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Analysis of a maritime transport chain with information asymmetry and disruption risk

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A R T I C L E   I N F O

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A B S T R A C T

Maritime transport chain is facing huge information asymmetry after the outbreak of major emergencies, such as COVID-19 epidemic. The previous literature has proved that information investing and information sharing are two effective tactics to relieve information asymmetry between supply chain nodes, and help them improve the performance of the supply chain. This paper assumes random demand disruption is the main cause of the information asymmetry in a maritime transportation chain. To explore how the random demand disruption and channel competition jointly impact operational decisions in a dual-channel maritime transport chain composed of one port, two carriers and shippers, we construct a game-theoretical basic model, and proposed two strategies, i.e., information investing and information sharing. Several significant managerial insights are derived. First, we find that inaccurate disruption information leads to inaccurate decisions and huge losses; Second, investing in precise information benefits the port only if the chain members are optimistic about the market, and improves the revenue of the carrier who invested in information if the investment cost is reasonable; Third, accepting information sharing benefits the port only when the precise disruption and the distortion of information are relatively large, as well as the misappropriate rate is relatively small; and only when the port is pessimistic about the market or the channel competition is weak, sharing information may hurt the carrier who invested in information. Finally, the strength of the channel competition will enhance the impact of information asymmetry on the maritime transport chain.

1. Introduction

Motivation: The frequent occurrence of major emergencies in recent years, such as the global SARS outbreak in 2003, the global financial crisis in 2008, and the global outbreak of the COVID-19 pandemic, has brought huge serious damage to global development. Corlett et al. (2020) stated that the COVID-19 pandemic is impacting all parts of human society, and Xu et al. (2021) presented that the COVID-19 pandemic has a non-negligible influence on the port, including increasing maritime transport chain management risk, by analyzing the data collected from 14 major ports in China from January to October 2020. The (maritime) supply chain management risk mainly comes from two broad categories, i.e., the problems of coordinating supply and demand, and disruptions of operational activities (please see Kleindorfer and Saad, 2005). Oke and Gopalakrishnan (2009) stated that the occurrence of the disruptions generally leads to increased vulnerability of supply chain members; and Simchi-Levi et al. (2014) indicated that demand disruption is the occurrence of unplanned or unanticipated events that may affect product liquidity and further affect supply chain members’ operational decisions and revenues, which adds complexity to the supply chain and leads to inaccurate decisions easily. In practice, the demand disruptions caused by COVID-19 are widely existed. For example, Malaysia responded to the Covid-19 pandemic by imposing lockdown, which resulted in a significant drop in demand for consumer goods, and led directly to port disruptions (Menhat et al., 2021). Similarly, the declining income of the majority of the population in India due to the ravages of the COVID-19 pandemic, coupled with rising prices, has led to a significant dampening of consumer demand and a decrease in the total amount of goods transported by sea (CCPIT, 2021; Narasimha et al., 2021). The above evidence suggests that in the post COVID-19 era, demand disruption is a non-negligible factor in the healthy development of the global ports and shipping market, and thus taking the disruption into consideration to make efficient operational events...
decisions and improve revenue is an urgent issue for maritime transport chain members.

Actually, the random demand disruption information is generally unknown to the maritime supply chain members. The previous literature (e.g., Sheng et al., 2017; Sundarakan et al., 2021; Ji et al., 2022; Gerakoudi-Ventouri, 2022; Wang et al., 2022) showed that information technologies, such as big data, blockchain, social media, Internet of Things, livestreaming, etc., are emerging to affect many aspects of decision-making in a supply chain network, such as information collection and operational decisions, which could help the chain members make accurate decisions and improve revenue substantially. Nowadays, more and more enterprises (including port terminals and shipping companies) apply information technology to alleviate the negative impact of information asymmetry. For example, Maersk, a global shipping leader, jointly created TradeLens with IBM in early 2018, a new trade platform based on blockchain technology, which could improve digital cooperation among maritime transport chains through the exchange of shipping information, and help reduce operational risks such as information asymmetry (Jensen et al., 2019). The Port of Antwerp collaborated with T-Mining, a blockchain solutions company, on a project to automate and secure the flow of documents through smart contracts. These contracts provide security for the documents flow between interested parties according to predefined rules, and all information that T-Mining collected in a database is shared securely with the interested parties in real time (Chang et al., 2020). Under such a circumstance, the other members only rely on the accurate decisions of those enterprises or platform for corresponding decisions, e.g., production plans and pricing decisions. However, these corresponding decisions are generally suboptimal to them, and thus they need to take measures to avoid more losses, for example, accepting information sharing with those enterprises or platforms. Previous literature has proved that information sharing between supply chain nodes is becoming increasingly frequent (Huang et al., 2018).

Motivated by the above discussions, this paper considers several scenarios to explore the operational decisions, including freight/service pricing, information investing and information sharing, in a three-level maritime transport chain composed of one port and two carriers. In the post COVID-19 era, the precise demand disruption is unknown to the chain members initially, but it could be obtained by one party through investing in an information channel, and thus there exists asymmetric information between the maritime transport chain members. We wish to answer the following research questions:

(1). How does the inaccurate demand disruption information affect the operational decisions, including freight and service prices, investment in information channel and information sharing?

(2). Under what conditions is one carrier willing to invest in an information channel for precise disruption information? And the conditions she competes or cooperates with the port?

(3). What is the impact of the carrier’s investment in an information channel on the port?

(4). How does the channel competition affect the port’s and the carrier’s operational decisions?

To answer the above research questions, we first build a stylized game-theoretical basic model, where the precise disruption are not available to the port and the carriers. Then, we extend the basic model by considering two strategies, i.e., (i) one carrier collects the precise information by investing in an information channel; (ii) information sharing exists between the chain members.

Main contributions: The main contributions of this paper can be concluded into three points. The first lies in the research framework. This paper is the first to explore how the asymmetry information effects operational decisions, including freight/service pricing, information investing and information sharing, in a three-level maritime transport chain composed of one port, two carriers and shippers. The demand disruption risk is the main cause of information asymmetry in this paper. Besides, the topic of this paper reflects the real port operating environment, especially in the post COVID-19 era, and thus we believe this paper provides the significant guidelines for the decision-making of the maritime transport chain. The second point of the contribution is that, from a methodological standpoint, the inaccurate disruption information makes the chain members substantially difficult to characterize operational decisions and revenues. This paper proposes and compares the actual yielded revenue and the expected yielded revenue when the actual and expected disruptions are divergent, to effectively obtain the optimal operation decisions, as well as the value of two strategies, i.e., investing in information channel and sharing information. The third point relies on the significant results. For example, investment information channels is not always conducive to the maritime transport chain, and it strongly depends on chain members’ attitude toward the risk of disruption. Specifically, if the port is pessimistic about the market or the channel competition is weak, the carrier who invested in information channel will not share information with the port. Besides, the impact of inaccurate information on the maritime transport chain increases with the intensity of channel competition. We believe these are of great value to the ports and carriers in practice.

Organization: The reminder of this paper is organized as follows. Section 2 reviews the literature most relevant to this paper. Section 3 describes and analyzes the basic model. Section 4 extends the model by considering two strategies to eliminate information asymmetry. Section 5 conducts numerical experiments to explore the value of information investing and sharing to the maritime transport chain. Section 6 concludes this paper.

2. Literature review

This paper focuses on investigating how the demand disruption information and the channel competition jointly affect the operational decisions and revenues in a three-level maritime transport chain. The most representative and relevant literature to this paper is divided into three streams, i.e., disruption management, information asymmetry (including information collection and sharing), and co-opetition strategy. In the following we respectively review them.

The first stream is disruption management in supply chains or maritime transport chains, which has gradually become an extremely important research topic, please see Snyder et al. (2016) and Xu et al. (2020) for a comprehensive review. The existing literature on disruption management is mainly divided into two parts. The first part focuses on supply chain coordination and operational decisions in a (maritime) supply chain. For example, Soleimani et al. (2016) studied pricing strategies in the presence of demand and cost disruptions in both centralized and decentralized dual-channel supply chains, and they suggested a game-theoretic approach to help supply chain members set optimal prices under these disruptions. Pi et al. (2019) explored the impacts of the demand disruption on the pricing, production or service strategies in a dual-channel supply chain. Zhao et al. (2020) considered supply chain coordination by using revenue sharing contracts and a linear quantity discount contracts in a fashion supply chain with demand disruptions. Besides, the demand disruptions in the maritime transport chain have also received widely attention. Wu et al. (2020) studied sustainable trade promotion decisions under demand disruption in a manufacturer-retailer supply chain. Jiang et al. (2021) assessed the port vulnerability from a supply chain perspective, and they showed that ports are at high risk and disruption concerns, which includes demand disruption. Loh et al. (2017) used fuzzy comprehensive evaluation to evaluate port-centric supply chain disruption threats.

