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Cooperative investment strategies of ports and shipping companies in blockchain technology

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Abstract
Blockchain technology promotes the efficiency and transparency of the shipping supply chain, presenting new opportunities and challenges for various maritime stakeholders. To enhance the application of blockchain in the shipping industry, a vertical game model is constructed, involving a port and a shipping company (SP), to analyze the roles of maritime stakeholders and cooperative investment strategies. The study also investigates the impact of time value, investment cost, and blockchain operating cost on price, demand, and profit. Comparative analyses and numerical experiments provide insights into the equilibrium strategy and “free ride” behavior among stakeholders in blockchain adoption. Results indicate: (1) When the time value is higher, investment in blockchain benefits the SP regardless of the blockchain operating cost. The high-efficiency port (HP) should cooperate with the high-time-value SP in blockchain technology investment, while the low-efficiency port (LP) should cooperate with the low-time-value SP. (2) When the blockchain operating cost is lower, the port and the SP are more inclined to cooperate in blockchain technology investment. As the blockchain operating cost increases, the SP becomes proactive in investing to drive blockchain adoption, while the port “free rides”. The SP only exhibits a “free ride” motive when the time cost is low. These findings offer valuable insights for maritime stakeholders in making decisions regarding blockchain adoption.

Keywords Blockchain · Shipping supply chain · Cooperation · Investment strategy

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1 Introduction

In the international import and export container shipping trade, there are typically 30–40 documents that will be generated in a single transaction (Thai and Grewal 2007). These documents mainly include transportation documents (such as shipping orders or bills of lading), product-related documents (such as inspection and quarantine certificates), trade documents (such as quotations, sales contracts, and packing lists), as well as other relevant government documents (such as customs clearance declarations and import/export licenses) (Pu and Lam 2021b; Hinkelman and Mansergh 2002). Traditionally, seaborne trade must be based on paper documents. Usually in seaborne trade, certain documents must be physically transported with the goods. Due to the lengthy distance of goods transport, the transportation of documents can often take a considerable amount of time, leading to a reduction in trade efficiency (Lam and Zhang 2019). Additionally, Ganne (2018) highlighted that the consignee can expect to wait around 10 days for the processing and delivery of the relevant documents.. At present, ports in various countries have their own unique EDI (Electronic Data Interchange). However, due to the different policies of each country, the data exchange format has not been fully unified, making it difficult to guarantee efficient data exchange. In addition, in sea cargo transportation, shippers and carriers focus on the transportation of goods, while customs, commodity inspection, and sanitary inspection focus on the goods being transported. Especially during the COVID-19 pandemic, international maritime transportation has become a long-distance transmission carrier for the virus (Han et al. 2021). The COVID-19 virus can be reintroduced into disease-free countries and regions through maritime trade. Therefore, improving the efficiency and paperless level of the shipping supply chain, as well as increasing the traceability and transparency of the transportation process, are the issues that various shipping stakeholders are currently focusing on.

Blockchain technology offers several benefits, including information transparency and data integrity, traceability, and non-tampering, which can effectively address the challenges faced by the shipping industry (Pu and Lam 2022; Liu et al. 2021). Its application can significantly improve the service efficiency of the maritime sector by promoting the paperless operation (Nguyen et al. 2022). With Blockchain technology, electronic files are encrypted for storage and transmission in a common format, enabling rapid data exchange (Chang et al. 2020). On the blockchain platform, authorized members related to container shipping can securely access shipping information and trade documents in real time (Jovanovic et al. 2022). Digital signatures in the blockchain are also able to protect shipper information. Only designated recipients are able to decrypt without a central party (Christidis and Devetsikiotis 2016; Dai 2022). In addition, blockchain technology can accurately track the entire cargo transportation process, automatically recording every state from loading to transportation and delivery (Kshetri 2018). This creates a permanent and immutable historical record, allowing shippers and carriers to allocate cargo transportation responsibilities based on real-time tracking of the cargo's status. Simultaneously, the timestamp feature of blockchain facilitates the assessment of legal attributes and ensures easy accountability for stakeholders in the shipping supply chain (Tapscott and Tapscott 2017). Customs, commodity inspection, and sanitary inspection authorities can inspect the cargo based on transparent record data, eliminating the need for physical boarding inspections.

Numerous maritime stakeholders have started implementing blockchain technology in their operations. For example, the Maersk Group and IBM collaborated on developing a blockchain-based platform named TradeLens. This platform offers a cross-industry, real-time, and executable information sharing service for the shipping supply chain (Jensen et al. 2019). However, TradeLens failed to achieve complete global industry collaboration requirements due to the existence of competition (PierNext 2023). In November 2022, Maersk and IBM decided to withdraw the TradeLens offerings and discontinue the platform (Maersk 2022). The Global Shipping Business Network (GSBN), the first shipping blockchain alliance, launched its initial product, "paperless delivery", in July 2021. This innovative solution, based on blockchain technology, significantly simplifies data exchange and reduces the processing time for import cargo documents from several days to just a few hours (ZGSYB 2021).

Although blockchain technology holds great potential for enhancing the shipping supply chain, the high costs associated with investing in and operating the technology still pose an economic burden on maritime stakeholders (Chod et al. 2020). On one hand, adopting blockchain technology necessitates expensive adaptations, upgrades, and changes to existing business systems and processes. On the other hand, compared to centralized data storage systems, blockchain technology ensures information fidelity through multiple verifications, consensus mechanisms, and repeated storage across multiple nodes, thereby incurring higher costs for information verification and storage. Consequently, stakeholders in the shipping supply chain must carefully consider the positive impacts of blockchain technology alongside the cost burden when making their investment decisions.

When it comes to the construction of blockchain platforms, maritime stakeholders often have an incentive to "free ride". Business transactions among these stakeholders are required to operate on the blockchain platform. Maritime stakeholders who choose not to invest in the blockchain platform not only evade the high costs but also reap the benefits of blockchain technology. Therefore, further research is needed to explore the influential role of different maritime stakeholders and their "free ride" behaviors in the adoption of blockchain technology.

Currently, research on the adoption of blockchain in the maritime supply chain primarily focuses on subjects at the same level. Given the complexity of the maritime supply chain, this paper examines the cooperative investment strategies of maritime stakeholders throughout the entire upstream and downstream chain for blockchain implementation.

In the shipping industry, the port serves as the distribution center for goods and the connection point between ships and other means of transportation, playing the role of a transportation hub. The shipping company (SP) provides core transportation services. Therefore, this paper specifically investigates the cooperative investment strategies of ports and SPs in adopting blockchain technology. Fig. 1 details the transaction process among the primary business entities in the

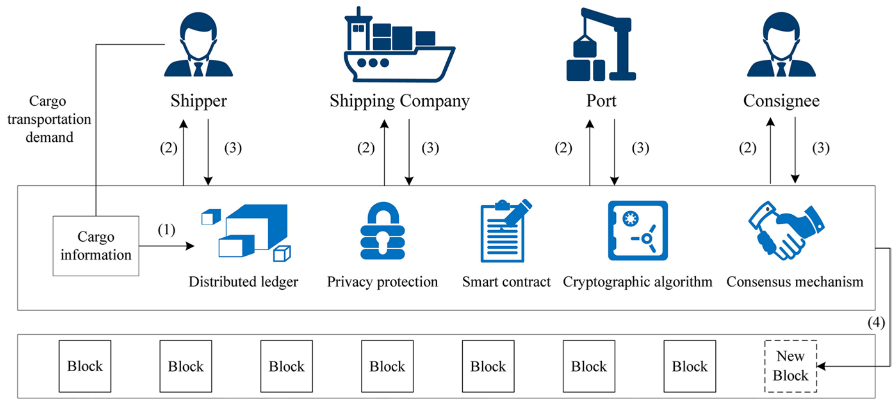

Fig. 1 Shipping blockchain platform transaction process

shipping blockchain platform. (1) Cargo information is stored in a distributed ledger. (2) When the shipper initiates a demand for freight transportation, the cargo information is broadcasted throughout the network. (3) All nodes verify the information, and upon confirmation of its legitimacy, add the cargo information to the newly generated block. Consensus algorithms are run across all nodes. (4) When all nodes reach a consensus, the block is time-stamped and stored in the longest chain for future access. Smart contracts trigger the execution of business in the blockchain (Dal Mas et al. 2020). Complex encryption mechanisms play an essential role in privacy protection during broadcast and storage (Bai et al. 2020). In this article, we use a consortium chain for shipping blockchain and not the public one, as the former has a better ability to meet the requirements of decentralization and confidentiality of private data (Wang et al. 2020). The primary content of this article includes: Firstly, we discuss the decision-making process involved in adopting blockchain technology and categorize the investment strategies of ports and SPs into four scenarios. We construct a two-stage vertical game model to analyze the optimal strategies for the port and the SP in each scenario, taking into account factors such as time value, investment cost and blockchain operating cost. Next, we examine the impact of these aforementioned factors on the optimal strategies. Comparative analyses and numerical experiments are conducted to better understand the leading role of the port and the SP in blockchain adoption, as well as their "free ride" behaviors. Through this research, we aim to provide valuable insights into the cooperative investment strategies of ports and SPs for blockchain implementation in the maritime supply chain.

This work makes the following main contributions. First, it comprehensively investigates the investment strategies of both ports and SPs in adopting blockchain. Second, it addresses the motivations driving ports and SPs and explores their respective roles in promoting the application of blockchain in the maritime industry.

The structure of this paper is as follows: Sect. 2 presents the literature review. Section 3 builds the model. Section 4 carries out the comparative analysis. Section 5 conducts the numerical experiments. Section 6 summarizes the paper.

2 Literature review

2.1 Investment strategies of ports and shipping companies

In the realm of investment strategies for ports and shipping companies, considerable research has been conducted.(Pujats et al. 2020). Port investment studies have predominantly focused on two key areas: port capacity investment (Balliauw et al. 2020; Chen and Liu 2016; Cheng and Yang 2017) and accessibility investment (Wan et al. 2016). Cheng and Yang (2017) studied the equilibrium of port capacity investment with two ports in China's Liaodong Peninsula, considering different objectives. Wan et al. (2016) developed a model wherein port authorities and inland governments collaborate to invest in port accessibility. Turning to shipping companies, their investment activities primarily encompass vertical investments in ports (Jiang et al. 2021; Song et al. 2018) and fleet-related investments (Fan et al. 2021; Fan and Luo 2013). Jiang et al. (2021) found through numerical analysis that the shipping company's investment in port throughput positively affects its profits but negatively impacts its competitors. Fan et al. conducted a series of studies that analyse shipping companies' motivations for investing in ship scale and second-hand ships (Fan et al. 2021; Fan and Luo 2013).

While existing literature covers various aspects of investment strategies in the maritime sector, there are notable gaps that warrant attention. Specifically, there is limited research addressing the intersection of investment strategies and the adoption of blockchain technology. This crucial gap in the literature presents an opportunity for comprehensive examination. In light of this gap, our study aims to explore the investment strategies employed by ports and shipping companies in the context of blockchain adoption. We undertake a two-fold analysis, considering the positive effects of blockchain technology, such as congestion reduction, cargo tracking, and improved transparency in shipping. However, it is imperative to acknowledge the potential negative consequences associated with blockchain adoption, including the high investment and operating costs that may pose challenges to stakeholders. By addressing these research gaps, we aim to contribute to the existing body of knowledge and offer valuable insights into the investment strategies of ports and shipping companies within the evolving landscape of blockchain technology adoption.

