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Demand Information Sharing in Port Concession Arrangements

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Abstract: This paper investigates the effects of demand information sharing on concession arrangements and market equilibria, when two ports, each managed by a welfare-maximizing port authority and a profit-maximizing port operator, compete for demands. The problem is formulated and analyzed as a multi-stage game, in which the authority and the operator at each port first decide whether to share demand information and make concession arrangements; then, the port operators compete à la *Cournot*. Alternative scenarios are compared to identify the effects of information sharing and market structure. Our analytical results identify the conditions under which demand information sharing is beneficial in port concession arrangements and highlight the importance of the underlying market structure and congestion levels in achieving these benefits. Specifically, we show that information sharing is a source of welfare improvement, and the effects are more significant when the positive externality of information sharing on welfare is large, inter-port competition is strong, and port congestion is costly. However, with no compensation, the port operators have no incentive to share their private information because otherwise, this is likely to increase concession unit-fees, limit their ability to compete effectively with each other, and ultimately reduce their expected profits. Therefore, transfer payments are necessary to encourage information sharing. With this arrangement and the assumed symmetric cost and service structure, we show that a port operator prefers sharing information if the externality of it on welfare exceeds a threshold. Furthermore, when this externality is sufficiently large, the operators at both ports benefit from sharing information. Finally, when the two ports compete in price, we show that a port operator's single-side information sharing may not always benefit its port authority.

Keywords: Port; Concession contract; Information sharing; Competition

1. Introduction

The landlord port model has been widely recognized and successfully implemented in numerous ports around the world. Although the actual arrangements may vary across different markets, in many cases, the port operator (PO) leases port infrastructure for an extended period and is responsible for daily operations and maintenance of the port's equipment. The port authority (PA) is responsible for strategic planning of essential port infrastructure and other investments, such as land development near the port, disaster prevention and relief facilities, and hinterland transportation and road networks. Capital investments in the transportation sector tend to be lumpy and involve substantial uncertainties (Kraus 1982; D'Ouville and McDonald 1990; Oum and Zhang 1990; Proost and Van der Loo 2010; Gao and Driouchi 2013; Xiao et al. 2013, 2015, 2016, 2017). Therefore, the PA must properly anticipate future demand when making these strategic decisions. POs are often better poised to secure good demand information. Many POs at landlord ports are well-established global operators with accumulated industry expertise. They also have access to the knowledge base of their branches and affiliated forwarders, and long-term business partners and customers.[1] By contrast, PAs want to encourage POs to share the demand information with them for many reasons. In the short term, more accurate demand information can help PAs make better-informed business decisions, such as the concession fees in POs' lease contract. PAs can also use the information to manage port congestion, and optimize port throughputs and operations. In the long term, the demand information can help PAs better plan port and supporting infrastructure to avoid, among other things, costly over-capacity or under-utilization. Nevertheless, a PO may be unwilling to share such information because it could potentially tip a PA to charge a higher concession fee. Therefore, understanding what concession arrangements would improve the outcome of the system as a whole is critical.

In a landlord port, the obligations and responsibilities of POs and PAs are usually specified in a concession contract, which covers issues such as the concession duration, throughput guarantee, concession fee, port governance and intra-port organizational structure, and sanctions (Notteboom, 2007). Although the information sharing arrangement can be integrated into such a contract, in

[1] In the economics literature, a common assumption is that private firms have better market information and are more responsive (the definition of "responsiveness" in our analysis is stated in the following discussions) to the market changes compared with government agencies (e.g., Osborne and Gaebler, 1992). In the port industry, PAs are government agencies, or public corporations. Therefore, a reasonable assumption is that POs have better demand information than PAs. Although few empirical studies have directly tested this assumption, supporting evidence and observations can be found in studies in the maritime industry (see, e.g., Gonzalez and Trujillo, 2009; Zheng and Yin, 2015). Specifically, Terada (2002) argued that port authorities in Japan, under the influences of both state and local governments, overinvested in capacity. As a result, even the Specifically Designated Major Ports faced financial troubles. Investments in Chinese container ports by local governments increased annually in the 1990s and 2000s, which led to huge excess, especially in the Yangtze Delta and the Pearl River Delta areas (Cullinance and Wang, 2007, Notteboom and Yang 2017). Such irrational investments can be partly attributed to PAs' poor market information and forecast techniques in these ports. Similar patterns have been observed in other industries. For example, Zhang et al. (2017) argued that local governments have been the "behind-the-scenes" operator of over-investment and redundant construction in China, whose interventions were the primary cause of coal overcapacity. Notably, government intervention may also lead port authorities to disrupt normal market outcomes and thus market signals and information. Terada (2002) argued that if a government subsidy is excessive, public services may be underpriced and thus provide more than the socially optimal quantity. He further argued that "*the port managers' accounting system and insufficient disclosure of financial statements of port business to the port users and taxpayers blur the reality of the port authority's activities.*"

practice, this issue has rarely been addressed formally in the maritime industry. Indeed, although information sharing has been studied extensively in other fields such as supply chain management (Chen, 2003), few have considered it in the maritime industry. This gap in the literature is surprising because many have argued that the port should be regarded as part of the maritime supply chain[2] (Bichou and Gray 2004; Song and Panayides 2008; Tongzon et al. 2009; Lau et al. 2013, 2017).

Port concession has been examined by many studies, including those on the definition, type, and structure of a concession contract (e.g., Trujillo and Nombela, 2000; De Monie, 2005; Notteboom, 2007); empirical studies on concession arrangements and landlord modes (e.g., Ferrari and Basta, 2009; Notteboom and Verhoeven, 2010; Cruz and Marques, 2012; De Langen et al., 2012; Farrell, 2012; Lee and Lee, 2012; Notteboom et al., 2012; Parola et al., 2012; Psaraftis and Pallis, 2012; Ferrari et al., 2015; Zhu et al. 2019); and concession contract design (e.g., Saeed and Larsen, 2010; Chen and Liu, 2014, 2015; Wang and Pallis, 2014; Wang et al., 2014; Chen et al., 2017; Liu et al., 2017a, 2017b). However, according to our review of the literature, no study has considered demand information sharing between PO and PA. This is in sharp contrast to supply chain management, where many studies have investigated information sharing. For example, Chen (2003) classifies studies on information sharing within supply chains into three categories: a central planner obtaining information to streamline the decision-making process among all parties in a supply chain; using signalling or screening to solve information asymmetry within members in a supply chain; and incentive-based information sharing between informed and uninformed parties. Jiang and Hao (2016) group the studies on incentive-based information sharing based on four criteria: the form of information sharing (horizontal or vertical), the signal structure (correlated or independent), the timing (*ex ante* or *ex post*), and the competition mode (price or quantity). These studies highlight the importance of an information sharing arrangement, because it may significantly influence the market outcome and result in asymmetric impacts on individual players.

Many studies have argued that the port sector shares common features of supply chains and thus a "supply chain approach" may be applied in the analysis and planning of sea ports (Bichou and Gray 2004; Song and Panayides 2008; Tongzon et al. 2009). For instance, in the landlord port, the PAs invest in the infrastructure and lease it to the POs. The POs pay concession fee and use the port infrastructure to handle the cargoes. The rights and obligations of the PAs and the POs are stipulated in the concession contracts. In this sense, the relationships between PAs and POs are similar to suppliers (who supply and sell the products or services) and buyers (who buy and use the products or services provided by the suppliers). Because of their professional expertise and experience, compared with PAs, POs are in better positions to obtain and learn more accurate demand information. This relationship is also similar to the information relationship between

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[2] A maritime supply chain comprises the PAs, the POs, the shipping companies, and other port users (e.g., shippers). A PA can be treated as an upstream player because she provides the infrastructure used by a PO, who is regarded as a downstream player.

suppliers and buyers, where the buyers know more about market demand than the suppliers. A concession contract has similarities as well as differences with a supply contract[3]. Thus, an expectation would be that information sharing would also play an important role in the port industry, and actually, the need for better information sharing has been well recognized by the maritime industry.