The second part focuses on exploring the impact of disruptions on the (maritime) supply chains, please see Nguyen et al. (2022) for a comprehensive review. Disruptions at a port directly impacts the port’s ability to continue operations, and further affects the supply chains and the parties served by the port. Notteboom et al. (2021) developed analysis and comparison of the financial crisis in 2008 and the impact
of the COVID-19 pandemic in 2019 on the demand for container ports and the container shipping industry, they found that between the financial crisis and the epidemic, different coping mechanisms should be adopted to adapt to the impact of demand disruption on members of the maritime chain. Similarly, Li et al. (2022) analyzed the impact of disruptions caused by environmental factors such as hurricanes, and they also considered the incompleteness and uncertainty of information. Through a multi-case study approach, Mańkowska et al. (2021) screened out the sources and types of disruptions caused by the COVID-19 pandemic to the maritime supply chain, and explored the impacts of these disruptions on maritime supply chain operations.

The second stream is information asymmetry between the (maritime) supply chain nodes, which has gradually received substantial attention in the era of the Internet. Information asymmetry in the existing literature mainly focuses on cost information and demand information. Please see Liu et al. (2019), Shao et al. (2020) and Gao et al. (2021) for the literature on the cost information asymmetry. This work is concerned with the effects of information asymmetries caused by demand disruptions, which is gradually becoming a hot topic, especially in the context of the frequent occurrence of emergencies. Lei et al. (2012) used a linear contract menu to analyze the impact on supply chain members and supply chain performance when demand is disrupted under asymmetric information. Zhang et al. (2021) investigated a dynamic contracting problem where the chain members do not know the demand information but the retailer can update the demand information, so information asymmetry exists in the system. Yang et al. (2019) used a screening model to study a carrier-shipping contracting problem consisting of two demand seasons, high and low, under demand information asymmetry in a maritime supply chain. Clearly, asymmetrical demand information significantly affects the chain members’ operational decisions and their revenues, and thus it is urgent and necessary to seek measures to alleviate the information asymmetry. In the following, We mainly review the existing literature on two strategies for mitigating information asymmetry, i.e., investing in information and sharing information.

Investing in precise information is an effective means to alleviate information asymmetry. Advances in technology facilitate access to accurate information (Shen et al., 2019; Chen et al., 2022). Li et al. (2017) used a news vendor model to demonstrate that information accuracy is critical in determining the value of disrupted information, despite the high cost of deriving accurate information. Verschuur et al. (2020) proved that collecting vessel tracking data through technical support systems, combined with data from past port disruptions, could better predict the extent of disruptions and reduce the impact. The previous literature also explored the value of digital (information) technology investment in alleviating disruption asymmetry information, for example, Mehrrota and Schmidt (2021) examined the link between the characteristics of supply chain disruptions and the value of information, the research results could help companies decide whether to invest in collecting information. Lan et al. (2017) considered a manufacturer investing in advanced algorithms or big data to alleviate when the retailer possesses private sales cost information. Liu et al. (2021) demonstrated that information technology such as blockchain can reduce the risk of information asymmetry from the perspective of supply chain finance.

Establishing information sharing contracts is another effective measure to eliminate the influence of the information asymmetry. Ha and Tong (2008) examined different contracts and information sharing in two competing supply chains, indicated the role of information sharing capabilities as an advantage in a competitive supply chain. Chen et al. (2016) designed an information disclosure model to study the asymmetry demand information between suppliers and retailers, and they found that retailers can derive precise information about demand interuption through contractual bundling. Chen et al. (2017) examined the value of information sharing in two competing supply chains when facing demand disruption. Yoon et al. (2020) studied the impact of information sharing strategies on manufacturers’ purchasing decisions in a three-tier supply chain under the risk of disruption, and they showed that the effectiveness of information sharing strongly depends on the information sharing costs. Thomas and Mahanty (2021) examined the value of sharing real-time disruption and inventory information for mitigating disruption risks when supply chains suffer from random disruptions. Shaw et al. (2017) proposed an approach that requires information sharing among stakeholders to reduce barriers to complexity, confidentiality, and political sensitivity, when a crisis disrupts a port.

The third stream is competition and cooperation in (maritime) supply chains, which has been extensively studied in the literature. For example, Hafezalkotob (2017), Jalali et al. (2021) and Li and Zhao (2022). Huang et al. (2016) studied a pricing competition and cooperation problem in a supply chain composed of duopoly retailers and a manufacturer, several game models are proposed to examine the influence of power structures and pricing strategies on supply chain members. Li et al. (2020) investigated the influences of the offline showroom’s optimal channel cooperation strategy and competition in the context of asymmetric demand information. Liu and Wang (2019) studied the motivation of horizontal alliances and the value of vertical cooperation between two competing carriers in a one-to-two competitive shipping service model. Xin et al. (2022) established a maritime supply chain composed of a single oligopoly port and two competing carriers, to discuss the value of applying blockchain technology to improve port customs clearance efficiency and logistics transparency, under different cooperation models in the post-COVID-19 pandemic era.

It is worth noting that the distinct features of this work from the above mentioned literature are as follows: first, the disruption in the above literature is generally assumed to be certain and known to the chain members, while in this paper we assume the disruption is random and only the expected disruption is common knowledge between the chain members. Second, the disruption information is unowned privately by any supply chain member, unless the members derive the precise information from outside, e.g., investing in information channel or sharing information. Third, we assume the chain members are in a competitive relationship if only one member invests in deriving precise information and the others still do not know the precise information, while they are in a cooperation relationship if they share information with each other.

3. Basic model

We consider a three-level maritime transport chain composed of one port and two carriers. Freights stocked in the port can be transported to shippers via dual distribution channels, i.e., carrier 1 and carrier 2, please see Fig. 1 for the maritime transport chain structure. We assume carrier 1 is self-controlled by the port, which means that the port and the carrier 1 can be viewed as one entity. The sequence of events in the maritime transport chain includes two stages. Specially, in stage 1, before the shippers arrive, the port first publicizes service charge $w$ per unit freight for the carrier 2, and simultaneously, the carrier 1 and the port set the freight transport price $p_1$; In stage 2, the carrier 2 sets freight transport price $p_2$. It is noted that the port in the channel

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1. For convenience, we use “he” to denote the port and “she” to denote the carrier 2 hereafter.

2. In practice, some port terminals have their own shipping companies (i.e., carriers) or some shipping companies have set up specialized terminal management companies, such as APM Terminals of Maersk and COSCO Shipping Ports of COSCO Group (Huang, 2020); Besides, some port terminals gain transportation pricing power or control of operations in transportation service through acquisitions. For example, in 2020, DP World had expanded its business scope in the maritime transport chain by acquiring 60% of Unico logistics, one of the largest independent shipping companies in South Korea. Moreover, as early as 2018, DP World completed the acquisition of Unifeeder, which means that the port and carrier 1 can be viewed as one entity.
through carrier 2 provides a storage service but does not participate in the transportation service, which is in line with the realistic, and there exists literature that makes similar assumption about the port and the carriers, such as, Liu and Wang (2019), Niu et al. (2021) and Xin et al. (2022). Beyond that, the transport price $p_i$ is subject to the following constraints, i.e., $0 < w < p_2$, such that the carrier 2 is profitable and willing to enter the market. For ease of reference, we summarize the notations in Table 1.