2.2 Application of blockchain in maritime transportation

The existing literature on blockchain technology in the maritime industry is limited, despite some pilot tests being conducted by stakeholders (Xu 2017). While a few scholars have explored the driving forces and obstacles associated with implementing blockchain in the maritime supply chain, significant gaps remain in the literature. Zhou et al. (2020) studied the key challenges and success factors of implementing blockchain technology in the maritime industry based on a case study. The authors conducted four interviews with maritime professionals in Singapore. Based on the feedback from experienced shipping company managers, Li et al. (2022) comprehensively applied a variety of theories to study the key success factors of implementing blockchain in the maritime field. Using interpretive structural models and cross-influence matrix multiplication, Balci and Surucu-Balci (2021) explored the factors influencing the adoption of blockchain technology in container international trade. Research showed that lack of support from influential stakeholders, lack of understanding of blockchain, and lack of government regulation are currently the main obstacles. Nguyen et al. (2021) applied inclusive qualitative analysis combined with directed acyclic graph analysis to explore the potential operational risks of a blockchain-integrated container transportation system. Gausdal et al. (2018) and Papathanasiou et al. (2020) also analysed the driving factors and obstacles of blockchain technology in the shipping industry through qualitative methods.

Moreover, while several studies have summarized the current state and the prospect of blockchain applications in shipping, most of them remain at a theoretical level. There is a scarcity of studies that provide empirical evidence on the actual implementation and outcomes of blockchain initiatives in the maritime sector. For example, Liu et al. (2021) conducted a comprehensive literature review and industry survey, detailing the status quo of blockchain-based offshore supply chain systems. The author made a statistical analysis of the application of blockchain in maritime affairs since 2015, and found that current maritime blockchain projects focus on logistics traceability, information sharing, electronic bills of lading and smart contracts. Munim et al. (2021) described the nature of blockchain and its application to the shipping industry, and suggested that in order to advance blockchain implementation, maritime stakeholders would need to achieve system diversity, privacy, and security in the future. Yang (2019) conducted a comprehensive investigation on the application of blockchain in the shipping supply chain based on the technology acceptance model. The study found that users had positive intentions to use blockchain in customs clearance and management, digitalizing and easing paperwork, standardization and platform development. Pu and Lam (2021a) conducted a systematic literature review of the application of blockchain technology in the maritime industry based on a conceptual framework. The authors pointed out the five current major blockchain applications in the maritime industry: electronic bills of lading, ship operations, ship finance, marine re/insurance, and distributed ledger platforms used by maritime companies.

To address these gaps, our paper seeks to contribute to the literature by providing a critical analysis of the advantages and disadvantages of blockchain technology through a game model. Additionally, we aim to explore the motivations of ports and shipping companies and their roles in promoting the application of blockchain. By doing so, we aim to offer a more comprehensive understanding of blockchain adoption in the maritime industry, highlighting areas that require further research and empirical investigation.

2.3 Blockchain research based on game theory

Traditional research in supply chain management has predominantly employed game theory to address various problems (Cachon and Netessine 2006). However, with the advent of blockchain technology, scholars have begun to explore the potential of game theory in the context of blockchain. While some studies have examined the application of game theory to blockchain platforms, the existing literature in this area is limited. De Giovanni (2020) compared the profitability of suppliers and retailers on traditional online platforms and blockchain platforms, emphasizing the advantages of blockchain due to features like smart contracts. Choi (2019) focused on the luxury goods supply chain and evaluated the value of blockchain in diamond certification. The study found that all stakeholders in the luxury supply chain can benefit from cost reduction on the blockchain certification platform. Jiang et al. (2020) developed a bilevel electricity price transaction model using blockchain in the energy sector.

In the maritime industry, some scholars have integrated game theory with blockchain for supply chain analysis. Zhong et al. (2021) proposed a decision-making model for shipping companies in the blockchain market based on Cournot and Stackelberg games. Based on the Hoteling model, Wang et al. (2021) examined decision-making by heterogeneous ports in a competitive condition, incorporating a "blockchain technology sharing + compensation" mechanism.

However, the existing literature applying game theory to study blockchain in the maritime industry primarily focuses on decision-making among stakeholders at the same supply chain level. There are fewer studies that investigate stakeholders at different levels. Our study aims to fill the void by examining the investments and pricing decisions of ports and shipping companies regarding blockchain technology. We also emphasize the interdependence between stakeholders at different levels and analyze the underlying motivations for "free ride" behaviors in blockchain investments.

3 Model

In this paper, a simple maritime transport chain consisting of one port (denoted by the subscript "p") and one SP (denoted by the subscript "c") is investigated. The port and the SP have two strategies under consideration: adopting blockchain technology (denoted by the superscript "B") and not adopting blockchain technology (denoted by the superscript "N"). The strategy matrix for the port and the SP is shown in Table 1.

Table 1 The strategy matrix

		SP	
		N	B
Port	N	Scenario NN	Scenario NB
	B	Scenario BN	Scenario BB

3.1 Problem description

During the pricing decision process, the upstream port is the leader, and the downstream SP is the follower. This game order is widely used in literature, such as Wang et al. (2022), Zheng and Luo (2021), Sheng et al. (2017). The port provides services to the SP and charges a service price denoted as w. The SP provides cargo transportation services to shippers and charges a freight price represented as r. The demand function is assumed to be influenced by the freight price of the SP, with an inverse relationship between them. We have employed the classic market demand function $Q = a - \alpha r$, which is widely applied in the game between upstream and downstream entities (Yang and Tang 2019; Liu and Wang 2019). In this equation, a is a positive constant that represents the largest scale of the shipper market. α represents the freight price elasticity of demand, and for the sake of convenience in calculation, it has been normalized to 1 (Xie et al. 2014). This normalization does not affect the research results.

To highlight the impact of blockchain technology costs, we assume that the operating costs of both the port and the SP are zero. In addition, we consider the time cost of the SP. When the container throughput significantly exceeds the port's container handling capacity, port congestion arises, exacerbating the time cost of the SP. Let's assume the time cost is nT, where n is the SP's value of time and T denotes the congestion delay time. The congestion delay time of the SP in the port is equal to the ratio of the demand to the port's container handling capacity (Basso and Zhang 2007). Thus, the time cost is $n\frac{Q}{k}$, where k is the port's container handling capacity. The time cost resulting from port congestion is not reflected in the port's profit function. As a consequence, the port bears the repercussions of losing market share due to the SP's dissatisfaction(Sheng et al. 2017).

The application of blockchain in the maritime industry brings positive developments for both the port and the SP. On one hand, blockchain enables automatically recording of every state of shipping, from loading and transportation to delivery, creating a comprehensive historical record. The timestamps and hash functions ensure that the information stored on the blockchain remains untampered and cannot be forged. This traceability feature significantly enhances the transparency of the shipping supply chain. On the other hand, the decentralized nature of blockchain reduces the need for intermediaries and simplifies the operational processes. Public keys, private keys and digital signatures facilitate rapid information exchange and sharing across the entire network (Pu and Lam 2021a). Blockchain has improved the efficiency of various aspects within the port and SP, resulting in reduced port congestion time. Let's assume that the increased transparency and time saved due to blockchain are e_i and Δt_i, respectively. i is the subscript, $i = c$ represents the SP and $i = p$ represents the port. The shippers attracted by e_i and Δt_i are βe_i and $\beta \Delta t_i$, respectively. β is the average sensitivity of shippers to transparency and time. $0 < \beta < 1$. The investment costs that the port or SP may incur to improve logistics transparency and efficiency using blockchain technology are $\frac{me_i^2}{2}$ and $\frac{m\Delta t_i^2}{2}$. m is the average effort cost coefficient. This form is widely used by scholars to describe the effort cost (Moon et al. 2020; Choi and Ouyang 2021; Dong et al. 2018; Karaer et al.

2017). In practice, third-party blockchain technology service providers (software companies, such as IBM, Cargosmart) usually offer their services to ports or shipping companies (Wang et al. 2021). Hence, the investment cost is paid by the ports or shipping companies to the third-party blockchain service provider. For example, IBM Blockchain Platform nodes are allocated on an hourly basis, at a flat rate of \$0.29 USD/VPC-hour (IBM 2023). In addition, the completion of each business on the blockchain platform will generate the cost of verification, digital identification, the implementation of smart contracts, and transaction monitoring (De Giovanni 2020). These costs are collectively referred to as the blockchain operating cost c_b. For example, Tradelens charges shippers a fee to use its services. The initial fee for Tradelens is \$25 per container per voyage (Jensen et al. 2019). Subsequently, based on various service contents, Tradelens devises personalized pricing for its customers (Tradelens 2018).

3.2 Basic model for the port and the SP

This section presents the models of the four scenarios in Table 1.

Scenario NN: In the event that both the port and the SP choose not to adopt blockchain technology, neither entity can avail themselves of the benefits associated with blockchain. The port decides w by maximizing its profit. The SP decides r by maximizing its profit. The demand Q^{NN} and the profit Π_i^{NN} can be formulated as follows:

$$Q^{NN} = a - r \tag{1}$$

$$\Pi_p^{NN} = wQ \tag{2}$$

$$\Pi_c^{NN} = (r - w)Q - \frac{nQ}{k} \tag{3}$$

Proposition 1 Π_p^{NN} *is a differentiable concave function of* w. Π_c^{NN} *is a differentiable concave function of* r. *The optimal decision results under scenario NN are as follows*.

$$Q^{NN*} = \frac{ak-n}{4k}, w^{NN*} = \frac{ak-n}{2k}, r^{NN*} = \frac{3ak+n}{4k},$$
$$\Pi_p^{NN*} = \frac{(ak-n)^2}{8k^2}, \Pi_c^{NN*} = \frac{(ak-n)^2}{16k^2}.$$

Proof See Appendix A. □

To ensure that all optimal decisions are positive, assume $n < ak$.

Scenario BN: The port utilizes blockchain technology, while the SP does not. The port decides w, e_p, and Δt_p by maximizing its profit. The SP decides r by maximizing its profit. The demand Q^{BN} and the profit Π_i^{BN} are modeled as follows:

$$Q^{BN} = a - r + \beta(e_p + \Delta t_p) \tag{4}$$

$$\Pi_p^{BN} = (w - c_b)Q - \frac{1}{2}m(e_p^2 + \Delta t_p^2) \tag{5}$$

$$\Pi_c^{BN} = (r - w)Q - n(\frac{Q}{k} - \Delta t_p) \tag{6}$$

Proposition 2 *Π_p^{BN} is a differentiable concave function of w, e_p, and Δt_p. Π_c^{BN} is a differentiable concave function of r. The optimal decision results under scenario BN are as follows.*

$$w^{BN*} = \frac{m(ak - n - kc_b) + k(2m - \beta^2)c_b}{k(2m - \beta^2)}, r^{BN*} = \frac{3akm + (m - 2\beta^2)(n + kc_b)}{k(4m - 2\beta^2)},$$
$$Q^{BN*} = \frac{m(ak - n - kc_b)}{k(4m - 2\beta^2)}, e_p^{BN*} = \Delta t_p^{BN*} = \frac{\beta(ak - n - kc_b)}{2k(2m - \beta^2)}, \Pi_p^{BN*} = \frac{m(ak - n - kc_b)^2}{4k^2(2m - \beta^2)},$$
$$\Pi_c^{BN*} = \frac{(akm)^2 + 2akn(A_1 - m^2) + n^2(m^2 - 2A_1) + 2kc_b(n(m^2 - A_1) - akm^2) + (kmc_b)^2}{4k^2(2m - \beta^2)^2}.$$

The expressions of the relevant parameters in this paper are shown in Appendix B.

