numerical experimental results, it can be concluded that when the port invests in blockchain technology, it can further improve customs clearance efficiency and logistics transparency compared with the shipping company 1. On the premise that the investment efficiency of blockchain investment entities remains unchanged, the closer the service capabilities of the shipping companies are, the weaker the blockchain technology will improve the logistics transparency level of shipping company 1. This may be because the greater the two shipping companies compete in terms of service capabilities, the harder it is for the two companies to agree on a level of logistics transparency, i.e., not wanting a higher level of service from competitors. For the port, its investment in blockchain technology can improve the efficiency of customs clearance to a greater extent. This is mainly related to its leadership in the Stackelberg game of the shipping supply chain.

The impact of blockchain investment on the profit of the investor in scenarios PB and CB is further shown in Fig. 7(a) to Fig. 7(d). Here, Fig. 7(a) and (b) show the changes in port profits in scenarios PB and CB, while Fig. 7(c) and (d) represent the changes in the profits of shipping company 1 in scenarios PB and CB. When the level of service competition between the two shipping companies remains the same, the lower the investment efficiency of the investor is, the higher the profits he/she will obtain. Under the premise of the same investment efficiency, when the service competition between the two shipping companies becomes more moderate, both port and shipping company 1 can obtain more profits. This may be because the greater the level of service competition between the two shipping companies moderates, the higher the level of logistics that can be improved by investing in blockchain technology. From the profit calculation equation, we find that the blockchain technology investor can obtain more profits.

We use Fig. 8(a) and 8(b) to represent the impact of blockchain investment on the profits of the shipping supply chain in scenarios PB and CB. Similar to Fig. 7(a) and (b), the upper limit of the profit of the shipping supply chain under scenario PB is slightly higher than that under scenario CB. By controlling the variables to observe, we can draw similar conclusions to the profit of the port and shipping companies in different scenarios. The profit of the shipping supply chain is inversely proportional to the investment efficiency and service competition of the two shipping companies.

Finally, Fig. 9(a) and Fig. 9(b) represent the impact of blockchain investment on social welfare. By observing these two figures, one can clearly see that the upper limit of the social welfare of the shipping supply chain under scenario PB is much larger than that under scenario CB. This confirms Proposition 12 and proves that port investment in blockchain technology is more beneficial to social welfare.

6.2. Discussion

Based on the above simulation experiments, we have the following findings:

1. Whether shipping company 1 or the port invests in blockchain, when the competition between shipping companies is more intense or the investment efficiency of investors is higher, the
The freight rate of two shipping companies and port service price will be reduced. When shipping company 1 invests in blockchain, the port service price ceiling that can be achieved will be higher. When the port invests in blockchain technology, both two shipping companies can reach higher freight rate caps.

(2) Compared with shipping company 1 investing in blockchain technology, port investment in blockchain technology is more conducive to improving customs clearance efficiency and logistics transparency. This shows that in a port-dominated shipping supply chain, the port has an inherent advantage.

(3) Comparing the profits of shipping companies, the port, and the shipping supply chain in different scenarios, it can be found that both the port and shipping supply chain can achieve higher profits in scenario PB. Under scenario CB, both two shipping companies can obtain higher profits. The higher the investment efficiency of blockchain investors or the more intense the service competition among shipping companies, the lower the profits of two shipping companies, the port, and the shipping supply chain.

(4) The upper limit of social welfare of the shipping supply chain under scenario PB is much greater than that under scenario CB, indicating that the port’s investment in blockchain technology is more conducive to social welfare.

7. Conclusions and policy implications

7.1. Conclusions

In the post-COVID-19 pandemic era, port congestion and port digitization have become important issues of concern to academia and industry. Motivated by this background, blockchain technology was born and has been flourishing in recent years. Ports and shipping companies in various countries have started to invest more in developing different types of shipping blockchain platforms and have played an active role in improving customs clearance efficiency and enhancing logistics transparency. However, a series of research questions have arisen when applying blockchain to carry out shipping supply chain cooperation. For example, which model of cooperation is most beneficial? What impact will different cooperation models have on consumer surplus and social welfare? To answer the abovementioned questions, three scenarios are constructed. By comparing the cost effect, input effect, economic effect, and market effect in various scenarios, a balanced strategy for blockchain technology investment is obtained. On this basis, the impact of blockchain technology investment on consumer surplus and social welfare is further analyzed. Overall, we draw the following conclusions.