Following from Hua et al. (2010), Chen et al. (2012) and Matsui (2017), we format the demand functions in two channels are linear in self-price and cross-price effects. Specially, we respectively define $d_{i1}$ and $d_{i2}$ as the demand in direct and third-part channel. Then, we have

\[
d_{i1} = 1 - p_i + \gamma_i p_2, \quad d_{i2} = \alpha - \gamma_i p_1,
\]

where $\alpha$ denotes the shippers’ preference for the channel through the carrier 2 to carry the freight. A higher $\alpha$ implies that the shippers are more likely to choose the carrier 2. The cross-price sensitivities $0 < \gamma_1$, $\gamma_2 < 1$ reflect the effects of the other channel’s price on the target channel’s demand, it could also be viewed as a channel competition. Note that to maintain analytical tractability, we assume the cross-price effects are symmetric, i.e., $\gamma_1 = \gamma_2$, and the coefficients of self-price elasticity of $d_{i1}$ and $d_{i2}$ is 1. The assumption is widely applied in literature, e.g., Hua et al. (2010). The frequent occurrence of emergencies has intensified the uncertainty in global supply chains, including the maritime transport chain, and increased the supply chain disruption risk. The phenomenon promotes academia and industries to take the demand disruption risk into account. Hence, we redefine $d_{i1}$ and $d_{i2}$ as the demands on direct and third-part channels if we consider the random demand disruption, then

\[
d_{i1} = 1 - p_i + \gamma_1 p_2 + \theta, \quad d_{i2} = \alpha - \gamma_2 p_1 + \theta,
\]

where $\theta \in [\theta_L, \theta_H]$ is a random demand disruption caused by unexpected major emergencies, e.g., the COVID-19 pandemic, $\theta = [-\theta_H, \theta_H]$ implies that the demand fluctuate is relatively strong, $\theta = [-\theta_L, \theta_L]$ implies that the demand fluctuate is relatively weak, and we assume $\theta_H \geq \theta_L$. The port and the carriers are unknown the exact value of $\theta$, but know the expected demand disruption, i.e., $E(\theta) = \lambda \theta_1 + (1 - \lambda) \theta_2$, $\lambda$ is the probability $\theta = \theta_2$. Besides, we assume the demand disruption is either positive or negative, i.e., $(\theta_H, \theta_L)$ or $(-\theta_H, -\theta_L)$, please see more explanations on $\theta$ on Appendix B. Considering that the demand disruption is generally relatively stable after an emergency, e.g., in the post COVID-19 era, we assume that $\theta = \min(\theta_L, \theta_H)$, $i \in \{H, L\}$. It is worth noting that the demand disruption in this paper is assumed identically occurred in two channels, that is, each channel’s disruption is $\theta$, and the total demand disruption is $\theta$ in the market, please refer to Niu et al. (2019) for the similar assumption. The carriers and the port in this section do not know the full information on the demand disruption, but the partial information, i.e., the distribution of the disruption. Define $\pi_i(\pi_{i2})$ and $\pi_2$ respectively as the expected revenues\(^3\) of the port (carrier 1) and carrier 2. Then, we could immediately obtain that

\[
\pi_p = \pi_{i1} = E[p_i d_{i1} + w d_{i2}]
\]

\[
= p_i [(1 - p_i + \gamma_i p_2 + E(\theta)) + w(a - p_2 + \gamma_2 p_1 + E(\theta))], \tag{2}
\]

\[
\pi_{i2} = E[(p_2 - w)d_{i2}] = (p_2 - w)(a - p_2 + \gamma_2 p_1 + \gamma p_1 + E(\theta)). \tag{3}
\]

where part 1 denotes the revenue from the direct channel, and part 2 denotes the revenue from the third-party channel. Since carrier 1 is self-controlled by the port, and thus, the port does not need to charge a service fee to carrier 1.

We use backward induction to analyze the Stackelberg game, where the port and the carrier 1 play as a leader, the carrier 2 plays as a follower. First, we analyze the revenue functions $\pi_p$ and $\pi_{i2}$ to derive the subgame perfect Nash equilibrium (henceforth, SPNE), and obtain the following Lemma 1.

**Lemma 1.** In stage 2 of the Stackelberg game, given the service price $w$ and freight price $p_1$, the carrier 2’s optimal responsive price is given by $p_{i2}^{SPNE}(w, p_1) = \frac{a + p_1 E(\theta)}{2}$.

Lemma 1 suggests that with a higher expected disruption, if the port and the carrier 1 set a higher service fee and a higher freight price, or the shippers prefer to choose the carrier 2, the carrier 2 would set a higher freight price. The results are clearly consistent with reality. A higher expected disruption or the shippers prefer to choose the carrier 2, the carrier 2 would set a higher self-controlled by the port, and thus, the port does not need to charge a service fee to carrier 1.

Next, we explore the optimal prices of the port. The existence of the SPNE in stage 2 provides us with the foundation to derive the port’s optimal prices in stage 1. As a Stackelberg leader, he knows that carrier 2 will set the price of $p_{i2}^{SPNE}(w, p_1)$ to $p_{i2}^{SPNE}(w, p_1) = \frac{a + p_1 E(\theta)}{2}$. Substituting $p_{i2}^{SPNE}(w, p_1)$ into $\pi_p$ (see Eq. (2)), i.e.,

\[
\pi_p(p_i, w) = p_i \left(1 - p_i + \gamma_i p_2 + \gamma p_1 + E(\theta)\right) + w\left(a - p_2 + \gamma_2 p_1 + E(\theta)\right).
\]

\[
+ \left(a - p_i + \gamma p_1 + E(\theta)\right) + \gamma p_1 + E(\theta). \tag{4}
\]

\(^3\) Note that we set the unit ordering cost as zero. It follows immediately from Wang et al. (2021), Huh and Janakiraman (2008) and Shen et al. (2018) that a pricing/inventory model with a unit ordering cost can be equivalently changed into the one where the ordering cost is zero but the other parameters should suitably be modified.

\[\]
Proposition 1. \( \pi_2(p_1, w) \) is jointly concave in \( p_1 \) and \( w \); The optimal prices in equilibrium are given by

\[
p_{c1}^* = \frac{1 + \gamma y + (1 + \gamma)E(\theta)}{2(1 - \gamma^2)}, \quad p_{c2}^* = \frac{\gamma y + (1 + \gamma^2)E(\theta)}{4(1 - \gamma^2)}.
\]

\( w^* = \frac{\gamma + a + (1 + \gamma)E(\theta)}{2(1 - \gamma^2)}. \)

The expected revenues under the optimal prices are

\[
d_{c1}^* = \frac{2 + ay + (2 + y)E(\theta)}{4}, \quad d_{c2}^* = a + E(\theta).
\]

The expected optimal revenues of the port and carrier 2's are

\[
\pi_1^* = \frac{(a + E(\theta))^2}{8(1 - \gamma^2)}, \quad \pi_2^* = \frac{\gamma y + (1 + \gamma^2)(a + E(\theta))^2}{16}.
\]

Besides, the optimal solutions are nondecreasing in \( E(\theta) \) and \( \gamma \).

The concavity of \( \pi_2(p_1, w) \) with respect to \( (w, p_1) \) implies that there exists a unique pair \( (w, p_1) \) such that the port could optimize his revenue in dual channels, and subsequently, Proposition 1 presents the expected optimal solutions and demands of the port and the carrier 2, as well as the monotonicity of the optimal solutions w.r.t. \( E(\theta) \) and \( \gamma \). The monotonicity is consistent with reality. Specifically, a higher \( E(\theta) \) implies that both the port and the carrier 2 take optimistic views of the inaccurate decisions. In the following, we define \( d_{c1} \) and \( d_{c2} \) as the actual demands, \( \tilde{d}_{c1} \) and \( \tilde{d}_{c2} \) as the actual revenues, if the port and the carrier 1 implement the pricing decisions presented in Proposition 1, with the actual precise demand disruption is \( \tilde{\theta} \) in the market, then we have

\[
d_{c1} = \frac{2 + ay - (2 - y)E(\theta)}{4} \cdot \tilde{\theta} + \frac{a - 3E(\theta)}{4} + \tilde{\theta}, \quad d_{c2} = \frac{a + E(\theta)}{4} + \tilde{\theta},
\]

substituting \( \tilde{d}_{c1} \) and \( \tilde{d}_{c2} \) into Eqs. (2) and (3), we can obtain the actual expected revenues are

\[
\tilde{\pi}_1 = E_2[p_1^*\tilde{d}_{c1} + w^*\tilde{d}_{c2} - c_1(\tilde{d}_{c1} - d_{c1}^*)^y - c_2(\tilde{d}_{c2} - d_{c2}^*)^y],
\]

\[
\tilde{\pi}_2 = E_2\left[\left(p_1^* - w^*\right)\tilde{d}_{c1} - c_1(\tilde{d}_{c1} - d_{c1}^*)^y - c_2(\tilde{d}_{c2} - d_{c2}^*)^y\right],
\]

where \( c_1 \) and \( c_2 \) respectively denote the unit underage cost and the unit disposal cost. Generally, if the actual realized demand is larger than they expected, given the original pricing decisions, there will occur lost sales and sequentially underage costs. On the contrary, if the actual realized demand is smaller than they expected, there will occur leftover inventory and sequential disposal costs. Clearly, the unit disposal cost is smaller than the unit underage cost, i.e., \( c_1 > c_2 \). Beyond, in practical, both the unit disposal and underage costs are smaller than the unit selling prices, i.e., \( \max(c_1, c_2) \leq p_1, w, (p_1 - w) \), which is similar to Huang et al. (2012).