Proof See Appendix A. □

To ensure that all optimal decisions are positive, assume $n < ak - kc_b$, $a > c_b$.

Scenario NB: The SP utilizes blockchain technology, while the port does not. The port decides w by maximizing its profit. The SP decides r, e_c, and Δt_c by maximizing its profit. Under scenario NB, the demand Q^{NB} and the profit Π_i^{NB} are calculated as follows:

$$Q^{NB} = a - r + \beta(e_c + \Delta t_c) \tag{7}$$

$$\Pi_p^{NB} = wQ \tag{8}$$

$$\Pi_c^{NB} = (r - w - c_b)Q - n\left(\frac{Q}{k} - \Delta t_c\right) - \frac{1}{2}m(e_c^2 + \Delta t_c^2) \tag{9}$$

Proposition 3 Π_p^{NB} *is a differentiable concave function of* w. Π_c^{NB} *is a differentiable concave function of* r, e_c, *and* Δt_c. *The optimal decision results under scenario NB are as follows.*

$$Q^{NB*}=\frac{A_2-kmc_b}{4k(m-\beta^2)},w^{NB*}=\frac{A_2-kmc_b}{2km},\Pi_p^{NB*}=\frac{(A_2-kmc_b)^2}{8k^2m(m-\beta^2)},$$
$$e_c^{NB*}=\frac{\beta(A_2-kmc_b)}{4km(m-\beta^2)},\Delta t_c^{NB*}=\frac{4kmn+\beta(A_2-4kn\beta-kmc_b)}{4km(m-\beta^2)},$$
$$r^{NB*}=\frac{akm(3m-2\beta^2)+n(m^2+m\beta(3k-2\beta)-2k\beta^3)+kmc_b(m-2\beta^2)}{4km(m-\beta^2)},$$
$$\Pi_c^{NB*}=\frac{akm(akm-2(mn-kn\beta))+n^2A_3-2A_2kmc_b+(kmc_b)^2}{16k^2m(m-\beta^2)}.$$

Proof See Appendix A. □

To ensure that all optimal decisions are positive, assume $k>\frac{m}{\beta}$ and $a>c_b$; or $k<\frac{m}{\beta}$, $n<\frac{km(a-c_b)}{m-k\beta}$ and $a>c_b$; or $k>\frac{m}{\beta}$, $n>\frac{km(a-c_b)}{m-k\beta}$ and $a<c_b$.

Scenario BB: In this scenario, both the port and the SP choose strategy B. The port decides w, e_p, and Δt_p by maximizing its profit. The SP decides r, e_c, and Δt_c by maximizing its profit. Through the following equations, the demand Q^{BB} and the profit Π_i^{BB} are calculated:

$$Q^{BB}=a-r+\beta(e_p+e_c+\Delta t_p+\Delta t_c) \tag{10}$$

$$\Pi_p^{BB}=(w-c_b)Q-\frac{1}{2}m(e_p^2+\Delta t_p^2) \tag{11}$$

$$\Pi_c^{BB}=(r-w-c_b)Q-n\left(\frac{Q}{k}-\Delta t_p-\Delta t_c\right)-\frac{1}{2}m(e_c^2+\Delta t_c^2) \tag{12}$$

Proposition 4 Π_p^{BB} *is a differentiable concave function of* w, e_p, *and* Δt_p. Π_c^{BB} *is a differentiable concave function of* r, e_c, *and* Δt_c. *The optimal decision results under scenario BB are as follows.*

$$Q^{BB*} = \frac{A_2 - 2kmc_b}{4km - 6k\beta^2}, e_p^{BB*} = \Delta t_p^{BB*} = \frac{\beta(A_2 - 2kmc_b)}{2km(2m - 3\beta^2)},$$
$$w^{BB*} = \frac{A_2(m - \beta^2) - kmc_b\beta^2}{km(2m - 3\beta^2)}, \Pi_p^{BB*} = \frac{(A_2 - 2kmc_b)^2}{4k^2m(2m - 3\beta^2)},$$
$$e_c^{BB*} = \frac{\beta(A_2 - 2kmc_b)}{2km(2m - 3\beta^2)}, \Delta t_c^{BB*} = \frac{n(4km - m\beta - 5k\beta^2) + km\beta(a - 2c_b)}{2km(2m - 3\beta^2)},$$
$$r^{BB*} = \frac{akm(3m - 2\beta^2) + n(m^2 + m\beta(3k - 4\beta) - 2k\beta^3) + 2kmc_b(m - 4\beta^2)}{2km(2m - 3\beta^2)},$$
$$\Pi_c^{BB*} = \frac{(akm)^2(m - \beta^2) + 2akmnA_4 + n^2A_5 - 4kmc_bA_6 + 4(kmc_b)^2(m - \beta^2)}{4k^2m(2m - 3\beta^2)^2}.$$

Proof See Appendix A. □

To ensure that all optimal decisions are positive, assume $k > \frac{m}{\beta}$ and $a > 2c_b$; or $k > \frac{m}{\beta}$, $a < 2c_b$ and $n > \frac{km(a-2c_b)}{m-k\beta}$; or $k < \frac{m}{\beta}$, $a > 2c_b$ and $n < \frac{km(a-2c_b)}{m-k\beta}$.

3.3 Model analysis

According to section 3.1, the models involve three cost-related parameters: the time value n associated with time cost, the investment cost coefficient m, and the blockchain operating cost c_b. When making decisions, both the port and the SP need to consider the impact of these three cost parameters. Therefore, we assume the triple cost parameter $G_g = (n, m, c_b)$, $g = 1, 2, 3$. $G_1 = n$, $G_2 = m$, $G_3 = c_b$. This section aims to analyze the influence of G_g on the optimal decisions of the port and the SP.

Proposition 5 *In Scenario NN*:

$$\frac{\partial w^{NN*}}{\partial n} < 0, \frac{\partial r^{NN*}}{\partial n} > 0, \frac{\partial Q^{NN*}}{\partial n} < 0, \frac{\partial \Pi_p^{NN*}}{\partial n} < 0, \frac{\partial \Pi_c^{NN*}}{\partial n} < 0.$$

Proof $\frac{\partial w^{NN*}}{\partial n} = \frac{-1}{2k}, \frac{\partial r^{NN*}}{\partial n} = \frac{1}{4k}, \frac{\partial Q^{NN*}}{\partial n} = \frac{-1}{4k}, \frac{\partial \Pi_p^{NN*}}{\partial n} = \frac{n-ak}{4k^2}, \frac{\partial \Pi_c^{NN*}}{\partial n} = \frac{n-ak}{8k^2}.$ □

In Scenario NN, as the time value increases, there is a subsequent decrease in the port's service price and market demand, resulting in a decline in the port's profit. Additionally, with an increase in the time value, the freight charges also increase, but this leads to a decrease in the overall profit of the SP.

Proposition 6 *In Scenario BN*:

$$\frac{\partial w^{BN*}}{\partial n} < 0, \frac{\partial w^{BN*}}{\partial m} < 0, \frac{\partial w^{BN*}}{\partial c_b}\begin{cases} < 0, \ if(m < \beta^2) \\ > 0, \ if(m > \beta^2) \end{cases}.$$

$$\frac{\partial r^{BN*}}{\partial n}\begin{cases} < 0, \ if(m < 2\beta^2) \\ > 0, \ if(m > 2\beta^2) \end{cases}, \frac{\partial r^{BN*}}{\partial m} < 0, \frac{\partial r^{BN*}}{\partial c_b}\begin{cases} < 0, \ if(m < 2\beta^2) \\ > 0, \ if(m > 2\beta^2) \end{cases}.$$

$$\frac{\partial \Pi_c^{BN*}}{\partial G_g}\begin{cases} < 0, \ if(k < k_{G_g}, c_b < a, n < n_1) or (k > k_{G_g}, c_b < a, n_{G_g} < n < n_1) \\ > 0, \ if(k > k_{G_g}, c_b < a, n < n_{G_g}) \end{cases},$$

$$\frac{\partial Q^{BN*}}{\partial G_g} < 0, \frac{\partial \Pi_p^{BN*}}{\partial G_g} < 0, g = 1, 2, 3.$$

Proof See Appendix A. □

According to Proposition 6, in Scenario BN, the port can consider increasing its investment in blockchain technology when the three cost parameters are lower. The implementation of blockchain technology enhances transparency and efficiency, which in turn helps the port attract more shippers and expand its market scale. Additionally, the improved service quality resulting from blockchain adoption enables the port to set higher service prices, thereby increasing profits. Moreover, when the investment cost coefficient is larger, the higher operating cost of blockchain prompts the port to adjust its service prices accordingly.

Furthermore, when the investment cost coefficient is larger, the freight charges increases due to higher time costs and blockchain operating costs. If the SP calls at the port with a smaller container handling capacity, referred to as a low-efficiency port (LP), the SP's profit increases as the cost parameter decreases. In contrast, if the SP calls at a high-efficiency port (HP), the SP should evaluate the time cost. Only when the time cost is high will the SP's profit increase as the cost parameters decrease.

Proposition 7 *In scenario NB: the impacts of m on r^{NB*} and Q^{NB*} are similar. Assume S_{cj}^{NB*} is the optimal decision of the SP in Proposition 3. $j = 1, 2$.*

$$\frac{\partial w^{NB*}}{\partial n}\begin{cases} <0, & if(k<k_1) \\ >0, & if(k>k_1) \end{cases}, \frac{\partial Q^{NB*}}{\partial n}\begin{cases} <0, & if(k<k_1) \\ >0, & if(k>k_1) \end{cases}.$$

$$\frac{\partial r^{NB*}}{\partial n}\begin{cases} <0, & if(m<2\beta^2, k>k_3) \\ >0, & if(m>2\beta^2) or (m<2\beta^2, k<k_3) \end{cases}.$$

$$\frac{\partial \Pi_p^{NB*}}{\partial n}\begin{cases} <0, & if(k<k_1, c_b<a, n<n_2) \\ >0, & if(k>k_1, c_b<a, n<n_3) or (k>k_1, c_b>a, n>n_2) \end{cases}.$$

$$\frac{\partial \Pi_c^{NB*}}{\partial n}\begin{cases} <0, & if(k<k_1, c_b<a, n<n_4) or (k>k_1, c_b>a, n_2<n<n_4) \\ >0, & if(k<k_1, c_b<a, n_4<n<n_2) or (k>k_1, c_b<a, n<n_3) \\ & or (k>k_1, c_b>a, n>n_4) \end{cases}.$$

$$\frac{\partial w^{NB*}}{\partial m}<0, \frac{\partial \Pi_p^{NB*}}{\partial m}\begin{cases} <0, & if(k<k_2, c_b<a, n<n_2) or (k>k_2, c_b<a, n<n_3) \\ & or (k>k_1, c_b>a, n>n_5) \\ >0, & if(k>k_1, c_b>a, n_2<n<n_5) \end{cases}.$$

$$\frac{\partial \Pi_c^{NB*}}{\partial m}<0, \frac{\partial S_{cj}^{NB*}}{\partial m}\begin{cases} <0, & if(k<k_1, c_b<a, n<n_2) or (k>k_{S_{cj}}^{NB*}, c_b<a, n<n_3) \\ & or (k>k_1, c_b>a, n>n_{S_{cj}}^{NB*}) \\ >0, & if(k>k_1, c_b>a, n_2<n<n_{S_{cj}}^{NB*}) \end{cases}.$$

$$\frac{\partial w^{NB*}}{\partial c_b}<0, \frac{\partial r^{NB*}}{\partial c_b}\begin{cases} <0, & if(m<2\beta^2) \\ >0, & if(m>2\beta^2) \end{cases}, \frac{\partial Q^{NB*}}{\partial c_b}<0, \frac{\partial \Pi_p^{NB*}}{\partial c_b}<0, \frac{\partial \Pi_c^{NB*}}{\partial c_b}<0.$$

Proof See Appendix A. □

According to Proposition 7, In Scenario NB, if the time value significantly impacts operations, the SP should cooperate with the HP and increase its investment in blockchain technology. Blockchain provides the SP with a competitive advantage by improving transparency and efficiency, leading to increased demand and profit. Even though the HP has not invested in blockchain, its profit will also increase due to market expansion.