The Business Performance Innovation Network surveyed more than 200 executives and professionals in 2017 and concluded that information sharing and collaboration are of critical importance to the industry, particularly in the areas of carrier to terminal coordination, supply chain visibility and information sharing, terminal operations, cargo flow visibility and predictability, and coordination across carrier alliances.[4] The National Transport Commission Australia (2013) pointed out that companies in the maritime industry "*have discovered a need for an 'honest broker' to bring parties together in order to share common data whilst protecting commercial interests*", although the related deals "*can be very sensitive and time consuming to arrange*", and it is critical to ensure that "*efficiencies are gained in a collaborative fashion and benefit as many players as possible*." In October 2016, the United States' (U.S.) Department of Commerce Advisory Committee on Supply Chain Competitiveness recommended a list of key measures fundamental to promoting effective information sharing among ports and their stakeholders. The U.S. Department of Commerce (2016) subsequently decided that it ought to "*facilitate further coordination, communication, and information sharing at the local level*", and recommended that "*port complexes and terminal operators should implement integrated scheduling programs and appointment systems at major terminals, to improve information and data sharing, forecasting, and cargo flow*", and that "*one or more third-party data services should be established to serve as central repositories for information on freight flow and market trends*."

Despite the strong aspiration to promote information sharing and collaboration, few studies have investigated whether stakeholders have incentive to share information in the first place and whether information sharing arrangements can be sustainable. Instead, there seems to be an unproven belief that information sharing and collaboration will benefit all stakeholders and can be

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[3] Both need to specify the basic elements, e.g., duration, price, obligations and rights of both parties. However, the throughput guarantee clause is one of the specialties in the concession contract. For the other sides, e.g., the purchase frequency, demand feature, historical data, their comparisons are as follows. The purchase frequencies in supply chains show the great variety. However, the information sharing is a strategic decision, and thereby a long term relation establishment between a supplier and a buyer. The interaction between PAs and POs are also generally a long term arrangement. Port demand shows the trend of both long-term growth and short-term volatility. It is basically determined by the growth of the regional trade and economy. However, the unexpected incidents (e.g., terrorist attacks and accidents) have the suddenly impacts and difficult to predict. This basic characteristic (demand is determined by both long-term trend and short-term volatility) is similar to the demand in a supply chain. The historical deal data in supply chains is generally richer than in ports, because most of them have higher deal frequencies than ports (which have monthly throughput data). Fewer historical data may affect the accuracy of the demand information, which will be discussed in details through our model.

[4] Report titled "Competitive Gain in the Ocean Supply Chain: Innovation That's Driving Maritime Operational Transformation", prepared by Business Performance Innovation (BPI) Network in coordination with Navis and XVELA. Report released in 2017 and accessible at https://www.bpinetwork.org/thought-leadership/studies/63/download-report-competitive-gain-in-the-ocean-supply-chain

easily coordinated by government agencies.[5] Apparently, forming business strategies and government policies on solid foundations is critical, and there is an urgent need to conduct a formal investigation of this issue.

To fill this gap in the literature, we develop an analytical model to investigate the effects of demand information sharing on market equilibria when two ports, each managed by a welfare-maximizing PA and a profit-maximizing PO, compete for demands. Alternative scenarios are compared to identify the effects of information sharing and market structure. Our analytical results identify the conditions under which demand information sharing is beneficial in port concession arrangements and highlight the importance of the underlying market structure and congestion levels in achieving these benefits. Specifically, we show that information sharing is an important source of welfare improvements and that the effects are more significant when the positive externality of information sharing on welfare is larger, when there is stronger inter-port competition, and when port congestion is more costly. However, absent compensation, POs have no incentive to share their private information, because this is likely to increase concession unit-fees, limit their ability to compete effectively with each other, and ultimately reduce their expected profits. Therefore, transfer payments are necessary to encourage information sharing. With this arrangement and assuming a symmetric cost and service structure, we show that a PO prefers sharing information if the externality of sharing on welfare exceeds a threshold. Furthermore, when this externality is sufficiently large, the operators at both ports benefit from sharing information. Finally, when the two ports compete in price, instead of in quantity, we show that a PO's information sharing may not always benefit its PA.

The contributions of this study are two-fold. First, our study is among the first to consider the impact of information sharing in managing port operations. The proposed model is related to the vertical information sharing models in the supply chain literature, which can be further classified into three classes based on the supply chain structure: vertical information sharing within a one-to-one supply chain (e.g., Cachon and Lariviere, 2001; Mishra et al., 2009; Ozer et al., 2011; Li et al., 2014), vertical information sharing within a supply chain with competition (e.g., Li, 2002; Li and Zhang, 2008; Shang et al., 2016), and information sharing in a market with competing supply chains (e.g., Ha and Tong, 2008; Ha et al., 2011, 2017; Guo et al., 2014; Jiang and Hao, 2016; Shamir and Shin, 2016). Although all these studies have offered satisfactory insights into the problem specified in our paper, whether the results can be directly applied remains unclear. Supply chain studies have mostly focused on private firms that aim to maximize their respective profits, whereas many PAs are either publicly owned or *de facto* government agencies. Therefore,

[5] The Global Head Marine & Terminal Operations for the Hamburg Süd Group stated that "*everyone benefits from collaboration and data sharing. It starts with the customers and moves to the carriers, then the terminal operators, vendors, freight systems, truck companies, and keeps going down the line*." (https://worldmaritimenews.com/archives/223316/study-global-maritime-industry-needs-better-data-sharing-and-collaboration-but-change-is-coming/). The US Department of Commerce (2016) recommended better information sharing and coordination in the port sector and noted that federal funded freight project will be headed by "*a central, multimodal office in the U.S. Department of Transportation and based on the greatest payback or benefit to the supply chain*."

an investigation into the welfare implications and public-private stakeholders' interactions is critical. In addition, congestion and inter-port competition must also be explicitly addressed to reflect the industry's reality. All these topics call for a dedicated study. Second, our study identifies the pay-offs of individual stakeholders across different scenarios so that the best business practices and government policy can be determined. Because the proposed analytical framework incorporates key characteristics in the port sector, it can be used to address other initiatives proposed by government agencies such as the National Transport Commission Australia (2013) and the U.S. Department of Commerce (2016). Specifically, this paper considers the congestion cost and its impacts on demand information sharing.

The remainder of this paper is organized as follows. Section 2 presents the economic model and the benchmark case in which demand information may be shared between a PA and a PO in a monopoly port. In Section 3, we investigate the behaviour of PAs and POs when two ports compete à la *Cournot*. In Section 4, we investigate their behaviour when two ports compete in price. The last section concludes the paper and identifies areas for future investigation.

2. The economic model

In this section, we present the model to analyze a benchmark case that considers demand information between a PA and a PO in a monopoly port. We compare the outcomes with and without information sharing, respectively, to identify the conditions under which an information sharing arrangement can be sustained and examine their effects.

2.1 Model basics

We consider a port managed by a PA and a PO under the landlord model. The demand function for port service is assumed to have a linear form

$$Q = a + \theta - p \, , \qquad (1)$$

where Q is the port throughput, and a measures the demand potential. Here, θ is a random variable with zero mean and variance σ^2, which captures the influence of demand uncertainty (i.e., θ may be regarded as a demand shifter presenting uncertainty). p is a generalized price that is the sum of the port charge and congestion cost that takes the following form

$$p = f + tQ / K \, , \qquad (2)$$

where f is the per unit port charge, K is the port capacity, and t is a parameter of port delay cost. This expression of generalized price has been used extensively in studies of the port industry and of other transport terminals (see Zhang and Zhang, 2006; Xiao et al., 2012; Zheng and Negenborn, 2014).