Proposition 2. For any \( 0 < a, y \) and \( 0 \leq \delta \leq 1 \), (i) if \( \tilde{\theta} < E(\theta) \), \( d_{c1}^* \geq \tilde{d}_{c1}, d_{c2}^* \geq \tilde{d}_{c2}, \pi_1^* \geq \tilde{\pi}_1 \) and \( \pi_2^* \geq \tilde{\pi}_2 \); (ii) if \( \tilde{\theta} > E(\theta) \), \( d_{c1}^* \leq \tilde{d}_{c1}, d_{c2}^* \leq \tilde{d}_{c2}, \pi_1^* \leq \tilde{\pi}_1 \) and \( \pi_2^* \leq \tilde{\pi}_2 \).

Proposition 2 shows that if the actual demand disruption is larger than the chain members' expected demand disruption, which implies that they are pessimistic about the market, they will set lower prices, including service fee and freight price, then the actual revenues they yielded will be larger than the revenues they expected to yield. The opposite is true if they are optimistic about the market. Proposition 2 further reflects that the inaccurate demand information has a great impact on pricing decisions and revenues of the port and the carrier 2, and brings substantial losses to them, especially when the chain members are optimistic about the market.

The above theoretical results presented in this section inspire us to ponder the following questions: since inaccurate disruption information would bring substantial losses, how could they get accurate disruption information to make more accurate decisions? How to redesign a highly flexible maritime transport chain? Under the design chain, how the port and the carrier 2 choose competition or cooperation? In the following sections, we attempt to answer the above questions.

4. Analysis under two information strategies

In this section, we propose two strategies from the perspective of carrier 2, i.e., information strategy (IS) and sharing strategy (SS), to explore whether collecting accurate disruption information is necessary for the port or the carrier 2, and with accurate disruption information, what is the conditions that the port chooses competition or cooperation with the carrier 2. Under IS, the carrier 2 collects precise disruption information by investing \( I \) to establish an information channel, while the port still only knows the partial information on the disruption. Under SS, the carrier 2 shares the collected disruption information with the port, but charges a fixed unit fee from the port. Please see Fig. 2 for the chain structures under two strategies. The sequence of events in this section is as follows, see Fig. 3. At the beginning of the selling horizon, both the port and the carrier 2 roughly predicted the demand disruption in the market. Then, the carrier 2 decides whether to invest in an information channel, i.e., whether applies IS or not. Next, with the actual information released, the carrier 2 decides whether to share information with the port, i.e., whether applies SS or not. The port could choose to accept or not accept information sharing. Finally, the port determines \( w \) and \( p_1 \), and the carrier 2 set \( p_2 \) sequentially.

In each strategy, we first apply a two-stage optimization technology to derive the optimal prices of the port and the carrier 2, as well as their expected yield and actually yielded revenues. By comparing the expected revenues and actually yielded revenues, we would obtain the conditions for the carrier 2 to invest in an information channel, and the conditions for either the port or the carrier 2 to be willing to share information. In line with the pricing sequence in the basic model, under two strategies: the port will publicize the port service price \( w \) and the freight price \( p_1 \) in stage 1; \( p_2 \) is proposed by the carrier 2 in stage 2. Both the port and the carriers are risk neutral and seek to maximize their individual revenues.

4.1. Investment strategy (IS)

Here, we assume that carrier 2 invests in an information acquisition channel to obtain the precise demand disruption at the cost of \( I \), please see Fig. 2(a). Then, she knows the exact demand disruption, i.e., \( \tilde{\theta} = \tilde{\theta}_1 \) or \( \tilde{\theta} = \tilde{\theta}_2 \) after the investment, while the port still only know the expected disruption, i.e., \( E(\theta) \), and he will still adopt the pricing decisions in the original plan, i.e., \( p_1^* \) and \( w^* \). Then, the demands and revenues if the carrier 2 invests in an information channel can be rewritten as follows:

\[
d_{c1}^{IS} = 1 - p_1^* + \gamma p_2^{IS} + \delta, \quad d_{c2}^{IS} = a - p_2^{IS} + \gamma p_1^* + \delta.
\]

\[
\pi_1^{IS} = \pi_2^{IS} = \pi_1^{IS} = \pi_2^{IS} = E_2[p_1^{IS}d_{c1}^{IS} + w^{IS}d_{c2}^{IS} - c_1(d_{c1}^{IS} - d_{c1}^*)^y - c_2(d_{c2}^{IS} - d_{c2}^*)^y].
\]

\[
\pi_1^{IS} = (p_2^{IS} - w)\delta - I.
\]

where the notations with the superscript “IS” denote the corresponding notations if the carrier 2 invests in an information channel, and with “s” denotes the corresponding notations under the optimal decisions. Note that there is no disposal or underage cost for the carrier 2 since she knows the precise demand disruption information and could make accurate ordering decision.
It immediately follows from Eq. (9) that $\pi^{IS}_{2}\!\!\!_C$ is concave in $p^{IS}_{2}C$, and thus the carrier 2's problem in this subsection can be formulated as,

$$
\pi^{IS}_{2}(p^{IS}_{2}) = \max_{p^{IS}_{2}\geq 0} \left\{ \left( p_{2} - \frac{\gamma + a + (1 + \gamma)E(\theta)}{2(1 - \gamma^{2})} \right) \times \left( a - p_{2} + \frac{\gamma + 2\gamma(1 + \gamma)E(\theta)}{2(1 - \gamma^{2})} + \theta \right) - I \right\}.
$$

In the following, we discuss the model in two cases: the actual demand disruption is relatively large, i.e., $\hat{\theta} = \theta_{H}$ and the actual demand disruption is relatively small, i.e., $\hat{\theta} = \theta_{L}$.

4.1.1. The demand disruption is relatively large

If $\hat{\theta} = \theta_{H}$, given $p^{\ast}$ and $w^{\ast}$, by optimizing $p^{IS}_{2}C$ to maximize $\pi^{IS}_{2}C$, we obtain the following results.

**Proposition 3.** If the carrier 2 invests in an information channel, given $p^{\ast}$, $w^{\ast}$ and the actual demand disruption $\hat{\theta} = \theta_{H}$, we obtain that $p^{IS}_{2}C = 2\lambda^{[3(\lambda^{2} - \lambda + 1)]^{T}}E(\theta) + [\theta_{H}]$, and the expected optimal and the actual demands of the port and the carrier 2 are,

$$
\begin{align*}
\pi^{IS}_{2}C_{c1} &= 2 + E(\theta)(2 - \gamma) + a_{\gamma} + 2\gamma[\theta_{H}], \quad d^{IS}_{2}C_{c1} = \frac{a + 3E(\theta) - 2[\theta_{H}]}{4}, \\
\pi^{IS}_{2}C_{c2} &= 2 + a_{\gamma} - 2\gamma(2 + \gamma)E(\theta) + 2[\theta_{H}], \quad d^{IS}_{2}C_{c2} = \frac{a - E(\theta) + 2[\theta_{H}]}{4}, \\
\end{align*}
$$

and the expected optimal and the actual revenues of the port and the carrier 2 are,

$$
\begin{align*}
\pi^{IS}_{2}C_{p1} &= p^{\ast}_{1}d^{IS}_{1}C_{p1} + w^{\ast}_{1}d^{IS}_{1}C_{p2}, \\
\pi^{IS}_{2}C_{p2} &= \frac{(a + 3E(\theta) - 2[\theta_{H}])}[a - E(\theta)]I - I, \\
\pi^{IS}_{2}C_{c1} &= p^{\ast}_{1}d^{IS}_{1}C_{c1} + w^{\ast}_{1}d^{IS}_{1}C_{c2} - c_{1}([\theta_{H}] - E(\theta)), \\
\pi^{IS}_{2}C_{c2} &= \frac{(a - E(\theta))^{2} + 2[\theta_{H}]}{16} - I.
\end{align*}
$$

Besides, we have $p^{IS}_{2} > p^{\ast}_{2}, d^{IS}_{2} > d^{IS}_{1}, d^{IS}_{2} > d^{IS}_{1}, \pi^{IS}_{2} > \pi^{IS}_{1}C_{c1}$ and $\pi^{IS}_{2} > \pi^{IS}_{1}C_{c2}$.

**Proposition 3** presents the chain members' expected optimal demand and revenues, as well as their actual demand and revenue, if the actual disruption is positive and relatively larger than their expected. Proposition 3 also show that if the carrier 2 invests in an information channel and the obtained actual disruption is relatively large, she will set a large price. Besides, the results further suggest that if the chain members are pessimistic about the market, i.e., their expected disruption is smaller than the actual disruption, their actual demands and revenues will be larger than they expected. The results are consistent with the factual and Proposition 2. From Proposition 2, we further conclude that whether the carrier 2 invests or does not invest in an information channel, if the chain members are pessimistic about the market, their actual demands and revenues are larger than they expected.