The increase in investment and blockchain operating costs will reduce the SP's profit, thereby diminishing its willingness to adopt blockchain. The SP should carefully consider the trade-off between increased investment costs, blockchain operating costs, and the reduction in time costs.

Proof See Appendix A. □

Proposition 8 *In scenario BB: the impacts of m on w^{BB*}, Π_p^{BB*}, r^{BB*}, and Q^{BB*} are similar. Assume S_{pj}^{BB*} and S_{cj}^{BB*} are the optimal decisions of the port and the SP in Proposition 4, respectively. $j=1,2$. The result of $\frac{\partial S_{cj}^{BB*}}{\partial m}$ is similar to that of $\frac{\partial S_{pj}^{BB*}}{\partial m}$.*

$$\frac{\partial w^{BB*}}{\partial n}\begin{cases} <0, \ if(k<k_1) \\ >0, \ if(k>k_1) \end{cases}, \frac{\partial w^{BB*}}{\partial c_b}<0.$$

$$\frac{\partial \Pi_p^{BB*}}{\partial n}\begin{cases} <0, \ if(k<k_1, c_b<\frac{a}{2}, n<n_6) \\ >0, \ if(k>k_1, c_b<\frac{a}{2})or(k>k_1, c_b>\frac{a}{2}, n>n_6) \end{cases}, \frac{\partial \Pi_p^{BB*}}{\partial c_b}<0.$$

$$\frac{\partial r^{BB*}}{\partial n}\begin{cases} <0, \ if(\frac{3\beta^2}{2}<m<4\beta^2, k<k_4) \\ >0, \ if(m>4\beta^2)or(\frac{3\beta^2}{2}<m<4\beta^2, k>k_4) \end{cases}, \frac{\partial r^{BB*}}{\partial c_b}\begin{cases} <0, \ if(m<4\beta^2) \\ >0, \ if(m>4\beta^2) \end{cases}.$$

$$\frac{\partial Q^{BB*}}{\partial n}\begin{cases} <0, \ if(k<k_1) \\ >0, \ if(k>k_1) \end{cases}, \frac{\partial Q^{BB*}}{\partial c_b}<0.$$

$$\frac{\partial \Pi_c^{BB*}}{\partial n}\begin{cases} <0, \ if(k<k_5, c_b<\frac{a}{2}, n<n_6)or(k>k_1, c_b>\frac{a}{2}, n_6<n<n_7) \\ \quad or(k_5<k<k_6, c_b<\frac{a}{2}, n<n_7) \\ >0, \ if(k_5<k<k_6, c_b<\frac{a}{2}, n_7<n<n_6)or(k>k_6, c_b<\frac{a}{2}) \\ \quad or(k>k_1, c_b>\frac{a}{2}, n>n_7) \end{cases},$$

$$\frac{\partial \Pi_c^{BB*}}{\partial c_b}\begin{cases} <0, \ if(k<mk_6, c_b<\frac{a}{2}, n<n_6)or(k>k_1, c_b>\frac{a}{2}, n>n_8) \\ \quad or(k>mk_6, c_b<\frac{a}{2}) \\ >0, \ if(k>k_1, c_b>\frac{a}{2}, n_6<n<n_8) \end{cases}.$$

$$\frac{\partial S_{pj}^{BB*}}{\partial m}\begin{cases} <0, \ if(k<k_{S_{pj}}^{BB*}, c_b<\frac{a}{2}, n<n_6)or(k>k_{S_{Pj}}^{BB*}, c_b<\frac{a}{2}) \\ \quad or(k>k_1, c_b>\frac{a}{2}, n>n_{S_{pj}}^{BB*}) \\ >0, \ if(k>k_1, n_6<n<n_{S_{pj}}^{BB*}) \end{cases}, \frac{\partial \Pi_c^{BB*}}{\partial m}<0.$$

According to Proposition 8, in Scenario BB, the profit of the HP increases as the time cost increases, while the profit of the LP decreases under the same circumstances. The impact of blockchain operating costs on port profit is negative, meaning that higher blockchain operating costs result in lower port profits.

When the SP calls at the LP and the time cost is lower, the SP's profit increases as the time cost decreases. Similarly, When the blockchain operating cost is low, the SP's profit increases as the blockchain operating cost decreases, regardless of the port's efficiency. We have observed that cooperation in blockchain investment between the HP and the high-time-value SP can benefit both parties. The LP should cooperate with the low-time-value SP to invest in blockchain in order to increase profits. In particular, when the blockchain operating cost is low and the time value is high, the SP should actively promote joint investment in blockchain technology with the port, regardless of the port's efficiency.

The investment cost has the same impact on port and SP profits. When the container handling capacity and the time cost are high the impact is negative.

4 Comparisons

4.1 Comparisons of SP strategies

The performance of the SP varies across different port strategies. Therefore, this section compares the freight, demand, and profit of the SP under different strategies.

First, we analyze the equilibrium decisions of the SP when the port adopts Strategy N. Proposition 9 provides a comparison of the optimal SP decisions between Scenario NB and Scenario NN.

Proposition 9 *When any condition in* $(9a_1)$ *is satisfied,* $r^{NB*} < r^{NN*}$; *when any condition in* $(9a_2)$ *is satisfied,* $r^{NB*} > r^{NN*}$. *When any condition in* $(9b_1)$ *is satisfied,* $Q^{NB*} < Q^{NN*}$; *when any condition in* $(9b_2)$ *is satisfied,* $Q^{NB*} > Q^{NN*}$. *When condition* $(9c_1)$ *is satisfied,* $\Pi_c^{NB*} < \Pi_c^{NN*}$; *when any condition in* $(9c_2)$ *is satisfied,* $\Pi_c^{NB*} > \Pi_c^{NN*}$. *In the cases of* $(9c_1)$ *and* $(9c_2)$, *the following conditions need to be met*: $c_b \in (0, a)$ *and* $n \in (0, min(n_3, n_2))$; *or* $k \in (k_1, \infty)$, $c_b \in (a, \frac{k\beta a}{m})$ *and* $n \in (n_2, n_3)$.

$$(9a_1)\begin{cases} condition1 : k \in (k_1, \infty), c_b \in (0, a), n \in (0, n_9) \\ condition2 : k \in (0, k_1), c_b \in (0, a), n \in (n_9, min(n_3, n_2)) \end{cases};$$

$$(9a_2)\begin{cases} condition1 : k \in (k_1, \infty), c_b \in (0, \frac{k\beta a}{m}), n \in (max(n_2, n_9), n_3) \\ condition2 : k \in (0, k_1), c_b \in (0, a), n \in (0, min(n_9, n_3, n_2)) \end{cases};$$

$$(9b_1)\begin{cases} condition1 : k \in (\beta, \infty), c_b \in (0, a), n \in (0, min(n_3, n_2, n_{10}) \\ condition2 : c_b \in (min(a, \frac{k\beta a}{m}), max(a, \frac{k\beta a}{m})), n \in (min(n_{10}, n_2), max(n_{10}, n_2)) \end{cases};$$

$$(9b_2)\begin{cases} condition1 : k \in (\beta, \infty), c_b \in (0, \frac{k\beta a}{m}), n \in (n_{10}, n_3) \\ condition2 : k \in (0, \beta), c_b \in (0, a), n \in (0, min(n_{10}, n_3)) \end{cases};$$

$$(9c_1)\{\, c_b \in (c_{b1}, c_{b2}), n \in (0, n_{11})\ ;$$

$$(9c_2)\begin{cases} condition1 : c_b \in (0, c_{b1}) \cup (c_{b2}, \infty), n \in (0, n_{11}) \\ condition2 : n \in (n_{11}, \infty) \end{cases}.$$

Proof See Appendix A. □

Proposition 9 states that when the SP's time value is low, the SP calling at the HP will experience higher freight and demand under Scenario NN. Conversely, the SP calling at the LP will have higher freight and demand under Scenario NB. Since the SP's time value is relatively low, the efficiency of the port has minimal impact. The HP's service level, even without blockchain technology, can meet the SP's needs. However, the LP provides a lower level of service, necessitating the adoption of blockchain technology by the SP to improve its competitive advantage.

The comparison of profits primarily depends on the SP's time value and the blockchain operating cost. When the time value is small and the blockchain operating cost is either smaller or larger, the SP's profit under Scenario NB exceeds that under Scenario NN. A higher time value indicates that improving operational efficiency is crucial for the SP. In such cases, regardless of the high blockchain operating cost, the SP's profit under Scenario NB will be greater.

Moreover, we analyze the comparison of the optimal SP decisions between Scenario BB and Scenario BN. The results are shown in Proposition 10.

Proposition 10 *When any condition in* $(10a_1)$ *is satisfied,* $r^{BB*} < r^{BN*}$; *when any condition in* $(10a_2)$ *is satisfied,* $r^{BB*} > r^{BN*}$. *When any condition in* $(10b_1)$ *is satisfied,* $Q^{BB*} < Q^{BN*}$; *when any condition in* $(10b_2)$ *is satisfied,* $Q^{BB*} > Q^{BN*}$. *When condition* $(10c_1)$ *is satisfied,* $\Pi_c^{BB*} < \Pi_c^{BN*}$; *when any condition in* $(10c_2)$ *is satisfied,* $\Pi_c^{BB*} > \Pi_c^{BN*}$. *In the cases of* $(10c_1)$ *and* $(10c_2)$, *the following conditions need to be met:* $c_b \in (0, \frac{a}{2})$ *and* $n \in (0, min(n_1, n_6))$; *or* $k \in (k_1, \infty)$, $c_b \in (\frac{a}{2}, \frac{k\beta a}{k\beta+m})$ *and* $n \in (n_6, n_1)$.

$$(10a_1)\begin{cases} condition1 : c_b \in (0, \frac{k\beta a}{k\beta+m}), n \in (max(0, n_6), min(n_{12}, n_1)) \\ condition2 : k \in (0, k_1), c_b \in (\frac{a}{2}, \frac{k\beta a}{k\beta+m}), n \in (n_{12}, min(n_6, n_1)) \end{cases};$$

$$(10a_2)\begin{cases} condition1 : k \in (k_1, \infty), c_b \in (0, \frac{k\beta a}{k\beta+m}), n \in (max(n_{12}, n_6), n_1) \\ condition2 : k \in (0, k_1), c_b \in (0, \frac{a}{2}), n \in (0, min(n_{12}, n_6, n_1)) \end{cases};$$

$$(10b_1)\begin{cases} condition1 : k \in (0, k_1), c_b \in (0, \frac{a}{2}), n \in (n_{13}, min(n_6, n_1) \\ condition2 : k \in (k_1, \infty), c_b \in (0, \frac{a}{2}), n \in (0, min(n_{13}, n_1)) \end{cases};$$

$$(10b_2)\begin{cases} condition1 : k \in (0, k_1), c_b \in (0, \frac{a}{2}), n \in (0, min(n_{13}, n_1)) \\ condition2 : k \in (k_1, \infty), c_b \in (0, \frac{k\beta a}{k\beta+m}), n \in (max(n_{13}, n_6), n_1) \end{cases};$$

$$(10c_1)\{ c_b \in (c_{b3}, c_{b4}), n \in (0, n_{14}) ;$$

$$(10c_2)\begin{cases} condition1 : c_b \in (0, c_{b3}) \cup (c_{b4}, \infty), n \in (0, n_{14}) \\ condition2 : n \in (n_{14}, \infty) \end{cases}.$$

Proof See Appendix A. □

The analysis results of Proposition 10 are the same as those of Proposition 9, therefore, we will not explain them in detail.