First, from the perspective of the cost effect and market effect, the more incentivized the service competition between the two shipping companies is, the lower the service price (freight rate) and market demand for investors. The higher the investment efficiency of the investor is, the lower the service price (freight rate) and market demand of investors. This shows that the investment in blockchain technology has achieved the effect of double-pulling price and demand.

Second, the weaker the service competition between the two shipping companies, the more obvious the improvement of blockchain technology to the overall logistics capability and the investor can obtain more profits. When the investment efficiency of the investment subject is lower, the shipping supply chain participants will obtain greater profits.

Third, by comparing the profits of the port, shipping company 1 and the entire shipping supply chain in scenarios PB and CB, we find that shipping company 1 can obtain more profits in scenario CB. In scenario PB, the port and the shipping supply chain gain more profits.

*Fig. 5. The impact of blockchain investment on the service price of investors.*
Fig. 6. The impact of blockchain investment on the investment level (logistics capability) of the investor.

(a) Changes in logistics transparency in scenario PB  (b) Changes in logistics transparency in scenario CB

(c) Changes in customs clearance efficiency in scenario PB  (d) Changes in customs clearance efficiency in scenario CB

Fig. 7. The impact of blockchain investment on the profits of investment entities.

(a) Changes in port profits under scenario PB  (b) Changes in port profits under scenario CB

(c) Changes in shipping company 1’s profits under scenario PB  (d) Changes in shipping company 1’s profits under scenario CB
Fourth, whether the port or shipping company 1 invests in blockchain technology, the consumer surplus value and social welfare value will decrease with the increase in investment efficiency. Similarly, when the competition between the two shipping companies is more intense, the consumer surplus value brought by the blockchain technology investment is smaller. From the perspective of maximizing consumer surplus, blockchain investment in the port will bring more consumer surplus and social welfare than shipping company 1’s blockchain investment, and it will also reduce the price transmission effect to a certain extent.

7.2. Policy implications

In the post-COVID-19 pandemic era, the research conclusions of this paper have a certain enlightening effect on improving the logistics capabilities of participants in the shipping supply chain.

On the one hand, the inclusion of supply chain participants in blockchain networks within their economic capacity has a positive impact on improving logistics capabilities and increasing profits. Meanwhile, participants must consider their position in the supply chain (i.e., leader or follower). If a participant has already invested in blockchain technology, subsequent participants should carefully assess whether it is profitable to invest again as a stakeholder.

On the other hand, although investment in blockchain technology reduces overall societal benefits, it can improve the logistics efficiency of the port and shipping industry, ease port congestion, and thus reduce economic losses for shippers. The government should prioritize blockchain technology in the formulation of relevant policies to achieve the dual goal of improving the logistics efficiency and economic benefits of the shipping supply chain. For a port in an oligopolistic position in the shipping supply chain, the government can formulate incentive policies to promote the application of blockchain technology to improve the profit of the shipping supply chain.

Finally, it should be noted that the leading investor can usually set the open level of the blockchain system in practical application scenarios of blockchain technology. When an enterprise is the major investor, it is highly probable that it will not let the opening level of other participants be the same as its own. Therefore, we can explore the game of various stakeholders under the premise of the major investor control opening level to enrich the game theory of blockchain technology cooperation in the shipping supply chain.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Proof of Propositions

Proof of Proposition 1.
Since $\frac{\partial \pi}{\partial w} = -2$, Proposition 1 is proven.

Proof of Proposition 2.
Since $\frac{\partial \pi}{\partial v} = -2$, Proposition 2 is proven.