**Proposition 4.** If the carrier 2 invests in an information channel, given $p^{\ast}$, $w^{\ast}$ and the actual demand disruption $\hat{\theta} = -[\theta_{H}]$, we obtain that

$$
p^{IS}_{2}C = \begin{cases} 
2\lambda^{[3(\lambda^{2} - \lambda + 1)]^{T}}E(\theta) + [\theta_{H}] & \text{if } 0 < \lambda \leq \lambda_{0}; \\
\frac{\theta_{H}}{2} & \text{if } \lambda_{0} < \lambda < 1.
\end{cases}
$$

where $\lambda_{0} = \min\{1, \frac{\alpha \theta_{H} = \lambda}{\theta_{H}}\}$. If $0 < \lambda \leq \lambda_{0}$, the expected optimal and actual demands and revenues are given the same with Proposition 3, and $\pi^{IS}_{2}C_{c1} < \pi^{IS}_{1}C_{c1}$ and $\pi^{IS}_{2}C_{c2} < \pi^{IS}_{1}C_{c2}$.

If $\lambda_{0} < \lambda < 1$, the actual demands and revenues of the port and the carrier 2 are

$$
\begin{align*}
d^{IS}_{1}C_{c1} &= 2 + E(\theta), \quad d^{IS}_{1}C_{c2} = \frac{a + E(\theta)}{2}, \\
d^{IS}_{2}C_{c1} &= 2 - [\theta_{H}] + a_{\gamma}, \quad d^{IS}_{2}C_{c2} = \frac{a - E(\theta) - 2[\theta_{H}]}{2},
\end{align*}
$$

Fig. 2. Maritime transport chain structures under two strategies.

Fig. 3. The timing of the game.
\[ x_{c1}^{IS} = \frac{1 + a^2 + 2E(\theta)(1 + E(\theta))(1 + \gamma) + 2a(1 + E(\theta) + E(\theta)\gamma)}{4(1 - \gamma^2)}, \]
\[ x_{c2}^{IS} = -I, \]
\[ \hat{\xi}_{c1} = 1 + a^2 - 2E(\theta)^2 + 2a(1 + E(\theta)^2 + 2(1 + a + 2E(\theta)(1 + \gamma))|\theta|H - c_2(E(\theta) + |\theta|H), \]
\[ \hat{\xi}_{c2} = -I. \]

Besides, \( \hat{\xi}_{c1}^{IS} < d_{c1}^{IS} + \hat{\xi}_{c2}^{IS} < a_1 + \hat{\xi}_{c2}^{IS} \) and \( \hat{\xi}_{c1}^{IS} = \pi_1^{IS} \) and \( \hat{\xi}_{c2}^{IS} = \pi_2^{IS} \).

Proposition 4 presents the demands and revenues of the maritime transport chain members, if the actual disruption is negative and relatively larger than they expected. Results show that if the actual demand disruption is negative and relatively smaller than their expected, i.e., the chain members are optimistic about the market, investing in information channel will always benefit the carriers 1 and 2, especially when \( \lambda \) is small, i.e., the deviation between their expected demand disruption and the actual disruption is large. The results are consistent with the factual and Proposition 2 and contrary to Proposition 3.

4.1.2. The demand disruption is relatively small

If \( \hat{\theta} = \theta_1 \), given \( p_t^* \) and \( w_t \), by optimizing \( p_t^{IS} \) to maximize \( \pi_{c2} \), we obtain the following results.

Proposition 5. If the carrier 2 invests in an information channel, given \( p_t^* \), \( u_t^\circ \) and the actual demand disruption is \( \theta = \theta_1 \), we obtain that \( p_t^{IS} = \frac{1 + a^2 + 2E(\theta)(1 + E(\theta))(1 + \gamma) + 2a(1 + E(\theta) + E(\theta)\gamma)}{4(1 - \gamma^2)}, \)
\[ d_{c1}^{IS} = \frac{1 + a^2 - 2E(\theta)^2 + 2a(1 + E(\theta)^2 + 2(1 + a + 2E(\theta)(1 + \gamma))|\theta|H - c_2(E(\theta) + |\theta|H), \]
\[ d_{c2}^{IS} = -I, \]
\[ \hat{\xi}_{c1} = 1 + a^2 - 2E(\theta)^2 + 2a(1 + E(\theta)^2 + 2(1 + a + 2E(\theta)(1 + \gamma))|\theta|H - c_2(E(\theta) + |\theta|H), \]
\[ \hat{\xi}_{c2} = -I. \]

and the expected optimal and the actual revenues of the port and the carrier 2 are

\[ \hat{\xi}_{c1}^{IS} = \frac{\pi_1^{IS} + \pi_2^{IS}}{16} \]
\[ \hat{\xi}_{c2}^{IS} = \frac{\pi_1^{IS} + \pi_2^{IS}}{16} \]

Besides, we have \( \pi_1^{IS} < \pi_1^{c2} \) and \( \pi_2^{IS} > \pi_2^{c2} \).
4.2. Sharing strategy (SS)

In this subsection, we attempt to explore the conditions that the carrier 2 shares the collected demand disruption with the port will benefit her or the port, and analyze the optimal solutions for them under the SS strategy, please see Fig. 2(b). The sequence of the events here is as follows: The actual demand disruption information is realized after the investment, the carrier 2 decides whether to share the information with the port. Then, the port decides to accept the information or not, and sets \( p_1 \), \( w \). Finally, the carrier 2 determines \( p_2 \) sequentially. Under the SS strategy, both the port and the carrier 2 know the precise demand information. It is worth noting that there exists a contract between carrier 2 and the port once the latter accepts the disruption information, i.e., the carrier 2 appropriates a proportion, \( \kappa \in (0, 1) \), of the port revenue that from two channels. Then, the expected demands and actual demands of the port and the carrier 2 can be written as follows,

\[
d_s^{c1} = 1 - p_1^{SS} + p_2^{SS} + \theta, \quad d^{SS} = a - p_1^{SS} + y p_1^{SS} + \theta,
\]

where \( \theta = \theta_1 \) or \( \theta = \theta_2 \). Note that the notations with superscript “SS” denote the corresponding notations in this subsection, i.e., under the SS strategy. Integrating new strategic changes and new demand functions, their revenue functions can be written as:

\[
\begin{align*}
\pi_p^{SS} &= (1 - \kappa)(d_s^{c1} p_1^{SS} + d^{SS} w_s^{SS}), \\
\pi_{c2}^{SS} &= (p_2^{SS} - w_s^{SS}) + \kappa((d_s^{c1} p_1^{SS} + d^{SS} w_s^{SS}) - I).
\end{align*}
\]

We use backward induction to analyze the Stackelberg game, and Lemma 2 shows the optimal freight price response of the carrier 2.

**Lemma 2.** In stage 2 of the Stackelberg game, given the service price \( w \) and freight price \( p_1 \), the carrier 2’s optimal responsive price is given by

\[
p_2^{SS}(p_1^{SS}, w_s^{SS}) = \frac{1}{2} \left( \frac{a y + (1 + \gamma) \theta}{\theta} \right).
\]

The insights behind Lemma 2 are similar to Lemma 1, in which the chain members are unknown the actual precise demand disruption. Combining the constraint that \( p_2^{SS} \geq w_s^{SS} \), we have \( p_2^{SS} \geq w_s^{SS} - \frac{\theta}{\eta(1 + \gamma) y} \).

Substituting \( p_2^{SS}(p_1^{SS}, w_s^{SS}) \) into \( \pi_s^{SS} \) (see Eq. (12)), and combining the constraint, the carrier 2’s problem in this subsection can be formulated as

\[
\begin{align*}
\pi_s^{SS}(p_1^{SS}, w_s^{SS}) &= \max_{p_2^{SS}} \left\{ \left( 1 - \kappa \right) p_1^{SS} (1 - p_1^{SS}) + a y + (1 + \gamma) \left( p_1^{SS} + \theta \right) \right\} \\
&= \left( a - \kappa \left( a y + (1 + \gamma) \theta \right) \right) \frac{1}{2} \left( \frac{a y + (1 + \gamma) \theta}{\theta} \right).
\end{align*}
\]

**Proposition 6.** The port’s revenue function \( \pi_p^{SS}(p_1^{SS}, w_s^{SS}) \) is jointly concave in \( p_1^{SS} \) and \( w_s^{SS} \).