4.2 Comparisons of port strategies

We also analyze the preferences of the port when the SP adopts different strategies. Therefore, this section compares the service price, demand, and profit of the port under different strategies. Firstly, we analyze the comparison of the optimal port decisions between Scenario BN and Scenario NN.

Proposition 11 $w^{BN*} > w^{NN*}$; *when any condition in* $(11a_1)$ *is satisfied,* $Q^{BN*} < Q^{NN*}$; *When the condition in* $(11a_2)$ *is satisfied,* $Q^{BN*} > Q^{NN*}$; *when the condition in* $(11b_1)$ *is satisfied,* $\Pi_p^{BN*} < \Pi_p^{NN*}$; *When the condition in* $(11b_2)$ *is satisfied,* $\Pi_p^{BN*} > \Pi_p^{NN*}$.

$$(11a_1)\begin{cases} condition1\ :\ c_b \in (\frac{\beta^2 a}{2m}, a), n \in (0, n_1) \\ condition2\ :\ c_b \in (0, \frac{\beta^2 a}{2m}), n \in (n_{15}, n_1) \end{cases};$$

$$(11a_2)\{\ c_b \in (0, \frac{\beta^2 a}{2m}), n \in (0, n_{15})\ .$$

$$(11b_1)\{\ c_b \in (c_{b5}, min(a, c_{b6})), n \in (0, n_{15})\ ;$$

$$(11b_2)\{\ c_b \in (0, c_{b5}) \cup (min(c_{b6}, a), a), n \in (0, n_{15})\ .$$

Proof See Appendix A. □

Proposition 11 demonstrates that in Scenario BN, the port should set higher service prices. The comparison of demand and profit for the port between Scenario NN and Scenario BN depends on factors such as blockchain operating costs, basic market demand, and time value. When the blockchain operating cost exceeds a certain threshold, the increased port service price due to the high blockchain operating cost places a burden on shippers, which reduces the port's demand. However, when the blockchain operating cost is below this threshold and the time value is low, Scenario BN attracts more shippers and increases the port's demand. As a result, Scenario BN enhances the port's profit under either a smaller or larger blockchain operating cost.

Then, the comparison of the optimal port decisions between Scenario BB and Scenario NB is as follows:

Proposition 12 $w^{BB*} > w^{NB*}$; *when any condition in* $(12a_1)$ *is satisfied*, $Q^{BB*} < Q^{NB*}$; *When any condition in* $(12a_2)$ *is satisfied*, $Q^{BB*} > Q^{NB*}$; *when any condition in* $(12b_1)$ *is satisfied*, $\Pi_p^{BB*} < \Pi_p^{NB*}$; *when any condition in* $(12b_2)$ *is satisfied*, $\Pi_p^{BB*} > \Pi_p^{NB*}$.

$$(12a_1)\begin{cases} condition1\ :\ k \in (k_1, \infty), c_b \in (0, \frac{a}{2}), n \in (0, n_{16}) \\ condition2\ :\ k \in (0, k_1), c_b \in (0, \frac{a}{2}), n \in (n_{16}, n_6) \end{cases};$$

$$(12a_2)\begin{cases} condition1\ :\ k \in (k_1, \infty), c_b \in (0, \frac{a}{2}) \cup (a, \infty), n \in (max(n_6, n_{16}), \infty) \\ condition2\ :\ k \in (0, k_1), c_b \in (0, \frac{a}{2}), n \in (0, n_{16}) \end{cases}.$$

$$(12b_1)\begin{cases} condition1\ :\ k \in (0, k_1), c_b \in (c_{b7}, min(c_{b8}, \frac{a}{2})), n \in (0, n_6) \\ condition2\ :\ k \in (k_1, \infty), c_b \in (a, min(c_{b8}, a)), n \in (n_6, \infty) \end{cases};$$

$$(12b_2)\begin{cases} condition1\ :\ k \in (0, k_1), c_b \in (0, c_{b7}) \cup (min(c_{b8}, \frac{a}{2}), \frac{a}{2}), n \in (0, n_6) \\ condition2\ :\ k \in (k_1, \infty), c_b \in (max(c_{b8}, a), \infty), n \in (n_6, \infty) \end{cases}.$$

Proof See Appendix A. □

Proposition 12 demonstrates that the port in Scenario BB should sell its services at a higher price. Based on Propositions 11 and 12, we can conclude that, regardless of the strategy adopted by the SP, the port service price under Strategy B must exceed that under Strategy N.

The comparison of demand and profit depends on several factors: blockchain operating cost, basic market demand, port container handling capacity, and the time value. For the HP, a larger time value emphasizes the importance of improving efficiency through blockchain technology. In this case, the port in Scenario BB shortens the time spent on handling the shipper's cargo, thus attracting more cargo. Conversely, for the LP, Scenario NB can attract more sources of goods when the time value is higher. Compared to the HP, the LP provides lower-quality service. If blockchain technology is adopted, the service price of the LP will rise. Although both the time cost and the port service price are costs incurred by the SP, they are ultimately transferred to the shipper through the SP's freight rate. Therefore, when the time cost is high, shippers may be unable to afford the higher port service price. In such cases, Scenario NB with a lower price will attract more shippers.

As for the HP, the profit in Scenario BB is higher when the blockchain operating cost is greater. For ports with low efficiency levels, the profit in Scenario BB is higher when the blockchain operating cost is either smaller or larger.

5 Numerical experiment

This section analyzes the impact of different cost parameters on the preferences of the port and the SP regarding blockchain technology through numerical experiments. Its purpose is twofold: first, to validate certain propositions from Section 4, and second, to to offer additional management insights for the port and the SP. To enable a quantitative comparison of profits under different strategies, we set values for other parameters. We utilize data from Song et al. (2018) for numerical experiments, with the following reference data: $a = 30$, $\beta = 1$, and $k = 3$. According to Propositions 9–12, the results of the profit comparison are related to $k_1 = \frac{m}{\beta}$, that is, $m = k\beta = 3$. Thus, we conduct empirical analyses for $m = 4$ and $m = 2$. Figures 2 and 3 illustrate the strategic choices of the port and the SP when $m = 4$.

Figure 2 depicts the changing strategy of the port in response to variations in n and c_b. Area (1) indicates that when c_b is low, the port can benefit from blockchain technology regardless of the SP's investment. The port should take the lead in promoting blockchain adoption in the maritime supply chain. As c_b and n increase, the port's investment in blockchain depends the SP's strategy, as demonstrated in Areas (2) and (3). If the SP invests in blockchain, the port follows suit. If the SP abstains from blockchain, the port does the same. When c_b reaches a certain threshold, the port abstains from blockchain, irrespective of the SP's strategy. At this point, the market expansion brought by blockchain technology is insufficient to justify the high investment cost for the port. In particular, in Areas (4) and (5), the port can "free ride" on the SP to benefit from blockchain. Meanwhile, we observe that n has minimal direct impact on port decision-making but can influence the range of c_b that determines port decisions. Therefore, the impact of n on port decision-making is indirect.

Figure 3 illustrates the changing strategy of the SP in response to variations in n and c_b. In Areas (1) and (3), the SP's decisions align with the port's strategy: both invest in blockchain or both refrain from it. This occurs when n

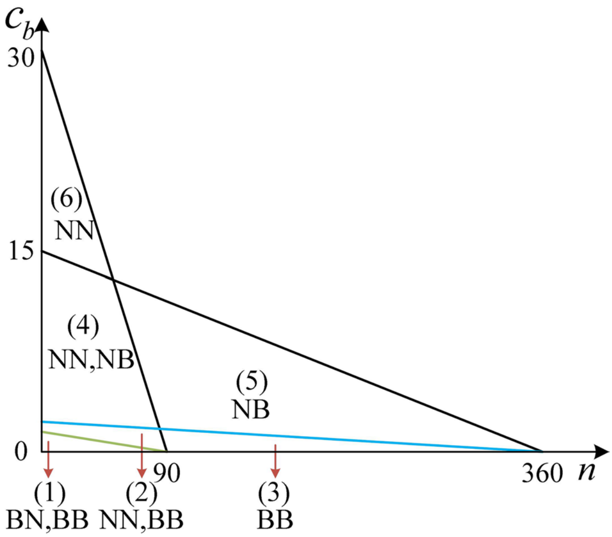

Fig. 2 The port's strategic choice, $m = 4$

and c_b are relatively low. In Area (2), the SP always makes the opposite decision to the port. If the port invests in blockchain, the SP "free rides" on the the port's investment to reap the benefits. In contrast, if the port does not invest in blockchain, the SP must increase the port efficiency by investing in blockchain to attract more shippers. In Area (4), regardless of the port's strategy, the SP chooses Strategy N. This implies that the SP can tolerate congestion costs but

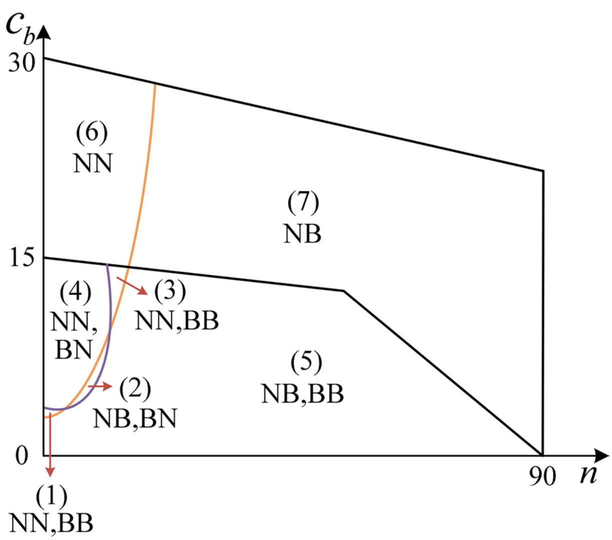

Fig. 3 SP's strategic choice, $m = 4$

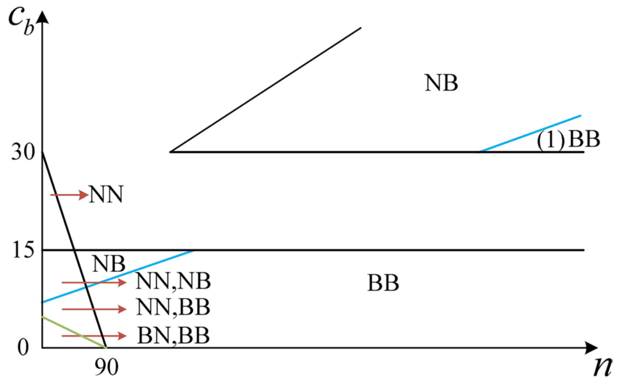

Fig. 4 The port's strategic choice, $m = 2$

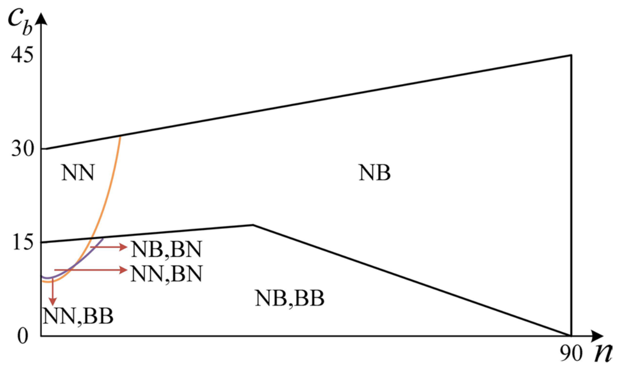

Fig. 5 SP's strategic choice, $m = 2$

not the blockchain operating costs in this area. As shown in Area (5), an increase in the SP's time value intensifies the impact of congestion costs, prompting the SP to enhance blockchain investment to reduce congestion time. The SP should take the lead in promoting blockchain adoption. Comparing Areas (4), (5), (6), and (7), we find that an increase in n leads to a shift in the SP's strategy from Strategy N to Strategy B, whereas a decline in c_b does not produce this change. Therefore, for the SP, the negative effect of increased blockchain operating costs is less significant than the negative effect of increased the time costs.