Proof of Proposition 3. According to the judgment conditions of differentiable concave functions, the necessary condition for Proposition 3 to be established is that the Hessian of the second derivative composed of $w$ and $t$ is a negative definite matrix. The Hessian is written as:

$$\begin{bmatrix}
\frac{\partial^2 \pi}{\partial w^2} & \frac{\partial^2 \pi}{\partial w \partial t} \\
\frac{\partial^2 \pi}{\partial t \partial w} & \frac{\partial^2 \pi}{\partial t^2}
\end{bmatrix} = \begin{bmatrix}
-2 \gamma \left( -3 + 2\beta + 4\gamma p \right) & 2 \gamma \left( -2 + \beta + 2\gamma p \right) \\
\left( -1 + \beta + 2\gamma p \right) & \left( -1 + \beta + 2\gamma p \right)^2
\end{bmatrix}
$$

The first order leading principal minor $\Delta_1 = -\frac{2\gamma \left( -3 + 2\beta + 4\gamma p \right)}{\left( -1 + \beta + 2\gamma p \right)^2}$.

The second order leading principal minor $\Delta_2 = \frac{2\gamma \left( -5 + 2\beta + 4\gamma p \right)}{\left( -1 + \beta + 2\gamma p \right)^2}$.

If $\Delta_1 < 0, \Delta_2 > 0$, the Hessian is a negative definite matrix. We obtain if $\frac{1}{2}(3 - 2\beta) < \gamma p < 1, \Delta_1 < 0, \Delta_2 > 0$. The Hessian is a negative definite matrix. Proposition 3 is proven.

Proof of Proposition 4. Similar to the proof of Proposition 3. The Hessian is:

$$\begin{bmatrix}
\frac{\partial^2 \pi}{\partial p^2} & \frac{\partial^2 \pi}{\partial p \partial t} \\
\frac{\partial^2 \pi}{\partial t \partial p} & \frac{\partial^2 \pi}{\partial t^2}
\end{bmatrix} = \begin{bmatrix}
-\frac{2}{2\gamma} & 1 \\
1 & -\gamma p
\end{bmatrix}
$$

The first order leading principal minor $\Delta_1 = -2$.

The second order leading principal minor $\Delta_2 = 2\gamma - 1$.

Set $\Delta_2 > 0$, we can obtain $\gamma p > \frac{1}{2}$. Therefore, when $\gamma p > \frac{1}{2}$, the Hessian is a negative definite matrix. Proposition 4 is proven.

Proof of Proposition 5. Similar to Proof of Proposition 3. The Hessian is:

$$\begin{bmatrix}
\frac{\partial^2 \pi}{\partial w^2} & \frac{\partial^2 \pi}{\partial w \partial t} \\
\frac{\partial^2 \pi}{\partial t \partial w} & \frac{\partial^2 \pi}{\partial t^2}
\end{bmatrix} = \begin{bmatrix}
\frac{4\gamma}{2\gamma - 1} & \frac{2\gamma}{2\gamma - 1} \\
\frac{-1 + \beta + 2\gamma p}{-1 + \beta + 2\gamma p} & \frac{-1 + \beta + 2\gamma p}{\left( -1 + \beta + 2\gamma p \right)^2}
\end{bmatrix}
$$

The first order leading principal minor $\Delta_1 = -\frac{4\gamma}{2\gamma - 1}$.

The second order leading principal minor $\Delta_2 = \frac{2\gamma \left( -2 + \beta + 4\gamma p \right)}{\left( -1 + \beta + 2\gamma p \right)^2}$.

If $\Delta_1 < 0, \gamma < 0$ or $\gamma > \frac{1}{2}$. The value range of $\gamma$ must be greater than 0, so $\gamma > \frac{1}{2}$. $\Delta_2 > 0$. Thus, we obtain $\gamma > \frac{2 - \beta}{2}$. Therefore, $\gamma > \frac{2 - \beta}{2}$, and the Hessian is a negative definite matrix. Proposition 5 is proven.

Proof of Proposition 6. Similar to the proof of Proposition 3. The Hessian is:

$$\begin{bmatrix}
\frac{\partial^2 \pi}{\partial \alpha^2} & \frac{\partial^2 \pi}{\partial \alpha \partial \beta} \\
\frac{\partial^2 \pi}{\partial \beta \partial \alpha} & \frac{\partial^2 \pi}{\partial \beta^2}
\end{bmatrix} = \begin{bmatrix}
-2 & 1 \\
1 & -\gamma
\end{bmatrix}
$$

The first order leading principal minor $\Delta_1 = -2$.

The second order leading principal minor $\Delta_2 = 2\gamma - 1$.