We consider the case of a public PA, which is the dominant governance form in many markets.[6] As a government's agency, it should be appropriate to consider PAs as risk-neutral and welfare-maximizing.[7] In practice, many port concession contracts have been designed to promote traffic volumes (e.g., Notteboom et al., 2012; Lee and Lee, 2012; Chen and Liu, 2015). This practice may be ascribed to the challenges in specifying welfare in actual contracts, which is far more complex to measure compared with traffic volumes. Because welfare is likely to increase as a port handles more traffic, a reasonable assumption is that the throughput specification is consistent with the objective to maximize welfare. Another complexity is that the leading POs in the industry are multinational/foreign companies, whose profits are of little concern to local port authorities and governments. Therefore, in this study, we specify the objective of the PA as maximizing the "local" welfare, which comprises the port users' welfare, the PA's concession revenue, and potential gains from information sharing. This leads to the following specification:

$$SW = \int_0^Q p(\xi)d\xi - pQ + rQ + \tau K, \tag{3}$$

where r is the unit concession fee paid by the PO to the PA. Clearly, from the specification of welfare, it increases with port throughput Q. Parameter τ measures the positive externality/benefit to the (local) society, obtained from improved port planning and decision-making because of information sharing. Port operations benefit the port, marine shippers, and the local economy.[8] A port's activities benefit the local society include: (i) reducing production and transportation costs (Cohen and Monaco, 2008; Fujita et al., 1999), (ii) supplying inter-modal transport networks (Bryan et al., 2006), (iii) providing the function as a distribution center access to retailers and manufacturers (Cohen and Monaco, 2008; Talley, 2009), (iv) developing port-related activities (Ferrari et al., 2010), and (v) promoting employment (Acciaro, 2008). Among the aforementioned benefits, (i)–(iii) depend primarily on port capacity whereas (iv)–(v) depend primarily on port throughput. In summary, a port's positive externality can be related to both its throughput (from its demand side) and capacity (from its supply side) [9].

In our model, the contribution of throughput is captured by consumer surplus (i.e., the term "$\int_0^Q p(\xi)d\xi - pQ$" in social welfare function [3]). The positive externality dependent on port

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[6] For example, the U.S. Department of Commerce (2016) notes that almost all seaports in the United States are operated as landlord ports, with private operators leasing public, port authority-owned land to conduct day-to-day terminal operations. Only five major seaports (Houston, Savannah, Charleston, Virginia, and Baltimore) are operating ports in which state governments directly operate terminals through public port authorities. In either case, port authorities are public agencies under state governments.

[7] In the United States, port authorities such as the Massachusetts Port Authority, Port Authority of New York and New Jersey, Port of Seattle, and Port of Oakland manage both ports and airports in their cities. Welfare maximization has been a standard benchmark case for non-privatized airports. The consideration of a welfare-maximizing port authority would converge the literature on air transportation and maritime studies.

[8] Port and shipping services directly contribute to tax and employment and serve as the pillars for trade and value-added logistics services. Many studies have confirmed that port and shipping services promote the regional or national economy. Various empirical methods, e.g., input–output analysis, the multiplier model, and computable general equilibrium, have led to consistent findings of such benefits (e.g., Braun et al. 2002; Kwak et al. 2005; Pratt and Blake 2009, Lee et al. 2011, 2012, Danielis and Gregori 2013; Chang et al. 2014)

[9] For more in-depth discussions, see, e.g., Deng et al. (2013).

capacity is captured by the term "τK" in (3).[10] Improved information sharing and collaboration among stakeholders are expected to improve port planning and decisions, resulting in a positive externality on social welfare.[11] Evidently, the value of better planning and decisions should be higher for larger ports. However, according to our review of the literature, no empirical studies have suggested a particular function form to model such an effect. Intuitively, because mistakes for mega projects tend to be more costly, a convex function may be appropriate. On the other hand, there may be economies of scale effects for planning and operation, which would suggest a concave function. Absent empirical evidence, a linear specification is chosen. In our analysis, if the PA has shared information from the PO, $\tau > 0$; otherwise, $\tau = 0$.

With (1), the social welfare in (3) can be simplified as

$$SW = 1/2Q^2 + rQ + \tau K. \quad (4)$$

In practice, port concession contracts can take different forms, and concession payments may be based on unit-fee only, fixed-fee only, or a two-part tariff scheme (Notteboom, 2007; Chen and Liu, 2015; Liu et al., 2018). A fixed lump-sum payment, either in a fixed-fee payment scheme or a two-part tariff payment scheme, has no direct influence on throughput Q other than serving as a tool to transfer benefits between the PO and the PA. Because the main purpose of our study is to identify the effects of demand information sharing on the decisions of a PO and PA and the market outcomes, a unit-fee scheme is adopted. [12]

The clauses of the minimum throughput guarantee play a critical role in concession contracts for PAs to secure reasonable port productivity and revenue, lower the entry barriers to newcomers, and provide necessary incentives to POs to increase terminal utilization rates (Notteboom, 2007; Pallias et al., 2008). A few studies on port concession contracts (e.g., Chen and Liu, 2015; Liu et al., forthcoming) have explicitly incorporated the minimum throughput constraint. However, we exclude this constraint from our model because the welfare term in the objective function (i.e., the term $\int_0^Q p(\xi)d\xi$ in Eq. 3) already captures the positive externality of port operations and

[10] With more demand information shared by the PO, the PA can have better plans for port development of the related activities. Moreover, the port congestion relief (achieved by its capacity expansion) may also affect the local society. These positive externalities depend on port capacity. Some empirical studies have indicated that port capacity has positive impacts on the local society, e.g., Deng et al. (2013). Similar arguments (the effects of transport infrastructure capacity on welfare) can be found in other transportation industries, e.g., railway and road (see Pradhan and Bagchi, 2013).

[11] Ports Australia (2013) argues that better port planning creates additional economic value through increased industry and investment confidence; assists overall supply chain management by integrating the port into broader network consideration and better understanding within regional and local planning agencies; provides increased environmental protection; promotes alignment between National and State/Territory port strategies; and identifies beyond the port infrastructure requirements, e.g., surface transport corridors, allied infrastructure requirements on power, water, sewerage, telecommunications, and inland terminals/hubs. Therefore, it is important to manage and plan a port beyond the port boundary. Anthony Albanese, the Australian Minister for Infrastructure, Transport, Regional Development and Local Government, stated that "*If we are to meet the challenge of growth we must move away from ports being treated like islands; unconnected from broader planning and transport links in the cities and regions where they are sited*".

[12] In the social welfare function (4), r is a decision variable determined by the PA (more discussions in the following sections). *Ceteris paribus*, a PA prefers more concession revenue. From Liu et al. (2018), we know that the unit-fee contract is the best choice to achieve more concession revenue, which supports the choice of the unit-fee contract in out paper.

throughput to the local community (hence, a PA's desired to maximize the social welfare). Such a simplification also ensures that closed-form solutions can be obtained and compared.