(a) If \( 0 < \kappa < \frac{1}{2} \), the optimal solutions of the port and the carrier 2 are given by

\[
\begin{align*}
p_1^{SS} &= \frac{1 + a y + (1 + \gamma) \theta}{2(1 - \gamma^2)}, \\
p_2^{SS} &= \frac{2 y + (3 - y) a + (3 - y)(1 + y) \theta}{2(1 - \gamma^2)}, \\
w_s^{SS} &= \frac{(1 - y) y + (1 - y) a + (1 - y)(1 + y) \theta}{2(1 - \gamma^2)}, \\
d_s^{SS} &= \frac{2(1 - \kappa)(1 + a y + (1 + \gamma) \theta) + (1 - \gamma^2)(a + \gamma)^{2}}{8(1 - \gamma^2)}, \\
d_s^{c2} &= \frac{8(1 - \gamma^2)}{4(1 - \gamma^2)} + \frac{(a + \gamma)^2}{16} - I.
\end{align*}
\]

(b) If \( \frac{1}{2} < \kappa < 1 \), the optimal solutions of the port and the carrier 2 are given by

\[
\begin{align*}
p_1^{SS} &= \frac{1 + a y + (1 + \gamma) \theta}{2(1 - \gamma^2)}, \\
p_2^{SS} &= \frac{\gamma + ay^2 + (1 + \gamma) \theta}{2(1 - \gamma^2)} + \frac{a + \gamma}{1 + \kappa}, \\
w_s^{SS} &= \frac{\gamma + ay^2 + (1 + \gamma) \theta}{2(1 - \gamma^2)} + \frac{a + \gamma}{1 + \kappa}, \\
d_s^{SS} &= \frac{1 + ay + (1 + \gamma) \theta}{2(1 - \gamma^2)}, \\
d_s^{c2} &= \frac{\gamma a(a + \gamma)}{1 + \kappa}, \\
\pi_p^{SS} &= \frac{(1 - \kappa)^2}{4(1 - \gamma^2)} \left( \frac{a y + (1 + \gamma) \theta}{1 + \kappa} \right), \\
\pi_{c2}^{SS} &= \frac{\gamma a(a + \gamma)}{1 + \kappa} \left( \frac{a y + (1 + \gamma) \theta}{1 + \kappa} \right).
\end{align*}
\]

**Proposition 6** presents the optimal solutions if the carrier 2 shares the collected information with the port. Clearly, the chain members should dynamically adjust the prices under varies of \( \kappa \). A higher \( \kappa \) reflects that the port will appropriate higher revenue to the carrier 2, and he will adjust his prices timely to avoid losing much revenue, and then the carrier 2 will change her price according to the port’s prices. In the following, we explore how the chain members’ prices and revenues change as \( \kappa \) increases.

We define the optimal solutions in Proposition 6 with subscript “1” denote the optimal solutions if \( 0 < \kappa < \frac{1}{2} \), and define the optimal solutions with subscript “2” denote the optimal solutions if \( \frac{1}{2} < \kappa < 1 \). The following results hold.

**Proposition 7.** \( p_1^{SS} > w_s^{SS} = p_2^{SS} > w_s^{SS} > d_s^{c1} > d_s^{c2} > d_s^{c1} > d_s^{c2} > d_s^{c1} < d_s^{c2} \).

**Proposition 7** suggests that with a higher \( \kappa \), i.e., the port will appropriate more revenue to the carrier 2, the port will set low price to attract more shippers to choose the third-part channel and then avoid losing more revenue. Then, the carrier 2 will also lower price to maximize the revenue. The results also show that the port will lose a lot of revenue with a higher \( \kappa \), but the carrier 2 will yield more revenue.

The above results encourage us to think about whether the port is always willing to accept the sharing information strategy at any \( \kappa \). In the following, we compare the revenues of the carrier 2 with and without an information sharing strategy, i.e., the revenues in Section 4.1 and Proposition 6, we obtain the following Theorem 2.

**Theorem 2.** Given \( 0 < \kappa < \frac{1}{2} \), under various actual demand disruptions, we have

(a) If \( \theta = \theta_1 \), \( \pi_{c2}^{SS} \geq \pi_{c2}^{IS} \), if \( \kappa_1 < \kappa < \frac{1}{2} \); Otherwise, \( \pi_{c2}^{SS} < \pi_{c2}^{IS} \).

(b) If \( \theta = \theta_1 \) or \( \theta = \theta_2 \), \( \pi_{c2}^{SS} \geq \pi_{c2}^{IS} \).

(c) If \( \theta = \theta_2 \), \( \pi_{c2}^{SS} \geq \pi_{c2}^{IS} \), if \( \kappa_2 < \kappa < \frac{1}{2} \); Otherwise, \( \pi_{c2}^{SS} < \pi_{c2}^{IS} \).

where \( \kappa_1 = \frac{1-(1-\gamma)(1+\gamma \theta^2)(1+\gamma \theta^2)}{4(1+y+ay+1+y \theta)} \), \( \kappa_2 = \frac{1-(1-\gamma)(1+\gamma \theta^2)(1+\gamma \theta^2)}{4(1+y+ay+1+y \theta)} \).

**Theorem 2** presents the conditions that the carrier 2’s investment benefits her. The results in Theorem 2 suggests that when the carrier 2 is optimistic about the market, i.e., her expected demand disruption is larger than the actual demand disruption, \( \theta = -\theta_1 \) or \( \theta = \theta_2 \), sharing the collected disruption with the port will always benefit her. On the contrary, if the carrier 2 is pessimistic about the market, i.e., her expected demand disruption is smaller than the actual demand disruption, \( \theta = \theta_2 \) or \( \theta = \theta_1 \), sharing the collected disruption conditionally benefits her. Specifically, there exists two thresholds \( \kappa_1 \) and \( \kappa_2 \), if the proportion \( \kappa \) is larger than the threshold, the carrier 2 is willing to share the information with the port. Otherwise, sharing the collected information will hurt her.

Since the complexity of the optimal actual revenue of the carrier 2 when \( \frac{1}{2} < \kappa < 1 \), as well as the actual revenues of the port under the IS and SS strategies, in the following, we numerically compare the
revenues of the chain members under the two strategies, to yield the conditions that the carrier 2 shares the information or not, as well as the conditions that the port accepts the information.

5. Numerical study

In this section, we numerically discuss the following problems in the maritime transport chain. Firstly, we explore the value of the precise demand disruption to the maritime transport chain, including the pricing decisions and the revenues. Then, we examine the value of the carrier 2’s investment in the information channel to the maritime transport chain, i.e., the value of IS strategy, and finally, we explore the value of information sharing between the chain members, i.e., the value of the SS strategy.

5.1. The value of the precise disruption information

Here, we compare the revenues, i.e., \( \pi_p, \pi_c, \hat{\pi}_c \), if the chain members do not know the actual disruption information \( \theta \) but know the expected disruption \( E(\theta) \) to examine the value of the precise disruption information to the chain members’ revenues. The default parameters are \( \lambda = 0.5, |\theta_H| = 0.8, |\theta_L| = 0.2, c_1 = 0.1 \) and \( c_2 = 0.05 \). It is worth noting that the notations in the following figures with subscript \( H \) denote that the actual disruption is \( \theta_H \), and with subscript \( L \) denote that the actual disruption is \( \theta_L \).

Figs. 4 and 5 present the optimal prices, the expected and actual revenues for the chain members as the channel competition gradually intensifies, if they do not know the precise demand disruption, while the actual disruption is positive (i.e., \( |\theta_L| < |\theta_H| \)) in Fig. 4 and the actual disruption is positive (i.e., \(-|\theta_L| < -|\theta_H|\)) in Fig. 5. From Figs. 4 and 5, we find that to attract more shippers to choose the direct channel, the port generally sets higher service price to promote the carrier 2 sets a higher freight price. The gap between the port’s freight price \( p_1 \) and service price \( w \) is shrinking as the channel competition intensifies. If the chain members are pessimistic (optimistic) about the market, i.e., \( E(\theta) < |\theta_H| (E(\theta) > |\theta_L|) \), the actual revenue they will yield is higher (smaller) than their expected. The results are consistent with Propositions 2, 3 and 5. Besides, from the third figures in Figs. 4 and 5, we find that given the same deviation, i.e., \( |\theta_H - E(\theta)| = |\theta_L - E(\theta)| \), more revenue will be lost if the chain members are optimistic about the market.

5.2. The value of the IS strategy

Next, we explore the value of the carrier 2’s investment in an information channel to the port and the carrier 2. If the carrier 2 obtains the precise disruption information after investing in an information channel, she generally sets a higher (smaller) freight price if the obtained disruption is higher (smaller) than her originally expected. The port will still set original prices since he does not know the precise information. Fig. 6 shows that the investment will benefit (hurt) the port when the actual disruption is \( \theta_L \), i.e., \( E(\theta) > \hat{\theta} \) (\( E(\theta) < \hat{\theta} \)).