If $\Delta_2 > 0$, we obtain $\gamma > \frac{1}{2}$. Therefore, $\gamma > \frac{1}{2}$, and the Hessian is a negative definite matrix. Proposition 6 is proven.

Proof of Proposition 7(i).
Since $w^{MB} - w^{NB} = \frac{-\delta + \epsilon + \zeta}{10 - 4\delta - 8\gamma p} > 0$, when $\frac{1}{2}(5 - 2\beta) < \gamma p < 1$, we have $w^{NB} < w^{MB}$. Proposition 7(i) is proven.

Proof of Proposition 7(ii).
Since $w^{CA} - w^{NB} = \frac{\delta - \epsilon - \zeta}{5 \left( -2 + \beta + 2\gamma p \right)} > 0$, when $\frac{1}{2}(5 - 2\beta) < \gamma p < 1$, we have $w^{NB} < w^{CA}$. Proposition 7(ii) is proven.

Proof of Proposition 8(i).
We have $\frac{\partial \pi}{\partial \gamma p} > 0$ and $\frac{\partial \pi}{\partial \gamma} = -\frac{8\delta - \epsilon - \zeta}{\left( -5 + 2\beta + 4\gamma p \right)^2} < 0$. Proposition 8(i) is proven.

Proof of Proposition 8(ii).
We have $\frac{\partial \pi}{\partial \gamma} = \frac{-\delta + \epsilon + \zeta}{\left( -2 + \beta + 2\gamma p \right)^2} < 0$ and $\frac{\partial \pi}{\partial \gamma} = \frac{-\delta + \epsilon + \zeta}{\left( -2 + \beta + 2\gamma p \right)^2} < 0$. Proposition 8(ii) is proven.

Proof of Proposition 8(iii).
Proof of (a), see Proof of Proposition 8(i).
Proof of (b) and (c):
We have \( \rho_{PB} - \rho_{CB} = \frac{1}{4}(\lambda - \rho_0 + \rho_1) \left( \frac{2}{\rho_1 - \rho_0} + \frac{1}{\rho_1 - \rho_2} \right) \).
Solving the above equation shows that:
If \( \frac{1}{2}(5-2\beta) < \rho_p < 1 \) and \( \frac{1}{2}(1 + 4\beta) < \rho_s < 1 \), then \( \rho_{PB} > \rho_{CB} \).
If \( \frac{1}{2}(5-2\beta) < \rho_p < 1 \) and \( \frac{1}{2} \gamma < \rho_s < \frac{1}{2}(1 + 4\beta) \), then \( \rho_{PB} < \rho_{CB} \).

Proposition 8(iii) is proven.

Proof of Proposition 8(iv).
Proof of (a).
See Proof of Proposition 8(ii).
Proof of (b) and (c).
We have \( \rho_{PB} - \rho_{CB} = \frac{1}{4}(\lambda - \rho_0 + \rho_1) \left( \frac{2}{\rho_1 - \rho_0} + \frac{1}{\rho_1 - \rho_2} \right) \).
Solving the above equation shows that:
If \( \frac{1}{2}(5-2\beta) < \rho_p < 1 \) and \( \frac{1}{2}(1 + 4\beta) < \rho_s < 1 \), then \( \rho_{PB} > \rho_{CB} \).
If \( \frac{1}{2}(5-2\beta) < \rho_p < 1 \) and \( \frac{1}{2} \gamma < \rho_s < \frac{1}{2}(1 + 4\beta) \), then \( \rho_{PB} < \rho_{CB} \).

Proposition 8(iv) is proven.

Proof of Proposition 9(i).
We have \( \kappa_{PB}^{cl} - \kappa_{CB}^{cl} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) + \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \) and \( \kappa_{PB}^{CB} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \). Proposition 9(i) is proven.

Proof of Proposition 9(ii).
We have \( \kappa_{PB}^{cl} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) + \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \) and \( \kappa_{PB}^{CB} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \). Proposition 9(ii) is proven.

Proof of Proposition 9(iii).
We have \( \kappa_{PB}^{cl} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \) and \( \kappa_{PB}^{CB} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \). Proposition 9(iii) is proven.