We assume that the PO has a private demand signal[13] Y, which is an unbiased estimator of θ. The expectation of θ conditional on the signal is a linear function of the signal, namely,

$$E[\theta \mid Y] = \frac{\eta\sigma^2}{1+\eta\sigma^2} Y, \tag{5}$$

where $\eta = 1/Var[Y \mid \theta]$ measures the accuracy of the demand signal, with a bigger η indicating lower accuracy. The PO and the PA (if she obtains the shared information from the PO) can use the signal Y to improve their estimations on the random part of the demand, namely, θ, through (5).[14]

The PO maximizes her operating profit as follows:

$$\pi = (f - c - r)Q, \tag{6}$$

where c is her constant marginal cost. Here, we assume that $a > c$. Notably, π denotes the PO's profit associated with port services and does not include any transfer payment related to information sharing, as discussed in the following sections. Such a definition facilitates our discussions and solutions.

Formally, the behaviour of the PA and the PO is described in the following multi-stage game:

- Stage One: The PA offers a lump-sum payment T to promote the PO to share demand information. If the PO accepts this payment, she promises to share her private demand information. Otherwise, no payment is made.
- Stage Two: The PO observes a demand signal Y and truthfully reports it to the PA if she agreed to share the information in Stage One.
- Stage Three: The PA determines the unit concession fee r.
- Stage Four: The PO makes a quantity decision (i.e., port throughput) and pays the concession fee rQ to the PA.

In the maritime industry, the transfer payments T, as the rewards from the PAs to the POs, can be actually arranged in various ways through their long-term collaboration. Once the POs agree to information sharing with the PAs, they want to establish the coordination relationship with their corresponding PAs and therefore get the payments under the agreement. This payment can take the form of subsidies, or based on other preferential policies to the POs. In reality, a variety of

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[13] The demand signals may come from different sources, e.g., the throughput development trend learned by the PO from the historical data, the market information acquired by the PO's branches and subsidiaries, affiliated forwarders, and the PO's major customers with long-term contracts. The main assumption here is that the PA does not have access to all of the PO's information and expertise.

[14] Without the signal Y, $Var(\theta) = \sigma^2$. With the signal Y, $Var(\theta \mid Y) = \frac{\eta^2\sigma^4}{(1+\eta\sigma^2)^2} Var(Y \mid \theta) = \frac{\eta\sigma^4}{(1+\eta\sigma^2)^2} < \sigma^2 = Var(\theta)$. Therefore, signal Y can help the PO to reduce her estimation variance on θ (i.e., improve her estimation accuracy, with a bigger η indicating lower accuracy). A similar definition is common in the information sharing literature, e.g., Li (2002), Li and Zhang (2008).

subsidies are provided to the POs[15]. These subsidy or preferential policies do not always take the form as a concession unit-fee and are often paid after certain conditions are satisfied. Although these subsidies/preferential policies may not be formally connected to information sharing, they demonstrate that it is possible to separate the transfer payments and the unit-fee in the port concession arrangements.

Notably, (i) the information sharing clause is negotiated *ex ante* when neither the PA nor the PO has the demand signal, and (ii) the unit-fee is determined conditionally on a demand signal. Although more information is available, demand is still not deterministic.[16] Such a feature allows us to capture significant market dynamics in the maritime sector[17].

In practice, a PO could cheat, namely, provide false information to the PA. In this paper, for several reasons, we assume that the PO will truthfully reveal her demand information to the PA when she agrees to share. First, the port demand can be verified *ex post*. The cargo flow in and out of ports are routinely monitored and reported. If the PO misreports demand information, it may be caught by the *ex post* data[18]. The POs' cheating behaviour may trigger a penalty and reduce her payoff in the next contract period. In practice, even with observed data, such cheating behaviour may not be precisely and completely identified. As a result, a proper way to model this issue may involve the specification of a probability of identifying false reporting behaviour; this, however, would further complicate our model and analytical results, making it difficult to obtain economic intuitions. Second, concession contracts are usually long-term agreements that span decades, and on such a time scale, a player's incentive to cheat usually diminishes. Third, as many port operations and management concerns call for cooperation among stakeholders, PAs have various types of leverage to discourage POs' cheating behaviour (Notteboom, 2007; Notteboom et al., 2012).[19] Because many POs are global operators that have a presence in many ports, false

[15] For instance, PAs can use a lump-sum subsidy or the reduction of the pilot and tug fees (see the report of "The subsidies and preferential policies proposed by the Fuzhou city government to promote the development of port production" in http://www.chineseport.cn/bencandy.php?fid=47&id=246558).

[16] When the PA makes the decision on the unit-fee, even under the information sharing case, she still does not know the exact demand because the signal shared by the PO, i.e., Y, can only be used to improve her prediction of the future demand. Notably, Y is not equal to θ, and using Y can only obtain the expectation of θ through Eq. (5).

[17] There may be alternative means to specify the game structures. For example, let the transfer payments and the unit-fees be offered together, BEFORE the POs receive their demand information signals (i.e. both the payments and the unit-fee are offered in Stage 1). Notably, the POs' demand for information sharing with their PAs is of little value under such a setting because the PAs cannot use the shared information in their decisions (the unit-fees have been determined before the PAs obtain the shared information from the POs). If the transfer payments and the unit-fees are offered together, AFTER the POs receive and share their demand information signals (i.e., both the payments and the unit-fees are offered in Stage 3), the PAs may unilaterally reduce the payments to the POs, who by this time have already made information sharing and hence have no bargain power. Therefore, no PO would be willing to share information under such a game structure. Therefore, we use the game structure described, which ensures the mutual benefits of both parties (i.e., the PAs offering payments in Stage 1 to encourage the POs to share their information and the PAs' unit-fee decision is made after the POs' information sharing).

[18] When the demand information sharing occurs, it is the PO's signal, i.e., Y, to be shared and that should be verified *ex post*. Because of the PO's professional expertise, market survey efforts, and experiences, the demand signal is positively related to the realized demand, or the port throughput, which is easy to verify *ex post*.

[19] For example, although (terminal) related port charges are usually determined by the PO in a landlord port, many port operation and navigation related charges (e.g. navigation services fees, pilotage and anchorage charges, environment and pollution charges, dangerous goods/oil inspection) are determined and collected by the PA. Many port operations require close cooperation between POs and PAs (Lam et al. 2013) or competing ports in adjacent

reporting not only destroys the long-term relationship with the PA in question but may also harm the POs' global reputation and the goodwill at other ports. For various reasons, including those discussed, honest information sharing has been found sustainable in real markets across different transportation sectors. For example, the Port of Hamburg applies a cloud-based IT platform developed and provided by SAP that links transportation and logistics partners to share information and specific route sections and monitor the movements of trucks (Interreg 2018). In the aviation industry, airports commonly supply airlines route-specific demand information and forecasts, to attract more direct aviation/flight services (for specific cases in Australia for example, see Lohmann and Vianna 2016). An airport could have an incentive to over-report/overestimate future demand in such a case; however, doing so leads the airport to lose its credibility in attracting more airlines' services. All these real industry practices suggest that when stakeholders' interests are taken care of, it is common for them to honestly cooperate under realistic market settings. Finally, explicitly incorporating cheating and its prevention into the analysis would complicate the model considerably and make the analytical results difficult to interpret[20]. Instead, we focus on whether information sharing can provide sufficiently large benefits such that both the PO and the PA can be better off, and as a result, it is rational for them to truthfully cooperate.[21] We shall leave the relaxation of the "truthful revealing assumption" to a further research.

2.2 Market outcome with information sharing

The multi-stage game is solved with backward induction. The PO's decision problem is as follows[22]:

$$\max_{Q} E(\pi) = E[(f - c - r)Q]. \tag{7}$$

With (1) and (2), we have $f = a + \theta - Q(1 + t / K)$, and the PO's best strategy is obtained as

areas (Wang et al. 2012; Homsombat et al. 2013, 2016; Zhu et al. 2019).