When the actual disruption is \( |\theta_H| (|\theta_L|) \), only when the investment cost \( I < I_1 (I < I_2) \), the investment will benefit her, where \( I_1 = 0.0585 > I_2 = 0.0435 \), which further suggests that given the same deviation, investing in an information channel will bring more revenue for the carrier 2 when the actual disruption is smaller than she expected.

Fig. 7 shows that after obtaining the precise disruption information, i.e., the actual disruption is negative, the carrier 2 will set a higher (smaller) freight price if the obtained disruption is higher (smaller) than her originally expected, the results are similar to the case that the actual disruption is positive. The investment will benefit (hurt) the port when the actual disruption is \(-|\theta_H| (-|\theta_L|)\), i.e., \( E(\theta) > \hat{\theta} \) (\( E(\theta) < \hat{\theta} \)). When the actual disruption is \(-|\theta_H| (-|\theta_L|)\), only when the invest cost \( I < I_1 (I < I_2) \), the investment will benefit her, where \( I_1 = 0.0585 > I_2 = 0.0435 \). Combining the case that the actual disruption is positive, we conclude that given the same deviation, investing in an information channel will bring more revenue for the carrier 2 when the actual disruption is smaller than she expected.

5.3. The value of the SS strategy

In the following, we examine the value of the SS strategy, i.e., how the chain members’ actual revenues and prices with and without the SS strategy change under various parameters. Specifically, we consider two cases, i.e., \( \kappa_1 = 0.25 \in (0, \frac{1}{2}) \) and \( \kappa_2 = 0.75 \in (\frac{1}{2}, 1) \), in each case, two scenarios are explored, i.e., the actual disruption is positive and negative. From Section 5.2 we know that whether the actual disruption is negative or positive, the carrier 2 will be willing to invest in an information channel if the investment cost \( I < I_1 = I_2 \), and thus we choose the invest cost \( I = 0.02 \) here. It follows from Proposition 6 that the chain members should adjust prices timely as \( \kappa \) varies. Figs. 8 and 9 present the chain members’ optimal solutions under \( \kappa = 0.25 \). It follows from Figs. 8 and 9 that the higher the actual disruption, the higher the prices both the port and the carrier 2 would set, the result is consistent with Section 5.1. The second and third figures in Figs. 8 suggest that when the actual disruption is positive and the appropriate rate is relatively small, accepting the information sharing, i.e., the SS strategy, is detrimental to the port while beneficial to the carrier 2, especially when the channel competition is strong. The second and third figures in Figs. 9 suggest that when the actual disruption is relatively small, i.e., \( \hat{\theta} = -|\theta_H| \), accepting the information sharing will be beneficial to both the port and the carrier 2. When the actual disruption is relatively large, i.e., \(-|\theta_L| \), sharing information will be detrimental to the port, and may also be harmful to the carrier 2, especially when the channel competition is strong, see the second and third figures in Fig. 9.

Figs. 10 and 11 present the chain members’ optimal solutions under \( \kappa = 0.75 \). Clearly, when the misappropriation rate is relatively large, the port will set higher service price (comparing with Figs. 8 and 9) to promote the carrier 2 to increase freight price, and then more shippers will choose to the direct channel. The first figures in Figs. 10 and 11 suggest that the revenue of the carrier 2 only from the misappropriation of the port but not from the operation. Besides, from the second and
Fig. 5. Optimal solutions if the chain members do not know the actual disruption is negative.

Fig. 6. The value of the IS strategy if the actual disruption is positive.

Fig. 7. The value of the IS strategy if the actual disruption is negative.

Fig. 8. The value of the SS strategy when the actual disruption is positive and $\kappa = 0.25$.

Fig. 9. The value of the SS strategy when the actual disruption is negative and $\kappa = 0.25$. 
third figures, we find that when the misappropriation rate is relatively large, whether the actual disruption is positive or negative, accepting the SS strategy will be harmful to the port, while the SS strategy generally benefits the carrier 2, especially when the actual disruption is positive and the channel competition is strong.

Another result we could conclude from the above figures is that the strength of the channel competition will enhance the impact of information inaccuracy on the maritime transport chain.

6. Conclusions

This paper is the first to explore how asymmetry information and channel competition jointly influence operational decisions, including pricing, investing in an information channel and sharing information between chain members, in a three-level maritime transport chain composed of one port, two carriers and shippers. The demand disruption risk is the main cause of information asymmetry in this paper. Previous literature has confirmed that either the demand disruption or the channel competition significantly affect the chain members’ operational decisions and revenues, and precise demand disruption could help the chain members make accurate decisions and then improve the revenues. To explore how the precise demand disruption information and the channel competition jointly affect the chain members’ prices and revenues, we first propose a basic model in which both the port and the carriers do not know the actual disruption information but only know the expected disruption. We then extend the basic model by considering two strategies, i.e., IS strategy and SS strategy. Under the former strategy, one carrier invests in an information channel to obtain the precise disruption information while the other carrier still only knows the expected information. Under the latter strategy, the carrier who derived the precise information by investing in an information channel, shares the collected information with the other carrier and the port.

Several significant managerial insights through theoretical analysis and numerical experiments are derived. First, inaccurate disruption information generally results in inaccurate operational decisions and loss of revenue. Specifically, with inaccurate information, the prices both the port and the carriers set are generally higher than the actual optimal prices, and the revenues they actually yielded are smaller than they expected, if they are optimistic about the market, i.e., their expected disruption is higher than the actual disruption, and vice versa. Second, the carrier 2’s investment in information channel will benefit the port when they are optimistic about the market, otherwise the investment will hurt the port. For the carrier 2, the investment could help her improve the revenue if the cost of the investment is reasonable. Besides, given the same information deviation and investing cost, the investment brings more revenue for the carrier 2 when they are optimistic about the market than when they are pessimistic. Third, only when the demand disruption is negative, the deviation is relatively large, and the misappropriated rate is relatively small, accepting the information sharing is beneficial to the port. That is because the improved revenue from the precise information is greater than the decreased revenue caused by appropriating revenue to the carrier 2. For carrier 2, only when the misappropriated rate is relatively small, the port is pessimistic about the market or the channel competition is weak, sharing information may be harmful to him. That is because the decreased revenue from the port’s new pricing decision is greater than the improved revenue from the port’s sharing. Finally, the strength of the channel competition will enhance the impact of information inaccuracy on the maritime transport chain.

In spite of the significant managerial insights for investing in information channel and sharing information between the port and the carrier, there still exist several limitations, exemplified by these two: First, the demand disruption is evenly distributed over both channels and can only be high or low, which is restrictive. In practice, the disruption may be distributed over both channels based on their share of the market, and the disruption may be random. Further exploration in this direction may produce valuable results. Second, we assume the port appropriates a proportion of his total revenue to the carrier, while in practice, the port may be willing to contribute only a portion of his revenue from one channel, or contribute a fixed fee for a unit product.

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 Lemma 1. It immediately follows from Eq. (3) that \( \frac{\partial^2 \pi^S}{\partial \theta \partial \pi} < 0 \), i.e., \( \pi_2 \) is concave in \( \pi_2 \). Let \( \frac{\partial \pi_2}{\partial \pi} = 0 \), we obtain the subgame perfect Nash equilibrium as \( \pi_2^* = \frac{\pi_0 + \theta \mu}{2} \).

Proof of Proposition 1. Taking the derivatives of \( \pi_2(w, p_1) \) in Eq. (4), we obtain the Hessian matrix is,

\[
H = \begin{pmatrix}
\frac{\partial^2 \pi_2}{\partial p_1^2} & \frac{\partial^2 \pi_2}{\partial p_1 \partial \theta} \\
\frac{\partial^2 \pi_2}{\partial \theta \partial p_1} & \frac{\partial^2 \pi_2}{\partial \theta^2}
\end{pmatrix} = \begin{pmatrix}
\gamma & -1 \\
-1 & 2
\end{pmatrix}.
\]

Since \( \frac{\partial^2 \pi_2}{\partial p_1^2} < 0, \frac{\partial^2 \pi_2}{\partial \theta^2} < 0 \) and \( |H| = 2(1 - \gamma^2) > 0 \), we obtain \( \pi_2(w, p_1) \) is jointly concave in \( w \) and \( p_1 \). Thus, define \( \frac{\partial \pi_2}{\partial \theta} = 0 \) and \( \frac{\partial \pi_2}{\partial p_1} = 0 \), i.e.,

\[
\frac{\partial \pi_2}{\partial \theta} = 2 + 2p_1 + 2w + (3 + \gamma) E(\theta) + 2(1 - \gamma) = 0,
\]

\[
\frac{\partial \pi_2}{\partial w} = a + 2p_1 + E(\theta) - 2w = 0.
\]

we obtain \( p_1^* = \frac{\pi_0 + \theta \mu}{2} > 0 \). Similarly, substituting \( p_1^* \) and \( w^* \) into Eqs. (1) and (2), we obtain the expected demands of two channels and the expected optimal revenues of the port and the carrier 2.