Proof of Proposition 9(iv).
We have \( \kappa_{PB}^{cl} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \) and \( \kappa_{PB}^{CB} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \). Proposition 9(iv) is proven.

Proof of Proposition 9(iv).
We keep \( \beta = 0.6 \). If \( \rho_{PB} < \rho_{CB} \), we have \( \kappa_{PB}^{cl} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \).
If \( \rho_{PB} > \rho_{CB} \), we have \( \kappa_{PB}^{cl} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \).
Solving the above two inequalities, we can obtain:
If \( \rho_s > \frac{1}{2} \gamma \), then \( \rho_{PB}^{cl} < \rho_{PB}^{CB} \). If \( \rho_s < \frac{1}{2} \gamma \), then \( \rho_{PB}^{cl} > \rho_{PB}^{CB} \).

Meanwhile, if \( \kappa_{PB}^{cl} < \kappa_{CB}^{CB} \), then we have \( \kappa_{PB}^{cl} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \).
If \( \kappa_{PB}^{cl} > \kappa_{CB}^{CB} \), then we have \( \kappa_{PB}^{cl} - \kappa_{CB}^{CB} = \frac{1}{2}(\alpha + c_2) (\beta + c_2) \left( -1 + \frac{7}{2\gamma} \right) \left( \frac{c_3}{\rho_1 - \rho_0} \right) > 0 \).
Solving the above two inequalities, we finally obtain:
If \( \gamma < \gamma_{M(2)} \),
\[ \kappa_{PB}^{cl} < \kappa_{CB}^{CB} \] if \( \gamma < \gamma_{M(2)} \),
\[ \kappa_{PB}^{cl} > \kappa_{CB}^{CB} \] if \( \gamma > \gamma_{M(2)} \),
where
\[ M = \frac{625 - 1000\beta + 600\rho_0^2 - 160\rho_0^3 + 16\rho_0^4 - 2600\rho_0^2 + 3280\rho_0^2 - 1426\rho_0^2 \rho_0^2 + 232\rho_0^2 - 8\rho_0^2 + 4560\rho_0^2 - 704\rho_0^2 + 1652\rho_0^2 - 240\rho_0^2 + 16\rho_0^2 \rho_0^2 - 3584\rho_0^2 + 2816\rho_0^2 - 704\rho_0^2 + 64\rho_0^2 + 1024\rho_0^2 - 512\rho_0^2 + 64\rho_0^2 \rho_0^2}{(25 - 20\rho_0^2 - 4\rho_0^2 - 292\rho_0^2 - 16\rho_0^2)^2} \].

Proposition 9(iv) is proven.

Proof of Proposition 10(i).
Proof of (a).
We have \( p_{PB}^{cl} - p_{PB}^{CB} = \frac{(-7/2)\alpha + c_2 - \gamma}{4(\rho_1 - \rho_0)} > 0 \) and \( p_{CB}^{cl} - p_{CB}^{CB} = \frac{(-7/2)\alpha + c_2 - \gamma}{4(\rho_1 - \rho_0)} > 0 \).

Proof of (b) and (c).
If \( p_{PB}^{cl} > p_{PB}^{CB} \), then we can obtain \( p_{PB}^{cl} - p_{CB}^{cl} = \frac{(\alpha + c_2 - \gamma)(3 - \rho_0^2)(-1 + 2\rho_0^2 - 2\rho_0^2 + 7\rho_0^2)}{2(\rho_1 - \rho_0)} > 0 \).
If \( p_{PB}^{cl} < p_{PB}^{CB} \), then we can obtain \( p_{PB}^{cl} - p_{CB}^{cl} = \frac{(\alpha + c_2 - \gamma)(3 - \rho_0^2)(-1 + 2\rho_0^2 - 2\rho_0^2 + 7\rho_0^2)}{2(\rho_1 - \rho_0)} < 0 \).

Solving these inequalities, we can obtain:
If \( \frac{1}{2} (5 - 2p) < \gamma_p < 1 \) and \( \frac{2}{5} + \frac{2p}{2p} < \gamma_c < 1 \), then \( q^W_{2 \gamma} > q^W_{2 \gamma} \).

If \( \frac{1}{2} (5 - 2p) < \gamma_p < 1 \) and \( \frac{2}{5} + \frac{2p}{2p} < \gamma_c < 1 \), then \( q^W_{2 \gamma} > q^W_{2 \gamma} \).