[20] An argument could be that the principal–agent framework can be applied to our problem. However, if we use a principal–agent framework, a concession contract offered by the PA should be nonlinear (i.e., the unit-fee is a nonlinear function of Y). This adds more complexity to the concession contract and makes it difficult to implement. By contrast, because the PO's shared demand information can be verified *ex post* in our problem, the linear concession contract can guarantee truthful sharing with proper compensation. In addition, we aim to investigate the impact of the accuracy of the demand information on information sharing, which can be conveniently analyzed by η in our model. However, analyzing the signal accuracy under the principal–agent framework involves complex signaling game models (with the complicated discussions on the pooling equilibrium and separate equilibrium, even for the simplest case of the binary signals). These technical challenges add more difficulties to both the modeling work and the implementation concerns in reality. Therefore, we adopt the truthful reporting assumption and do not use the principal–agent framework in this paper. Further research could consider the principal–agent framework or the "cheap talk" mechanism (Crawford and Sobel 1982) to analyze how to avoid possible misreporting of the PO.

[21] The basic insights (the details are provided in the model discussions) from our model (based on the assumption that the PO's report can be verified) are similar to the principal–agent model (where the PO's truthful reporting should be incentivized). Both emphasize that volunteer information sharing is not possible unless the proper subsidy is offered.

[22] In Stage 1 of the game between the PA and the PO, when the PO decides whether to agree to share demand information, she cannot observe the demand signal Y. Therefore, Y is a random variable to her in Stage 1, and the PO calculates her expected profit to make the information sharing decision. In Stage 2, the PO observes Y, which becomes a deterministic parameter to her and is included in her quantity decision. The same logic applies to the PA when she decides the lump-sum payment T and calculates her expected local welfare.

$$Q = \frac{K[a + E(\theta \mid Y) - c - r]}{2(t+K)}. \tag{8}$$

If the PO shares her private demand signal with the PA, the PA's objective function can be expressed as

$$\max_r E(SW) = E(Q^2 \mid Y)/2 + rE(Q \mid Y) + \tau K. \tag{9}$$

Substituting (8) into (9) and solving it leads to the PA's optimal unit concession fee under information sharing

$$r^S = \frac{(2t+K)[a + E(\theta \mid Y) - c]}{4t+3K}, \tag{10}$$

where superscript "S" indicates the case of information sharing. Substituting (10) into (8), the PO's optimal throughput is obtained as

$$Q^S = \frac{K[a + E(\theta \mid Y) - c]}{4t+3K}, \tag{11}$$

Substituting (11) into $f = a + \theta - Q(1 + t/K)$, where θ should be treated as $E(\theta \mid Y)$, the port charge is obtained as

$$f^S = \frac{(3t+2K)[a + E(\theta \mid Y)] + (t+K)c}{4t+3K}. \tag{12}$$

Substituting (10), (11), and (12) into (7), the PO's *ex ante* expected profit is

$$E^S(\pi) = \frac{K(t+K)}{(4t+3K)^2}[(a-c)^2 + \delta], \tag{13}$$

where $\delta = E([E(\theta|Y)]^2) = \dfrac{\eta\sigma^4}{1+\eta\sigma^2}$.[23] Substituting (10) and (11) into (9), the PA's *ex ante* expected welfare is

$$E^S(SW) = \frac{K[(a-c)^2 + \delta]}{2(4t+3K)} + \tau K. \tag{14}$$

[23] $E[\theta^2 \mid Y]$ and $Var[\theta \mid Y]$ are the conditional expectations of θ^2 and the conditional variance of θ based on the PO's signal Y. From (5), we have $E[\theta \mid Y]^2 = \dfrac{\eta^2\sigma^4}{(1+\eta\sigma^2)^2} E[Y^2 \mid \theta]$. In addition, $E[Y^2 \mid \theta] = Var(Y \mid \theta) + [E(Y \mid \theta)]^2$. From the definition of η, we know that $\eta = \dfrac{1}{Var[Y \mid \theta]}$. $E[Y \mid \theta] = \theta$ because Y is an unbiased estimator of θ. Therefore, $E[E[Y^2 \mid \theta]] = 1/\eta + E[\theta^2] = 1/\eta + Var(\theta) + (E[\theta])^2 = 1/\eta + \sigma^2$. Finally, we have $E[E[\theta \mid Y]^2] = \dfrac{\eta\sigma^4}{1+\eta\sigma^2}$.

2.3 Market outcome without information sharing

Absent information sharing, we have $E(\theta\,|\,Y)=E(\theta)=0$. Therefore, the PA's response function to the PO, namely, (8), becomes $Q=\dfrac{K(a-c-r)}{2(t+K)}$.[24] Substituting this into the PA's objective function, which is now expressed as $\max_{r} E(SW)=E(Q^2)/2+rE(Q)$, the optimal unit concession fee without information sharing can be solved as

$$r^N=\frac{(2t+K)(a-c)}{4t+3K}, \tag{15}$$

where superscript "N" indicates the case without information sharing. Substituting (15) into (8), the PO's optimal output (port throughput) and port charge are solved as[25]

$$Q^N=\frac{K(a-c)}{4t+3K}+\frac{KE(\theta\,|\,Y)}{2t+2K}, \tag{16}$$

$$f^N=\frac{(3t+2K)a+(t+K)c}{4t+3K}+\frac{E(\theta\,|\,Y)}{2}. \tag{17}$$

Substituting (15)–(17) into (7), we obtain the PO's *ex ante* expected profit without information sharing as

$$E^N(\pi)=\frac{K(t+K)(a-c)^2}{(4t+3K)^2}+\frac{K\delta}{4(t+K)}, \tag{18}$$

Substituting (15) and (16) into the PA's *ex ante* expected welfare $E(SW)=E(Q^2)/2+rE(Q)$, we obtain

$$E^N(SW)=\frac{K(a-c)^2}{2(4t+3K)}+\frac{K^2\delta}{8(t+K)^2}. \tag{19}$$

2.4 Effects of information sharing

To identify the effects of information sharing, we compare the market outcomes in the cases with and without information sharing. From (5), clearly, the conditional expectation of θ (i.e.,

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[24] When the PA determines the unit concession fee r, she must consider the PO's response Q, which contains the PO's expectation on θ, i.e., $E(\theta\,|\,Y)$. In Section 2.2 with information sharing, $E(\theta\,|\,Y)=\dfrac{\eta\sigma^2}{1+\eta\sigma^2}Y$ to the PA because she knows the shared signal Y. In the section without information sharing, $E(\theta\,|\,Y)=E(\theta)=0$ to the PA because in this case, she does not know Y and only has an unconditional expectation of θ. In this case, the PA can still predict the PO's response Q but in a different manner.

[25] When the PO makes the quantity decision Q^N (given r^N) in the case without information sharing, she knows Y. Therefore, we must substitute (15) into (8), instead of into $Q=\dfrac{K(a-c-r)}{2(t+K)}$, to obtain Q^N.

$E(\theta \mid Y)$) is positively related to the demand signal Y. Therefore it is easy to check that $r^S > r^N$ ($r^S < r^N$) if the demand signal is $Y > 0$ ($Y < 0$). That is, with information sharing, the unit concession fee is higher or lower if the demand signal is positive or negative, respectively. The economic intuition is that the PA's decision (the unit-fee) is more effective for the demand signal. When she receives a positive demand signal from the PO, the demand is expected to be higher, leading to a higher unit-fee to extract more revenue. When she receives a negative demand signal from the PO, the demand is expected to be lower, leading to a lower unit-fee to encourage the PO to increase output. Therefore, the unit-fee is more responsive[26] under demand information sharing. Additionally, the port output is negatively affected by the unit-fee (hence, less responsive with information sharing), and the port charge is positively affected by the unit-fee (hence, more responsive with information sharing).