Proof of Proposition 2. If \( \theta \leq E(\theta) \), we have \( d_1^* - \bar{d}_1 = d_2^* - \bar{d}_2 = 0 \) and then

\[
\xi^*_2 - \bar{d}_1 = p_1^*(d_1^* - \bar{d}_1) + u^*(d_2^* - \bar{d}_2) + c_2(d_1^* - \bar{d}_1) \]

\[
= (p_1^* + u^* + c_2)(\theta - \bar{\theta}) \geq 0,
\]

\[
\xi^*_2 - \bar{d}_2 = (p_1^* - u^*)(d_1^* - \bar{d}_2) + c_2(d_1^* - \bar{d}_1) \]

\[
= (p_1^* - u^*)(\theta - \bar{\theta}) \geq 0
\]

Using the similar method, we obtain that the opposite is true if \( \theta > E(\theta) \).

Proof of Proposition 3. Consider the constraint \( p_2^S > w^* \) in Eq. (10), we use a Lagrange multiplier \( \xi \geq 0 \), thus, the KKT condition is given by

\[
\begin{align*}
\alpha - 2p_2^S + \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta) + \xi \theta_H + \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta) + \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta) + \xi &= 0, \\
\xi p_2^S &= \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta), \\
\xi &= 0.
\end{align*}
\]

(i) When \( \xi > 0 \), solving the equation, we obtain that

\[
\begin{align*}
p_2^S = \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta), \\
\xi = \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta).
\end{align*}
\]

Clearly, if \( \theta_H > |\theta_H| \), \( \xi = \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta) < 0 \);

(ii) When \( \xi = 0 \), solving the equation, we obtain that

\[
p_2^S = \frac{2 + p_1^* + u^* + c_2}{2} > w^*, \quad \text{if} \quad \theta_H = |\theta_H|.
\]

The above results implies that if \( \theta_H = |\theta_H| \), \( p_2^S = \frac{2 + p_1^* + u^* + c_2}{2} > w^* \). Then, substituting \( p_2^S \) into Eqs. (7)–(9), we obtain the actual demands and revenues. Note that, if \( \theta_H = |\theta_H| \), \( d_1^S = d_2^S = \theta_H - E(\theta) > 0 \), and thus \( \Delta_1 = d_1^S - d_1^S = (p_1^* + u^* + c_2)(\theta_H - E(\theta)) > 0 \) and \( \Delta_2 = d_2^S - d_2^S = 0 \).

Proof of Proposition 4. Using the similar method in Proposition 3, we obtain that

(i) When \( \xi > 0 \), solving the equation, we obtain that

\[
\begin{align*}
p_2^S = \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta), \\
\xi = \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta).
\end{align*}
\]

Clearly, if \( \theta_H = -|\theta_H| \), we obtain that when \( \min\{\frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta) \} < \lambda < 1 \), \( \xi = \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta) > 0 \), and then \( p_2^S = \frac{2 + p_1^* + u^* + c_2}{2} > w^* \). Then, substituting \( p_2^S > w^* \) into Eqs. (7)–(9), we obtain the actual demands and revenues.

(ii) When \( \xi = 0 \), solving the equation, we obtain that

\[
p_2^S = \frac{2 + p_1^* + u^* + c_2}{2} > w^*, \quad \text{if} \quad \theta_H = |\theta_H|.
\]

When \( 0 < \lambda \leq \min\{\frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta) \} \), \( p_2^S > w^* \). Similarly, substituting \( p_2^S \) and \( w^* \) into Eqs. (7)–(9), we obtain the actual demands and revenues.

Note that, if \( \theta_H = -|\theta_H| \), \( d_1^S - d_1^S = (p_1^* + u^* + c_2)(\theta_H - E(\theta)) < 0 \), and thus \( \Delta_1 = d_1^S - d_1^S = 0 \), \( \Delta_2 = d_1^S - d_1^S = 0 \). Otherwise, \( d_1^S > d_1^S \) and \( d_1^S > d_1^S \).

Proof of Proposition 5. Using the similar method in Propositions 3 and 4, we could obtain that \( p_2^S = \frac{2 + p_1^* + u^* + c_2}{2} > w^* \). Since \( p_2^S > w^* \) holds if \( \theta = \theta_L \). Then, we could immediately obtain the expected optimal and actual solutions. It is worth noting that \( d_1^S - d_1^S = d_1^S - d_1^S = \theta_H - E(\theta) < 0 \), and \( \Delta_1 = d_1^S - d_1^S = 0 \), \( \Delta_2 = d_1^S - d_1^S = 0 \).

Proof of Theorem 1.

(i) If \( \theta = |\theta_H| \),

\[
\begin{align*}
p_2^S - \pi_1^* &= E(\theta) - \theta H \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta), \\
\xi &= 0.
\end{align*}
\]

(ii) If \( \theta = |\theta_H| \), and \( 0 < \lambda \leq \min\{\frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta) \} \),

\[
\begin{align*}
p_2^S - \pi_1^* &= E(\theta) - \theta H \frac{\pi_0 + \theta \mu}{2(1 + 3\gamma)} E(\theta), \\
\xi &= 0.
\end{align*}
\]
\[
\begin{align*}
\text{(iii) If } \hat{\theta} &= -[\theta_L], \text{ and } \frac{\partial \hat{\theta}}{\partial \theta_H} < \lambda < 1, \\
\hat{g}_{c2}^{S^*} - \sigma_{c2}^{S^*} &= \frac{(a + \hat{E}(\theta))\hat{E}(\theta) - \theta}{4} > 0, \\
\text{if } I_f < \frac{1}{16}21(\theta_H - \theta_H - \theta_H - 4c_1); \\
\text{if } I_f < \frac{1}{16}22(\theta_H - \theta_H - 4c_1) - 4c_1).
\end{align*}
\]

Besides, since
\[
I_1 - I_2 = \frac{\left[\theta_L - (\lambda(\theta_L + (1 - \lambda)(\theta_H) + (1 - \lambda)(\theta_H) + (1 - \lambda)(\theta_H) + 4c_1)ight] + \left(-(\theta_H + (\lambda(\theta_H + (1 - \lambda)(\theta_H) + (1 - \lambda)(\theta_H) + (1 - \lambda)(\theta_H) + 4c_1)ight]}{4}
\]
\[
\frac{4(\theta_H - \theta_H)}{4} > 0.
\]

Proof of Lemma 2. It immediately follows from Eq. (13) that \( \frac{d^2g_{c2}^{S^*}}{\theta_H^2} < 0 \), i.e., \( \sigma_{c2}^{S^*} \) is concave in \( P_{c2}^{S^*} \). Let \( \frac{d^2g_{c2}^{S^*}}{\theta_H^2} = 0 \), we obtain the subgame perfect Nash equilibrium as \( P_{c2}^{S^*}(P_{c2}^{S^*}, \theta_H^{S^*}) = \frac{\theta_H^{S^*}}{4} + \frac{\lambda(\theta_H^{S^*} + 1 - \lambda)(\theta_H^{S^*} + 1 - \lambda)(\theta_H^{S^*} + 1 - \lambda)(\theta_H^{S^*} + 1 - \lambda)(\theta_H^{S^*} + 1 - \lambda)})}{4}. \) Combining \( P_{c2}^{S^*} \geq w^{S^*} \), we could obtain \( P_{c2}^{S^*} \geq \frac{w^{S^*}}{7} + \frac{a + \hat{E}(\theta)}{(1 + a + \hat{E}(\theta))} \) \( \Sigma^2 \).

Proof of Proposition 6. Considering the constraint \( P_{c2}^{S^*} \geq \frac{w^{S^*}}{7} + \frac{a + \hat{E}(\theta)}{(1 + a + \hat{E}(\theta))} \) \( \Sigma^2 \)

\[
\begin{align*}
&2 + (2(1 + \kappa)\gamma_2 - 4)P_{c2}^{S^*} + 2(2 + \gamma_2)\theta + 2(1 - \kappa)\gamma_2w^{S^*} - 2\xi = 0, \\
&\alpha + 2(1 - \kappa)P_{c2}^{S^*} + \theta + 2(1 - \kappa)w^{S^*} = 0 = 0, \\
&\xi(P_{c2}^{S^*} - \frac{w^{S^*}}{7} + \frac{a + \hat{E}(\theta)}{(1 + a + \hat{E}(\theta))}) = 0; \\
&\xi \geq 0.
\end{align*}
\]

(21)
larger than the demand disruption both the port and the carriers expected.

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