Next, we analyze the strategic choices of the port and the SP when $m = 2$.

In comparison to Figs. 2 and 3, the range of c_b in Figs. 4 and 5 is broader, which means that the reduction in investment costs has improved the acceptance of higher blockchain operating costs for both the port and the SP. The majority of strategic choices for the port and the SP align with those in Figs. 2 and 3. In Fig. 4, the area representing Strategy BB is larger than in Fig. 2, while the area for Strategy NN is smaller. Similarly, in Fig. 5, the areas for the SP's Strategy NB and Strategy BB are larger compared to Fig. 3. These changes can be attributed to the decrease in investment costs. Moreover, in Area (1), despite larger values of both c_b and n, Strategy BB remains the optimal decision for the port. The cargo volume attracted by blockchain technology has a positive effect on the port's revenue. The operating costs and investment cost of blockchain technology harm port revenue. In this scenario, the positive effect of lower investment costs outweighs the negative effect, prompting the port to choose Strategy BB.

According to Figs. 2, 3, 4 and 5, the equilibrium choices of the port and the SP are obtained in the Fig. 6 and the Fig. 7.

As shown in Fig. 6, we observe that the equilibrium strategy is Strategy BB only when the blockchain operating cost is low. The port and the SP should cooperate and invest in blockchain technology to benefit both parties. As the blockchain operating cost increases, the equilibrium strategy of the port and the SP depends on the time value. A lower time value means that the congestion cost has

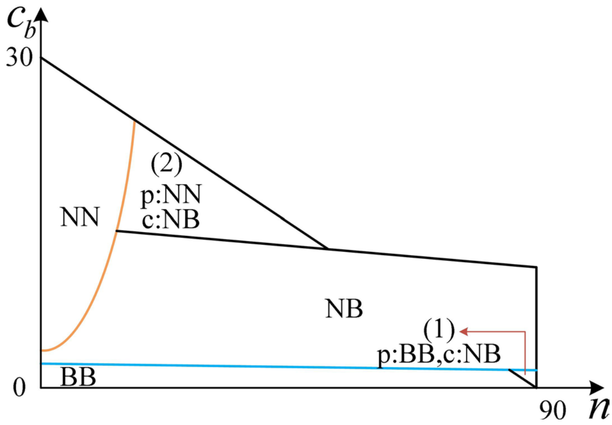

Fig. 6 Equilibrium choices of the port and the SP, $m = 4$

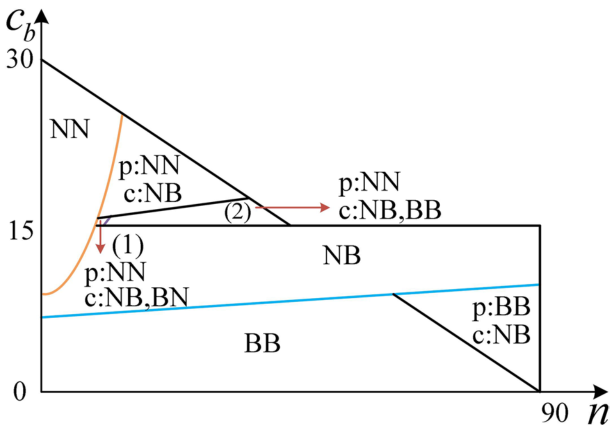

Fig. 7 Equilibrium choices of the port and the SP, $m = 2$

little effect, resulting in the equilibrium strategy being Strategy NN. An increase in the time value makes the congestion costs more significant for the SP, leading to the equilibrium strategy becoming Strategy NB. Notably, in Areas (1) and (2), the optimal strategies for the port and the SP differ. The optimal strategy for the port depends on the blockchain operating cost, while the optimal strategy for the SP depends on the time value. This finding is consistent with our previous conclusion. The time value is higher in Areas (1) and (2), indicating that the SP places greater emphasis on the efficiency improvements brought about by blockchain technology. Even if the port does not invest in blockchain, the SP will take the lead in adopting it.

Most of the equilibrium choices for the port and the SP in Fig. 7 are consistent with those in Fig. 6. However, in Areas (1) and (2) of Fig. 7, the optimal strategy choice for the SP differs. The blockchain operating costs in these two areas are moderate. In Area (1), the SP no longer ignores the congestion cost, making it necessary to utilize blockchain technology to reduce congestion time. However, the congestion cost is not yet burdensome enough for the SP. Therefore, if the port adopts blockchain technology, the SP will "free ride". As the congestion cost increases, the SP must take the lead in adopting blockchain. Consequently, in Area (2), the SP will invest in blockchain regardless of whether the port adopts it or not (Fig. 7).

6 Conclusion

The development of blockchain technology can effectively facilitate the digital transformation of the maritime industry. This paper aims to enhance the application of blockchain in the shipping supply chain, by considering the cost burden and positive outcomes associated with its adoption. A vertical game model is constructed to analyze the roles of various maritime stakeholders.

First, we consider four scenarios according to whether the port and the SP adopt blockchain: Scenario NN, Scenario BN, Scenario NB, and Scenario BB. Game models are then constructed for each scenario, incorporating the efficiency, transparency, and cost burden associated with blockchain. Furthermore, we examine the impacts of time cost, blockchain operating cost, and investment cost on the motivation of the port and the SP to adopt blockchain. The research indicates that the high-time-value SP should promote co-investment in blockchain technology with the HP, while the low-time-value SP should cooperate with the LP to invest in blockchain for increased profitability.

In addition, we compare decision-making outcomes across different scenarios to determine the equilibrium strategy for the port and the SP. The leading role of, and "free-ride" behavior by, the port and the SP regarding blockchain investment are explained through numerical experiments. It is observed that both the port and the SP invest in blockchain technology when the blockchain operating cost is low. However, when the blockchain operating cost is high, the increase in the market size attracted by blockchain technology is insufficient to offset the significant investment and operating costs, leading the port to abstain from investing in blockchain. As the time value increases, the SP assumes a leading role, while the port "free rides". The SP's motive for "free-riding" only exists when the time cost is not high. The reduction in investment cost has increased the port's and the SP's acceptance of blockchain.

Based on the findings of this paper, ports and SPs can make informed decisions on whether to invest in blockchain technology by weighing multiple costs and their circumstances. Additionally, ports and SPs can also judge whether there is a motive for "free-riding" or co-investment. In summary, we provide decision-making recommendations for ports and SPs regarding blockchain investment. Future research could explore multiple interactions and investment risk factors among stakeholders.

Appendix A Proof

Proof Proof of Proposition 1. $\frac{\partial^2\Pi_p^{NN}}{\partial^2 w} = -1 < 0, \frac{\partial^2\Pi_c^{NN}}{\partial^2 r} = -2 < 0.$ □

Therefore, Proposition 1 is proven.

Proof Proof of Proposition 2. For the port, the Hessian matrix is

$$\begin{pmatrix} \frac{\partial^2\Pi_p^{BN}}{\partial^2 w} & \frac{\partial^2\Pi_p^{BN}}{\partial w \partial e_p} & \frac{\partial^2\Pi_p^{BN}}{\partial w \partial \Delta t_p} \\ \frac{\partial^2\Pi_p^{BN}}{\partial e_p \partial w} & \frac{\partial^2\Pi_p^{BN}}{\partial^2 e_p} & \frac{\partial^2\Pi_p^{BN}}{\partial e_p \partial \Delta t_p} \\ \frac{\partial^2\Pi_p^{BN}}{\partial \Delta t_p \partial w} & \frac{\partial^2\Pi_p^{BN}}{\partial \Delta t_p \partial e_p} & \frac{\partial^2\Pi_p^{BN}}{\partial^2 \Delta t_p} \end{pmatrix} = \begin{pmatrix} -1 & \frac{\beta}{2} & \frac{\beta}{2} \\ \frac{\beta}{2} & -m & 0 \\ \frac{\beta}{2} & 0 & -m \end{pmatrix}.$$

□

When $m > \frac{\beta^2}{2}$, the first order leading principal minor $H_1 = -1 < 0$; the second order leading principal minor $H_2 = m - \frac{\beta^2}{4} > 0$; the third order leading principal minor $H_3 = m(\frac{\beta^2}{2} - m) < 0$. The Hessian matrix is negative definite, and thus the profit maximization problem has a unique optimal solution (Peng and Wang 2022; Liu and Wang 2019; Sheng et al. 2017). For the SP, $\frac{\partial^2\Pi_c^{BN}}{\partial^2 r} = -2 < 0$. Therefore, Proposition 2 is proven.

Proof Proof of Proposition 3. For the port, $\frac{\partial^2\Pi_p^{NB}}{\partial^2 w}=\frac{-m}{m-\beta^2}$. When $m>\beta^2$ we obtain, $\frac{\partial^2\Pi_p^{NB}}{\partial^2 w}<0$. For the SP, the Hessian matrix is

$$\begin{pmatrix}\frac{\partial^2\Pi_c^{NB}}{\partial^2 r} & \frac{\partial^2\Pi_c^{NB}}{\partial r\partial e_c} & \frac{\partial^2\Pi_c^{NB}}{\partial r\partial \Delta t_c}\\ \frac{\partial^2\Pi_c^{NB}}{\partial e_c\partial r} & \frac{\partial^2\Pi_c^{NB}}{\partial^2 e_c} & \frac{\partial^2\Pi_c^{NB}}{\partial e_c\partial \Delta t_c}\\ \frac{\partial^2\Pi_c^{NB}}{\partial \Delta t_c\partial r} & \frac{\partial^2\Pi_c^{NB}}{\partial \Delta t_c\partial e_c} & \frac{\partial^2\Pi_c^{NB}}{\partial^2 \Delta t_c}\end{pmatrix}=\begin{pmatrix}-2 & \beta & \beta\\ \beta & -m & 0\\ \beta & 0 & -m\end{pmatrix}.$$

□

Similar to the proof of proposition 2, when $m>\beta^2$, the Hessian matrix is negative definite.