It is straightforward to demonstrate that

$$\Delta E(\pi) = E^S(\pi) - E^N(\pi) = -\frac{K\delta(5K^2 + 16Kt + 12t^2)}{4(t+K)(4t+3K)^2} < 0, \tag{20}$$

which suggests that the PO's expected profit from a port's operation is lower with information sharing. The expected local welfare is higher because

$$\Delta E(SW) = E^S(SW) - E^N(SW) = \tau K + \frac{K\delta(K^2 + 4Kt + 4t^2)}{8(t+K)^2(4t+3K)} > 0. \tag{21}$$

If the PA provides the payment $|\Delta E(\pi)|$ to the PO for information sharing, it can guarantee that the PO's expected profit under information sharing is not less than the profit without information sharing, which is the PO's individual rationality (IR) constraint. Because $\Delta E(\pi) + \Delta E(SW) = \tau K - \dfrac{K\delta(7K^3 + 26K^2 t + 28Kt^2 + 8t^3)}{8(t+K)^2(4t+3K)^2}$, it can be concluded that $\Delta E(\pi) + \Delta E(SW) \geq 0$ if $\tau \geq \dfrac{\delta(7K^3 + 26K^2 t + 28Kt^2 + 8t^3)}{8(t+K)^2(4t+3K)^2}$, which means that the PA's gain in net local welfare after information sharing is positive, and the payment $|\Delta E(\pi)|$ can be afforded by the PA. In other words, if the externality of information sharing on local welfare is greater than a threshold, the local welfare increase is larger than the PO's profit loss after information sharing. Therefore, it is possible to improve the PA's profit (or satisfy her IR constraint) and local welfare simultaneously if a proper transfer payment is provided from the PA to the PO in exchange for information sharing. These analytical results are summarized in Proposition 1.

[26] In our paper, more (or less, respectively) responsiveness means that the target variables (e.g., the port output, port charge and unit-fee) are higher (or lower, respectively) under the positive demand signal and lower (or higher, respectively) under the negative demand signal, compared to the case without information sharing.

Proposition 1. *Demand information sharing allows both the PA and PO to incorporate a demand signal into their decisions on the unit concession fee and port charge, which leads to more responsive port output and higher local welfare. However, the PO's operation profit from port operation is lower. When the externality of information sharing on welfare is sufficiently high (i.e.* $\tau \geq \dfrac{\delta(7K^3 + 26K^2 t + 28Kt^2 + 8t^3)}{8(t+K)^2(4t+3K)^2}$ *in our model), it is possible to increase the PO's profit and local social welfare simultaneously. If the PA provides the payment* $\left|\Delta E(\pi)\right|$ *to the PO, voluntary information sharing from the PO can be achieved.*

The intuition of Proposition 1 is as follows. Information sharing improves local welfare by providing two benefits: a positive externality for local society from better port planning, and the PA's more effective decision-making. However, the demand information sharing makes the PO lose her information advantage and thereby lowers her operational profit. When the externality of information sharing on local welfare is sufficiently large, the PA can pay the PO for sharing information, leading to a win–win outcome: both receive benefits, and voluntary information sharing can be achieved.

Next, we explore the effects of port congestion, accuracy of the demand signal, and the variance of demand on information sharing. It is straightforward to show that $\dfrac{\partial[\Delta E(\pi) + \Delta E(SW)]}{\partial t} > 0$, $\dfrac{\partial[\Delta E(\pi) + \Delta E(SW)]}{\partial \eta} < 0$, and $\dfrac{\partial[\Delta E(\pi) + \Delta E(SW)]}{\partial \sigma^2} < 0$. As discussed, $\Delta E(\pi) + \Delta E(SW)$ is the overall change in a PO's profit and local social welfare, parameter t reflects the cost of port congestion, and η and σ^2 are the parameters reflecting the accuracy of the demand signal and the variance of demand shifter θ, respectively. Intuitively, as both the PA and the PO more effectively incorporate the demand signal, the benefit of information sharing is more significant when congestion is more costly. However, if the demand is very unpredictable and the signal is not at all reliable, information sharing does not help much. These results are summarized in the following corollary:

Corollary 1. *The total benefits of demand information sharing, defined as the sum of the change in a PO's operating profit and local welfare, increases in the cost of congestion and the accuracy of the demand signal, but decreases the variance of demand.*

Corollary 1 suggests that demand information sharing between the PO and PA is more likely to be sustainable in markets where congestion is more costly, when the demand signal is more accurate and the demand is less variable.

3. Demand information sharing between two ports

This section examines the effects of information sharing when two ports compete with substitutable services. We first present the model basics in two competing ports. Next, the market equilibria under different scenarios, namely, information sharing at both ports, information sharing at neither port, and information sharing in one port only, are analyzed. Finally, by comparing market equilibria across different scenarios, we investigate the PAs' decisions on demand information sharing.

3.1 Model basics in two competing ports

We consider two competing ports that provide substitutable but differentiated services, the demand of which can be expressed as

$$p_i = a + \theta - Q_i - bQ_j, \tag{22}$$

where Q_i and Q_j are the throughputs of Port *i* and Port *j*, respectively; p_i is the generalized price for port *i*, where $b \in (0,1]$ measures the substitutability of port services, which also reflects the degree of competition between the two ports. A larger b corresponds to more homogenous port services and thus more significant port competition. Here, we assume that $a > \max(c_i, c_j)$, where c_i and c_j are the marginal costs of PO *i* and PO *j*, respectively. Each PO has her own private demand signal, denoted as Y_i with accuracy $\eta_i = 1/Var[Y_i \mid \theta]$. Similar to the case of a monopoly port, we model that the expectation of the demand shifter θ is conditional on the signal Y_i; thus, we have

$$E[\theta \mid Y_i] = E[Y_j \mid Y_i] = \frac{\eta_i \sigma^2}{1 + \eta_i \sigma^2} Y_i, \tag{23}$$

Eq. (23) implies that PO *i* can use her signal Y_i to improve her estimation on θ and to predict PO *j*'s signal.[27] Moreover, the two POs' signals are independent from each other, or $\mathrm{cov}(Y_i, Y_j) = 0$. PA *i*'s objective is to maximize local welfare which is specified as[28]

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[27] Notably, PO *i* does not know PO *j*'s signal Y_j and has to use her own signal Y_i to estimate it by Eq. (23). Moreover, Eq. (23) means the estimation methods of θ and Y_j are the same.

[28] In our paper, PA *i*'s objective is to maximize local welfare, which is the sum of the net surplus of the consumers in the area of port *i*, PA *i*'s concession revenue, and her potential gains from information sharing. Here, the net surplus of the consumers in the area of port *i* is $CS_i = \int_0^{Q_i} p_i(x, Q_j)dx = (a+\theta)Q_i - Q_i^2/2 - bQ_iQ_j - p_iQ_i$. This form of consumer surplus differs from that used by Singh and Vives (1984), where $CS(Q_i, Q_j) = (a+\theta)(Q_i + Q_j) - (Q_i^2 + 2bQ_iQ_j + Q_j^2)/2 - p_iQ_i - p_jQ_j$. Their function can be used to represent consumer surplus for the whole area of Port *i* and Port *j*. Notably, $CS(Q_i, Q_j) > CS_i + CS_j$, which

$$SW_i = CS_i - p_iQ_i + r_iQ_i + \tau_iK_i = 1/2Q_i^2 + r_iQ_i + \tau_iK_i . \quad (24)$$

Following other models on port competition (e.g., Van Reeven 2010; Kaselimi et al. 2011; Wan and Zhang 2013; Yip et al. 2014; Chen and Liu 2016), we assume that the two POs compete in Cournot to maximize their individual profits. The behaviour of the PAs and POs is described as follows:

- Stage One: PA i offers a lump-sum payment T_i to PO i in exchange for sharing her demand information. PO i can either accept this payment and share her private demand information or decline the offer and associated payment. For the convenience of discussion, we assume that the PO shares information when she is indifferent toward the two options.
- Stage Two: PO i observes demand signal Y_i and truthfully reports it to PA i if information sharing has been agreed to.
- Stage Three: PA i determines her unit concession fee r_i.