**Proposition 10(i)** is proven.

**Proof of Proposition 10(ii).**

**Proof of (a).**

We have \( q^W_{2 \gamma} - q^W_{2 \gamma} = \frac{-(5-2p)(\alpha - c_c - c_p)}{2 \gamma_c (2p) + 2 \gamma_c} \) and \( q^W_{2 \gamma} - q^W_{2 \gamma} = \frac{-(2-2p)(\alpha - c_c - c_p)}{2 \gamma_c (2p) + 2 \gamma_c} \).

**Proof of (b) and (c).**

If \( q^W_{2 \gamma} > q^W_{2 \gamma} \), we can obtain \( q^W_{2 \gamma} - q^W_{2 \gamma} = \frac{1}{2} (\alpha - c_c - c_p) \left( \frac{2p}{5 - 2p} - \frac{2p}{2p} \right) > 0 \).

If \( q^W_{2 \gamma} > q^W_{2 \gamma} \), we can obtain \( q^W_{2 \gamma} - q^W_{2 \gamma} = \frac{1}{2} (\alpha - c_c - c_p) \left( \frac{2p}{5 - 2p} - \frac{2p}{2p} \right) < 0 \).

Solving the inequalities, we can obtain:

If \( \frac{1}{2} (5 - 2p) < \gamma_p < 1 \) and \( \frac{2}{5} + \frac{2p}{2p} < \gamma_c < 1 \), then \( q^W_{2 \gamma} > q^W_{2 \gamma} \).

If \( \frac{1}{2} (5 - 2p) < \gamma_p < 1 \) and \( \frac{2}{5} + \frac{2p}{2p} < \gamma_c < 1 \), then \( q^W_{2 \gamma} > q^W_{2 \gamma} \).

**Proposition 10(ii)** is proven.

**Proof of Proposition 12(i).**

We have \( \frac{\partial^2 C^{SW}}{\partial \gamma_p} = \frac{-(\alpha - c_c - c_p) p}{(2p - 2p) + (2p - 2p)} < 0 \) and \( \frac{\partial^2 C^{SW}}{\partial \gamma_c} = \frac{-(\alpha - c_c - c_p) p}{(2p - 2p) + (2p - 2p)} < 0 \). **Proposition 11(i)** is proven.

**Proof of Propositions 12(ii) and 12(iii).**

If \( C^{SW} < C^{WB} \), then we can obtain \( C^{SW} - C^{WB} = \frac{1}{2} (\alpha - c_c - c_p) \left( \frac{2p}{5 - 2p} - \frac{2p}{2p} \right) > 0 \). If \( C^{SW} > C^{WB} \), then we can obtain \( C^{SW} - C^{WB} = \frac{1}{2} (\alpha - c_c - c_p) \left( \frac{2p}{5 - 2p} - \frac{2p}{2p} \right) < 0 \).

Solving the inequalities, we can obtain:

If \( \frac{1}{2} (5 - 2p) < \gamma_p < 1 \) and \( \frac{2}{5} + \frac{2p}{2p} < \gamma_c < 1 \), then \( C^{WB} > C^{SW} \).

If \( \frac{1}{2} (5 - 2p) < \gamma_p < 1 \) and \( \frac{2}{5} + \frac{2p}{2p} < \gamma_c < 1 \), then \( C^{WB} > C^{SW} \).

**Proposition 11(ii) and Proposition 11(iii)** are proven.

**Proof of Proposition 13.**

We have \( \frac{\partial S^{WB}}{\partial \gamma_p} = \frac{-(\alpha - c_c - c_p) (12a + 4b(\alpha - c_c - c_p)) + 4(8 + 3c_c + 3c_p) - 26(\alpha + c_c + c_p) \gamma_p}{2(5 + 2p + 4p) \gamma_p} < 0 \) and

\( \frac{\partial S^{SW}}{\partial \gamma_c} = \frac{2(\alpha - c_c - c_p) (a + 4c_p + (\alpha - c_c - c_p) \gamma_p)}{(-5 + 2p + 4p) \gamma_p} < 0 \).

**Proposition 13** is proven.

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