Proof Proof of Proposition 4. For the port, the Hessian matrix is

$$\begin{pmatrix}\frac{\partial^2\Pi_p^{BB}}{\partial^2 w} & \frac{\partial^2\Pi_p^{BB}}{\partial w\partial e_p} & \frac{\partial^2\Pi_p^{BB}}{\partial w\partial \Delta t_p}\\ \frac{\partial^2\Pi_p^{BB}}{\partial e_p\partial w} & \frac{\partial^2\Pi_p^{BB}}{\partial^2 e_p} & \frac{\partial^2\Pi_p^{BB}}{\partial e_p\partial \Delta t_p}\\ \frac{\partial^2\Pi_p^{BB}}{\partial \Delta t_p\partial w} & \frac{\partial^2\Pi_p^{BB}}{\partial \Delta t_p\partial e_p} & \frac{\partial^2\Pi_p^{BB}}{\partial^2 \Delta t_p}\end{pmatrix}=\begin{pmatrix}\frac{-m}{m-\beta^2} & \frac{m\beta}{2(m-\beta^2)} & \frac{m\beta}{2(m-\beta^2)}\\ \frac{m\beta}{2(m-\beta^2)} & -m & 0\\ \frac{m\beta}{2(m-\beta^2)} & 0 & -m\end{pmatrix}.$$

□

Similar to the proof of proposition 2, when $m>\frac{3\beta^2}{2}$, the Hessian matrix is negative definite. For the SP, the Hessian matrix is similar to Proposition 3.

Proof Proof of Proposition 6.

$$\frac{\partial w^{BN*}}{\partial n}=\frac{-m}{k(2m-\beta^2)};\frac{\partial w^{BN*}}{\partial m}=\frac{-\beta^2(ak-n-kc_b)}{k(2m-\beta^2)^2};\frac{\partial w^{BN*}}{\partial c_b}=\frac{m-\beta^2}{2m-\beta^2}.$$

$$\frac{\partial Q^{BN*}}{\partial n}=\frac{-m}{2k(2m-\beta^2)};\frac{\partial Q^{BN*}}{\partial m}=\frac{-\beta^2(ak-n-kc_b)}{2k(2m-\beta^2)^2};\frac{\partial Q^{BN*}}{\partial c_b}=\frac{-m}{2(2m-\beta^2)}.$$

$$\frac{\partial \Pi_p^{BN*}}{\partial n}=\frac{-m(ak-n-kc_b)}{2k^2(2m-\beta^2)};\frac{\partial \Pi_p^{BN*}}{\partial m}=\frac{-\beta^2(ak-n-kc_b)^2}{4k^2(2m-\beta^2)^2};\frac{\partial \Pi_p^{BN*}}{\partial c_b}=\frac{1}{k}\left(\frac{\partial \Pi_p^{BN*}}{\partial n}\right).$$

$$\frac{\partial r^{BN*}}{\partial n}=\frac{m-2\beta^2}{2k(2m-\beta^2)};\frac{\partial r^{BN*}}{\partial m}=\frac{-3\beta^2(ak-n-kc_b)}{2k(2m-\beta^2)^2};\frac{\partial r^{BN*}}{\partial c_b}=\frac{m-2\beta^2}{2(2m-\beta^2)}.$$

$$\frac{\partial \Pi_c^{BN*}}{\partial n}=\frac{2n(m^2-4km\beta+2k\beta^3)+2k(m^2-2km\beta+k\beta^3)(c_b-a)}{4k^2(2m-\beta^2)^2};$$

$$\frac{\partial \Pi_c^{BN*}}{\partial m}=\frac{\beta(ak-n-kc_b)(n(-4km+m\beta+2k\beta^2)+km\beta(c_b-a))}{2k^2(2m-\beta^2)^3};$$

$$\frac{\partial \Pi_c^{BN*}}{\partial c_b}=\frac{n(m^2-2km\beta+k\beta^3)+km^2(c_b-a)}{2k(2m-\beta^2)^2}.$$

□

Let $\frac{\partial \Pi_c^{BN*}}{\partial n} = 0$, $n = \frac{k(m^2-2km\beta+k\beta^3)(a-c_b)}{m^2-4km\beta+2k\beta^3}$. When $k < \frac{m^2}{2\beta(2m-\beta^2)}$. $\frac{\partial \Pi_c^{BN*}}{\partial n} \lesseqgtr 0$, if $n \lesseqgtr \frac{k(m^2-2km\beta+k\beta^3)(a-c_b)}{m^2-4km\beta+2k\beta^3}$. At this time, $\frac{(m^2-2km\beta+k\beta^3)(ak-c_bk)}{m^2-4km\beta+2k\beta^3} - (ak - kc_b) = \frac{k\beta(2m-\beta^2)(ak-c_bk)}{m^2-4km\beta+2k\beta^3} > 0$. When $k > \frac{m^2}{2\beta(2m-\beta^2)}$, the results are the opposite. The proofs of Proposition 7 and Proposition 8 are similar to Proposition 6.

Proof Proof of Proposition 7.

$$\frac{\partial w^{NB*}}{\partial n} = \frac{-m+k\beta}{2km}; \frac{\partial w^{NB*}}{\partial m} = \frac{-n\beta}{2m^2}; \frac{\partial w^{NB*}}{\partial c_b} = \frac{-1}{2}.$$

$$\frac{\partial Q^{NB*}}{\partial n} = \frac{-m+k\beta}{4k(m-\beta^2)}; \frac{\partial Q^{NB*}}{\partial m} = \frac{\beta(n(\beta-k)+k\beta(c_b-a))}{4k(m-\beta^2)^2}; \frac{\partial Q^{NB*}}{\partial c_b} = \frac{-km}{4k(m-\beta^2)}.$$

$$\frac{\partial \Pi_p^{NB*}}{\partial n} = \frac{2(m-k\beta)(n(m-k\beta)+km(c_b-a))}{8k^2m(m-\beta^2)};$$

$$\frac{\partial \Pi_p^{NB*}}{\partial m} = \frac{-\beta(n(m-k\beta)+km(c_b-a))(n(-2km+m\beta+k\beta^2)+km\beta(c_b-a))}{8k^2m^2(m-\beta^2)^2};$$

$$\frac{\partial \Pi_p^{NB*}}{\partial c_b} = \frac{2km(n(m-k\beta)+km(c_b-a))}{8k^2m(m-\beta^2)}.$$

$$\frac{\partial r^{NB*}}{\partial n} = \frac{m^2-2m\beta^2+k\beta(3m-2\beta^2)}{4km(m-\beta^2)}; \frac{\partial r^{NB*}}{\partial c_b} = \frac{m-2\beta^2}{4(m-\beta^2)};$$

$$\frac{\partial r^{NB*}}{\partial m} = \frac{n(m^2\beta+k(-3m^2+4m\beta^2-2\beta^4))+km^2\beta(c_b-a)}{4km^2(m-\beta^2)^2}.$$

$$\frac{\partial \Pi_c^{NB*}}{\partial n} = \frac{n(m^2-2km\beta+k^2(8m-\beta^2))+km(m-k\beta)(c_b-a)}{8k^2m(m-\beta^2)};$$

$$\frac{\partial \Pi_c^{NB*}}{\partial m} = \frac{-F_1(c_b)}{16k^2m^2(m-\beta^2)^2}; \frac{\partial \Pi_c^{NB*}}{\partial c_b} = \frac{n(m-k\beta)+km(c_b-a)}{8k(m-\beta^2)}.$$

□

Proof Proof of Proposition 8.

$$\frac{\partial w^{BB*}}{\partial n}=\frac{(-m+k\beta)(m-\beta^2)}{km(2m-3\beta^2)};\frac{\partial w^{BB*}}{\partial c_b}=\frac{-\beta^2}{2m-3\beta^2};$$
$$\frac{\partial w^{BB*}}{\partial m}=\frac{\beta(n(m^2\beta-k(2m^2-4m\beta^2+3\beta^4))+km^2\beta(2c_b-a))}{km^2(2m-3\beta^2)^2}.$$
$$\frac{\partial Q^{BB*}}{\partial n}=\frac{-m+k\beta}{2k(2m-3\beta^2)};\frac{\partial Q^{BB*}}{\partial c_b}=\frac{-m}{2m-3\beta^2};$$
$$\frac{\partial Q^{BB*}}{\partial m}=\frac{\beta(n(3\beta-2k)+3k\beta(2c_b-a))}{2k(2m-3\beta^2)^2}.$$
$$\frac{\partial \Pi_p^{BB*}}{\partial n}=\frac{(m-k\beta)(n(m-k\beta)+km(2c_b-a))}{2k^2m(2m-3\beta^2)};\frac{\partial \Pi_p^{BB*}}{\partial c_b}=\frac{n(m-k\beta)+km(2c_b-a)}{k(2m-3\beta^2)};$$
$$\frac{\partial \Pi_p^{BB*}}{\partial m}=\frac{-\beta(n(m-k\beta)+km(2c_b-a))(n(-4km+3m\beta+3k\beta^2)+3km\beta(2c_b-a))}{4k^2m^2(2m-3\beta^2)^2}.$$
$$\frac{\partial r^{BB*}}{\partial n}=\frac{m^2-4m\beta^2+k\beta(3m-2\beta^2)}{2km(2m-3\beta^2)};\frac{\partial r^{BB*}}{\partial c_b}=\frac{m-4\beta^2}{2m-3\beta^2};$$
$$\frac{\partial r^{BB*}}{\partial m}=\frac{\beta(n(5m^2\beta-k(6m^2-8m\beta^2+6\beta^4))+5km^2\beta(2c_b-a))}{2km^2(2m-3\beta^2)^2}.$$
$$\frac{\partial \Pi_c^{BB*}}{\partial n}=\frac{nH_2+km(m(m-\beta^2)-k\beta(3m-4\beta^2))(2c_b-a)}{4k^2m(2m-3\beta^2)^2};$$
$$\frac{\partial \Pi_c^{BB*}}{\partial m}=\frac{-F_2(c_b)}{4k^2m^2(2m-3\beta^2)^3};$$
$$\frac{\partial \Pi_c^{BB*}}{\partial c_b}=\frac{n(m(m-\beta^2)-k\beta(3m-4\beta^2))+km(m-\beta^2)(2c_b-a)}{k(2m-3\beta^2)^2}.$$

□

Proof Proof of Proposition 9.

$$r^{NB*} - r^{NN*} = \frac{akm\beta^2 + n\beta(3km - m\beta - 2k\beta^2) + kmc_b(m - 2\beta^2)}{4km(m - \beta^2)};$$

$$Q^{NB*} - Q^{NN*} = \frac{kn\beta + (ak - n)\beta^2 - kmc_b}{4k(m - \beta^2)};$$

$$\Pi_c^{NB*} - \Pi_c^{NN*} = \frac{(ak\beta)^2 m + n^2 A_7 + 2akmn\beta(k - \beta) - 2kmA_3 c_b(2m - \beta^2) + (kmc_b)^2}{16k^2 m(m - \beta^2)}.$$

□

Proof Proof of Proposition 10.

$$r^{BB*} - r^{BN*} = \frac{\beta^2 A_3(3m - 2\beta^2) + kmc_b(2m^2 - 13m\beta^2 + 10\beta^4)}{4km(2m - 3\beta^2)(m - \beta^2)};$$

$$Q^{BB*} - Q^{BN*} = \frac{\beta^2 A_3 - kmc_b(2m - \beta^2)}{4k(2m - 3\beta^2)(m - \beta^2)};$$

$$\Pi_c^{BB*} - \Pi_c^{BN*} = \frac{akm\beta(akm\beta B_4 + 2n(-m\beta B_4 + kB_5)) + n^2(m\beta(m\beta B_4 - 2kB_5) + k^2 B_6)}{4k^2 m(4m^2 - 8m\beta^2 + 3\beta^4)^2} + \frac{km(12m^3 - 20m^2\beta^2 + 11m\beta^4 - 4\beta^6)c_b^2 - 2c_b(akmB_1 + n(kB_2 - mB_1))}{4k(4m^2 - 8m\beta^2 + 3\beta^4)^2}.$$