The aforementioned game setup also applies to PA j and PO j.

- Stage Four: The two POs compete in Cournot and pay concession fees to their respective PAs.

Notably, both PAs choose their corresponding payment independently and simultaneously in Stage One. In Stage Three, both PAs choose their unit-fees independently and simultaneously[29]. Moreover, because unit-fee r_i is a part of the concession contract between PA i and PO i, a reasonable assumption is that it is not observable to PA j and PO j. Because each pair of PA and PO can choose to share information or not, the following alternative scenarios are considered: both ports share their demand information, only one port shares the demand information, and no port shares their demand information.

3.2 Market equilibria under different scenarios

Using backward induction (detailed solutions are presented in the Appendix), we obtain the market equilibria under different scenarios (summarized in Table 1). Comparing these equilibria, it is evident that the PO's optimal throughput decision is a linear function of her demand signal. The information-sharing decisions only affect the slopes of the POs' throughput decisions with respect to their demand signals. This finding has notable implications for the sensitivity of port throughput, port charge, and the PAs' unit-fees (Section 3.3). Moreover, we know that PA i's unit-fee can be divided into two parts: (i) the "regular part" not related to PO's shared information, namely,

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satisfies the concave property of the consumer surplus function. Additionally, this inequality reflects the welfare loss caused by the competition between these two ports (compared with a centralized social planner). Such an approach is used to reflect the reality that competing ports and their PAs (e.g., Shanghai vs. Busan, Singapore vs. Hong Kong, Rotterdam vs. Hamburg) usually only consider benefits to their local economy instead of the whole regional/catchment area.

[29] Here, we do not consider the case of a sequential move by the PAs because it leads to more assumptions and complexities, e.g., the information disclosure problem between the two ports. We leave this topic to further research.

$\frac{(2m_i-1)}{4m_i-1}(a-bA_j-c_i)$, and (ii) the "signal dependent part" related to the shared demand information from PO i, namely, $\frac{(2m_i-1)}{4m_i-1}(1-bB_j^{SS})E(\theta\,|\,Y_i)$ and $\frac{(2m_i-1)}{4m_i-1}(1-bB_j^{NS})E(\theta\,|\,Y_i)$. The "signal-dependent part" is positively related to the demand expectation formed through the signals supplied by PO i. Similar properties are observed in the port charges, the POs' expected profits, and the PAs' expected local welfares. These properties provide insights into the POs' operation management and the policy implications for the PAs regarding their regulations, discussed in the last section.

Table 1 Market equilibria under different scenarios
when two POs engage in a Cournot competition

Port i	Port j: Sharing	Port j: Not sharing
Sharing	$Q_i^{SS}=A_i+B_i^{SS}Y_i$ $r_i^{SS}=\frac{(2m_i-1)}{4m_i-1}[a-bA_j+(1-bB_j^{SS})E(\theta\,|\,Y_i)-c_i]$ $f_i^{SS}=\frac{(3m_i-1)}{4m_i-1}[a-bA_j+(1-bB_j^{SS})E(\theta\,|\,Y_i)]+\frac{m_i}{4m_i-1}c_i$ $E_i^{SS}(\pi)=\frac{m_i[(a-c_i-bA_j)^2+(1-bB_j^{SS})^2\delta_i]}{(4m_i-1)^2}$ $E_i^{SS}(SW)=\frac{(a-c_i-bA_j)^2+(1-bB_j^{SS})^2\delta_i}{2(4m_i-1)}+\tau_iK_i$	$Q_i^{SN}=A_i+B_i^{SN}Y_i$ $r_i^{SN}=\frac{(2m_i-1)}{4m_i-1}[a-bA_j+(1-bB_j^{NS})E(\theta\,|\,Y_i)-c_i]$ $f_i^{SN}=\frac{(3m_i-1)}{4m_i-1}[a-bA_j+(1-bB_j^{NS})E(\theta\,|\,Y_i)]+\frac{m_i}{4m_i-1}c_i$ $E_i^{SN}(\pi)=\frac{m_i[(a-c_i-bA_j)^2+(1-bB_j^{NS})^2\delta_i]}{(4m_i-1)^2}$ $E_i^{SN}(SW)=\frac{(a-c_i-bA_j)^2+(1-bB_j^{NS})^2\delta_i}{2(4m_i-1)}+\tau_iK_i$
Not sharing	$Q_i^{NS}=A_i+B_i^{NS}Y_i$ $r_i^{NS}=\frac{(2m_i-1)}{4m_i-1}(a-bA_j-c_i)$	$Q_i^{NN}=A_i+B_i^{NN}Y_i$ $r_i^{NN}=\frac{(2m_i-1)}{4m_i-1}(a-bA_j-c_i)$

	$f_i^{NS} = \frac{(3m_i-1)(a-bA_j)}{4m_i-1} + \frac{(1-bB_j^{SN})}{2}E(\theta\mid Y_i) + \frac{m_i}{4m_i-1}c_i$ $E_i^{NS}(\pi) = \frac{m_i(a-c_i-bA_j)^2}{(4m_i-1)^2} + \frac{(1-bB_j^{SN})^2\delta_i}{4m_i}$ $E_i^{NS}(SW) = \frac{(a-c_i-bA_j)^2}{2(4m_i-1)} + \frac{(1-bB_j^{SN})^2\delta_i}{8m_i^2}$	$f_i^{NN} = \frac{(3m_i-1)(a-bA_j)}{4m_i-1} + \frac{(1-bB_j^{NN})}{2}E(\theta\mid Y_i) + \frac{m_i}{4m_i-1}c_i$ $E_i^{NN}(\pi) = \frac{m_i(a-c_i-bA_j)^2}{(4m_i-1)^2} + \frac{(1-bB_j^{NN})^2\delta_i}{4m_i}$ $E_i^{NN}(SW) = \frac{(a-c_i-bA_j)^2}{2(4m_i-1)} + \frac{(1-bB_j^{NN})^2\delta_i}{8m_i^2}$

Note: (1) In order to save the space, we only represent Port *i*'s outcomes. Because the two ports are symmetric, one can easily write out Port *j*'s outcomes based on Port *i*'s. (2) Definitions of the related parameters are presented in Appendix.

3.3 Comparisons across scenarios

The following proposition summarizes the differences between these scenarios. All proofs are provided in the Appendix.