□

Proof Proof of Proposition 11.

$$w^{BN*} - w^{NN*} = \frac{\beta^2(ak - n - kc_b) + kc_b(2m - \beta^2)}{k(4m - 2\beta^2)};$$

$$Q^{BN*} - Q^{NN*} = \frac{\beta^2(ak - n) - 2kmc_b}{4k(2m - \beta^2)};$$

$$\Pi_p^{BN*} - \Pi_p^{NN*} = \frac{(ak - n)^2\beta^2 - 4km(ak - n)c_b + 2k^2 mc_b^2}{8k^2(2m - \beta^2)}.$$

□

Proof Proof of Proposition 12.

$$w^{BB*} - W^{NB*} = \frac{\beta^2 A_3 + kmc_b(2m - 5\beta^2)}{2km(2m - 3\beta^2)};$$

$$Q^{BB*} - Q^{NB*} = \frac{\beta^2 A_3 - kmc_b(2m - \beta^2)}{4k(2m - 3\beta^2)(m - \beta^2)};$$

$$\Pi_p^{BB*} - \Pi_p^{NB*} = \frac{\beta^2 A_3^2 - 2kmA_3 c_b(2m - \beta^2) + (kmc_b)^2(6m - 5\beta^2)}{8k^2 m(2m - 3\beta^2)(m - \beta^2)}.$$

□

Appendix B Parameter

$$A_1 = k\beta(2m - \beta^2);A_2 = akm - mn + kn\beta;$$

$$A_3 = m^2 - 2km\beta + k^2(8m - 7\beta^2);A_4 = m\beta(3k + \beta) - m^2 - 4k\beta^3;$$

$$A_5 = m^2(m - \beta^2) + km\beta(8\beta^2 - 6m) + k^2(8m^2 - 19m\beta^2 + 11\beta^4);$$

$$A_6 = akm(m - \beta^2) + n(-m(m - \beta^2) + k\beta(3m - 4\beta^2));$$

$$A_7 = m\beta(\beta - 2k) + k^2(8m - 7\beta^2).$$

$$B_1 = 4m^3 - 4m^2\beta^2 + m\beta^4 - 2\beta^6;B_2 = 16m^3\beta - 28m^2\beta^3 + 8m\beta^5 + \beta^7;$$

$$B_3 = 4m^2 - 8m\beta^2 + 3\beta^4;B_4 = 4m^2 - 4m\beta^2 - \beta^4;B_5 = 4m^3 - 11m\beta^4 + 5\beta^6;$$

$$B_6 = 32m^4 - 108m^3\beta^2 + 128m^2\beta^4 - 63m\beta^6 + 11\beta^8.$$

$$C_1 = m^3 - m^2\beta^2 - k(m^2\beta - 2m\beta^3 + 2\beta^5);$$

$$C_2 = mC_1 - km(m^2\beta - 2m\beta^3 + 2\beta^5) - k^2(24m^3 - 41m^2\beta^2 + 13m\beta^4 - 5\beta^6).$$

$$H_1 = m^2n\beta(n\beta - 2k(n + a\beta)) + k^2(am^2\beta(2n + a\beta) + n^2(8m^2 - 14m\beta^2 + 7\beta^4));$$

$$H_2 = m^2(m - \beta^2) - 2km\beta(3m - 4\beta^2) + k^2(8m - 11\beta^2)(m - \beta^2);$$

$$H_3 = (akm\beta)^2H_4 + 2akm^2n\beta(kH_5 - \beta H_4) + n^2(m^2\beta^2H_4 - 2km^2\beta H_5 + k^2H_6);$$

$$H_4 = 4m - 3\beta^2;H_5 = 6m - 7\beta^2;H_6 = 16m^3 - 52m^2\beta^2 + 66m\beta^4 - 33\beta^6.$$

$$F_1(c_b) = H_1 - 2km^2\beta(n(k - \beta) + ak\beta)c_b + (km\beta c_b)^2;$$

$$F_2(c_b) = H_3 - 4km^2\beta(n(k(6m - 7\beta^2) - \beta H_4) + ak\beta H_4) + 4(km\beta c_b)^2H_4.$$

$$k_{G_1} = \frac{m^2}{2\beta(2m - \beta^2)};k_{G_2} = \frac{m\beta}{2(2m - \beta^2)};k_{G_3} = \frac{m^2}{\beta(2m - \beta^2)}.$$

$$n_{G_1} = \frac{k(m^2 - 2km\beta + k\beta^3)(a - c_b)}{m^2 - 4km\beta + 2k\beta^3};n_{G_2} = \frac{km\beta(a - c_b)}{m\beta - 4km + 2k\beta^2};$$

$$n_{G_3} = \frac{km^2(a - c_b)}{m^2 - 2km\beta + k\beta^3}.$$

$$k_1 = \frac{m}{\beta};k_2 = \frac{m\beta}{2m - \beta^2};k_3 = \frac{m(2\beta^2 - m)}{\beta(3m - 2\beta^2)};$$

$$k_4 = \frac{m(4\beta^2 - m)}{\beta(3m - 2\beta^2)};k_5 = \frac{\beta}{4m - 5\beta^2};k_6 = \frac{m - \beta^2}{\beta(3m - 4\beta^2)};$$

$$n_1 = ak - kc_b;n_2 = \frac{km(a - c_b)}{m - k\beta};n_3 = ak;n_4 = \frac{km(m - k\beta)(a - c_b)}{m^2 - 2km\beta + k^2(8m - \beta^2)};$$

$$n_5 = \frac{km\beta(a - c_b)}{m\beta + k\beta^2 - 2km};n_6 = \frac{km(a - 2c_b)}{m - k\beta};$$

$$n_7 = \frac{km(m(m - \beta^2) - k\beta(3m - 4\beta^2))(a - 2c_b)}{m^2(m - \beta^2) - 2km\beta(3m - 4\beta^2) + k^2(8m - 11\beta^2)(m - \beta^2)};$$

$$n_8 = \frac{km(m - \beta^2)(a - 2c_b)}{m(m - \beta^2) - k\beta(3m - 4\beta^2)};n_9 = \frac{km(a\beta^2 - (m - 2\beta^2)c_b)}{\beta(m\beta - k(3m - 2\beta^2))};n_{10} = \frac{k(a\beta^2 - mc_b)}{\beta(\beta - k)};$$

$$n_{11} = \frac{ak(\sqrt{8m}k - m)}{8k^2 - m};n_{12} = \frac{akm}{m - k\beta} + \frac{kmc_b(2m^2 - 13m\beta^2 + 10\beta^4)}{\beta^2(3m - 2\beta^2)(m - k\beta)};$$

$$n_{13} = \frac{km(a\beta^2 - c_b(2m - \beta^2))}{\beta^2(m - k\beta)};$$

$$n_{14} = \frac{ak^2m\sqrt{24m^5 - 64m^4\beta^2 + 50m^3\beta^4 - 10m^2\beta^6 - 3m\beta^8 + 4\beta^{10}} + akmC_1}{m^3(m - \beta^2) - 2km(m^2\beta - 2m\beta^3 + 2\beta^5) - k^2(24m^3 - 41m^2\beta^2 + 13m\beta^4 - 5\beta^6)};$$

$$n_{15} = \frac{ak\beta^2 - 2kmc_b}{\beta^2};n_{16} = \frac{km(a\beta^2 - (2m - \beta^2)c_b)}{\beta^2(m - k\beta)}.$$

$$\frac{\partial S_{c1}^{NB*}}{\partial m} = \frac{\partial r^{NB*}}{\partial m}, k_{S_{c1}}^{NB*} = \frac{m^2\beta}{3m^2 - 4m\beta^2 + 2\beta^4}, n_{S_{c1}}^{NB*} = \frac{km^2\beta(a - c_b)}{m^2\beta - k(3m^2 - 4m\beta^2 + 2\beta^4)};$$

$$\frac{\partial S_{c2}^{NB*}}{\partial m} = \frac{\partial Q^{NB*}}{\partial m}, k_{S_{c2}}^{NB*} = \beta, n_{S_{c2}}^{NB*} = \frac{k\beta(a - c_b)}{(\beta - k)}.$$

$$\frac{\partial S_{p1}^{BB*}}{\partial m} = \frac{\partial w^{BB*}}{\partial m}, k_{S_{p1}}^{BB*} = \frac{m^2\beta}{2m^2 - 4m\beta^2 + 3\beta^4}, n_{S_{p1}}^{BB*} = \frac{km^2\beta(a - 2c_b)}{m^2\beta - k(2m^2 - 4m\beta^2 + 3\beta^4)};$$

$$\frac{\partial S_{p2}^{BB*}}{\partial m} = \frac{\partial \Pi_p^{BB*}}{\partial m}, k_{S_{p2}}^{BB*} = \frac{3m\beta}{4m - 3\beta^2}, n_{S_{p2}}^{BB*} = \frac{3km\beta(a - 2c_b)}{-4km + 3m\beta + 3k\beta^2};$$

$$\frac{\partial S_{c1}^{BB*}}{\partial m} = \frac{\partial r^{BB*}}{\partial m}, k_{S_{c1}}^{BB*} = \frac{5m^2\beta}{6m^2 - 8m\beta^2 + 6\beta^4}, n_{S_{c1}}^{BB*} = \frac{5km^2\beta(a - 2c_b)}{5m^2\beta - k(6m^2 - 8m\beta^2 + 6\beta^4)};$$

$$\frac{\partial S_{c2}^{BB*}}{\partial m} = \frac{\partial Q_c^{BB*}}{\partial m}, k_{S_{c2}}^{BB*} = \frac{3\beta}{2}, n_{S_{c2}}^{BB*} = \frac{3k\beta(a - 2c_b)}{3\beta - 2k}.$$

$$c_{b1} = \frac{akm - mn + kn\beta - \sqrt{(a^2k^2m - 2akmn + n^2(m - 8k^2))(m - \beta^2)}}{km};$$

$$c_{b2} = \frac{akm - mn + kn\beta + \sqrt{(a^2k^2m - 2akmn + n^2(m - 8k^2))(m - \beta^2)}}{km};$$

$$c_{b3} = \frac{akmB_1 - n(mB_1 - kB_2) - \sqrt{B_3^2(a^2k^2m^3(m - \beta^2) - 2akmnC_1 + n^2C_2)}}{km(12m^3 - 20m^2\beta^2 + 11m\beta^4 - 4\beta^6)};$$

$$c_{b4} = \frac{akmB_1 - n(mB_1 - kB_2) + \sqrt{B_3^2(a^2k^2m^3(m - \beta^2) - 2akmnC_1 + n^2C_2)}}{km(12m^3 - 20m^2\beta^2 + 11m\beta^4 - 4\beta^6)};$$

$$c_{b5} = \frac{2m(ak - n) - \sqrt{4m(ak - n)^2(2m - \beta^2)}}{2km};$$

$$c_{b6} = \frac{2m(ak - n) + \sqrt{4m(ak - n)^2(2m - \beta^2)}}{2km};$$

$$c_{b7} = \frac{(2m - \beta^2)(akm - mn + kn\beta) - \sqrt{4(akm - mn + kn\beta)^2(2m^2 - 5m\beta^2 + 3\beta^4)}}{km(6m - 5\beta^2)};$$

$$c_{b8} = \frac{(2m - \beta^2)(akm - mn + kn\beta) + \sqrt{4(akm - mn + kn\beta)^2(2m^2 - 5m\beta^2 + 3\beta^4)}}{km(6m - 5\beta^2)}.$$

Declarations

Conflict of interest The authors have no Conflict of interest to declare that are relevant to the content of this article.

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