Proposition 2. *Given a positive signal Y_i, the port throughputs under the different scenarios have the following orders: $Q_i^{SN} < Q_i^{SS} < Q_i^{NS}$ and $Q_i^{SN} < Q_i^{NN} < Q_i^{NS}$; the port charges under the different scenarios have the following orders: $f_i^{NN} < f_i^{SN} < f_i^{SS}$ and $f_i^{NN} < f_i^{NS} < f_i^{SS}$; the unit-fees under the different scenarios have the following orders: $r_i^{NN} = r_i^{NS} < r_i^{SN} < r_i^{SS}$. Given a negative signal Y_i, these variables under the different scenarios have the opposite directions to the aforementioned orders. However, the expected PO's operating profits and the expected local social welfare under different scenarios always has the following orders: $E_i^{SN}(\pi) < E_i^{SS}(\pi) < E_i^{NS}(\pi)$, $E_i^{SN}(\pi) < E_i^{NN}(\pi) < E_i^{NS}(\pi)$, $E_i^{NN}(SW) < E_i^{SN}(SW) < E_i^{SS}(SW)$, and $E_i^{NN}(SW) < E_i^{NS}(SW) < E_i^{SS}(SW)$, regardless of the sign of signal Y_i.*

Proposition 2 suggests that a PO's decision to share information has different impacts on herself and the competitor. By comparing the coefficients of the conditional expectation of θ (i.e., $E[\theta|Y_i]$), clearly, information sharing makes a port's own throughput less responsive, whereas her competitor's throughput is more responsive, to the demand signals. Because ports compete in quantity, their output decisions have the opposite direction, which leads to the comparison results of the port throughputs under different scenarios. Additionally, information sharing makes the unit-fee strategies more responsive for both PAs, which explains the orders of the unit-fees under different scenarios. Because the port charge and the unit-fee are positively related, their orders are similar under different scenarios. As mentioned in Section 2, information sharing harms the POs but benefits the PAs, which explains the orders of the port profits and the local welfare under different scenarios.

The next result examines the impacts of port congestion and port competition on information sharing.

Corollary 2. *As congestion at Port i becomes more costly, (i) port throughput is less responsive to the demand signal in all scenarios; (ii) port charge is more responsive (less responsive, respectively) to the demand signal when demand information is shared (not shared, respectively), regardless of whether there is information sharing in the competing port; (iii) the unit concession fee is more responsive (has no responses, respectively) to the demand signal when information is shared (not shared, respectively), regardless if there is information sharing in the competing port. In a symmetric case, namely,* $K_i = K_j = K$, $c_i = c_j = c$, $\eta_i = \eta_j = \eta$, $m_i = m_j = m$, *as services at the two ports become more substitutable and thus inter-port competition is more intense, (i) port throughputs and charges are always less responsive to the demand signal so long as information is shared in at least one port, and (ii) the unit concession fee at Port i is less responsive (has no responses, respectively) to the demand signal when its PO shares (does not share, respectively) her demand information with its PA, no matter whether there is information sharing in the competing port.*

Corollary 2 demonstrates more congested ports have less responsive throughputs, more responsive port charges, and unit concession fees to the demand signals, respectively. Furthermore, increasing port competition makes a port's throughput, port charge, and unit concession fee less responsive to the demand signals. These results can help PAs better manage information sharing in their concession arrangements. When the port is more congested or faces severe competition, the PO's throughput decision should be conservative even when the demand is prosperous (i.e., it is less responsive to the demand signal). For a congested port, the PO's charge and the PA's unit-fee can be more responsive to the prosperous demand signals (i.e., they are more responsive to the demand signal) after information is shared. However, if the port faces sharp competition, the PO's charge and the PA's unit-fee must be conservative toward prosperous demand signals even with shared information.

3.4 PAs' decisions on demand information sharing

As discussed, without transfer payment T_i, the POs' operation profits decrease with information sharing. Therefore, it is important to check when/whether the PAs are willing to offer a transfer payment to encourage information sharing. If information is shared at rival port *j*, the decrease in PO *i*'s operating profit due to information sharing is

$$\Delta E_i^{SS}(\pi) = E_i^{NS}(\pi) - E_i^{SS}(\pi) = \delta_i[\frac{(1-bB_j^{SN})^2}{4m_i} - \frac{m_i(1-bB_j^{SS})^2}{(4m_i-1)^2}]. \quad (25)$$

To make information sharing sustainable, PA *i* must pay PO *i* an equivalent amount (i.e., $\Delta E_i^{SS}(\pi)$)[30], in which case, the "net" local welfare with information sharing can be calculated as

$$E_i^{SS}(SW) - \Delta E_i^{SS}(\pi) = \tau_i K_i + \frac{(a-c_i-bA_j)^2}{2(4m_i-1)} + \delta_i[\frac{(6m_i-1)(1-bB_j^{SS})^2}{2(4m_i-1)^2} - \frac{(1-bB_j^{SN})^2}{4m_i}] \quad (26)$$

Without information sharing, the net local welfare at port *i* is $E_i^{NS}(SW)$.

Similarly, if information is not shared in port *j*, PO *i*'s loss in operating profit due to information sharing is

$$\Delta E_i^{SN}(\pi) = E_i^{NN}(\pi) - E_i^{SN}(\pi) = \delta_i[\frac{(1-bB_j^{NN})^2}{4m_i} - \frac{m_i(1-bB_j^{NS})^2}{(4m_i-1)^2}]. \quad (27)$$

Therefore, PA *i* will have to offer an equivalent payment to PO *i*, thus, the "net" local welfare with information sharing is

$$E_i^{SN}(SW) - \Delta E_i^{SN}(\pi) = \tau_i K_i + \frac{(a-c_i-bA_j)^2}{2(4m_i-1)} + \delta_i[\frac{(6m_i-1)(1-bB_j^{NS})^2}{2(4m_i-1)^2} - \frac{(1-bB_j^{NN})^2}{4m_i}]. \quad (28)$$

Absent information sharing, the local welfare is $E_i^{NN}(SW)$. Similar calculations can be performed for PA *j* under different scenarios. The results are summarized in Table 2.

Table 2 PAs' net local welfare in different scenarios

PA *i*	PA *j*: Sharing	PA *j*: Not sharing
Sharing	$E_i^{SS}(SW) - \Delta E_i^{SS}(\pi)$, $E_j^{SS}(SW) - \Delta E_j^{SS}(\pi)$	$E_i^{SN}(SW) - \Delta E_i^{SN}(\pi)$, $E_j^{SN}(SW)$
Not sharing	$E_i^{NS}(SW)$, $E_j^{NS}(SW) - \Delta E_j^{NS}(\pi)$	$E_i^{NN}(SW)$, $E_j^{NN}(SW)$

Note: in each cell, the first and second expressions are the net local welfare of port *i* and *j*, respectively.

Next, we investigate the case with two symmetric ports and the following proposition can be

[30] Strictly, this is the minimum amount the PO is willing to accept. The actual payment should be determined by the bargaining power between the PA and the PO. This issue is not investigated further as the main objective of this study is to analyse the implications on market outcome instead of mechanism design for information sharing.

obtained. The proof is provided in the Appendix, whereas no clear analytical results can be obtained for the cases when the two ports are asymmetric.

Proposition 3. *In a symmetric case in which* $\tau_i = \tau_j = \tau$, $K_i = K_j = K$, $c_i = c_j = c$, $\eta_i = \eta_j = \eta$, $m_i = m_j = m$, $B_i^{SS} = B_j^{SS} = B^{SS}$, $B_i^{SN} = B_j^{SN} = B^{SN}$, $B_i^{NS} = B_j^{NS} = B^{NS}$, *and* $B_i^{NN} = B_j^{NN} = B^{NN}$, *define* $\Gamma_1 = \delta[\frac{(2m+1)(1-bB^{NN})^2}{8m^2} - \frac{(6m-1)(1-bB^{NS})^2}{2(4m-1)^2}]$, $\Gamma_2 = \delta[\frac{(2m+1)(1-bB^{SN})^2}{8m^2} - \frac{(6m-1)(1-bB^{SS})^2}{2(4m-1)^2}]$ *; then it can be concluded that: if the externality of information sharing on welfare is small so that* $\tau K \in [0, \Gamma_1)$*, no information is shared (in either port); if the externality of information sharing on welfare is moderate so that* $\tau K \in [\Gamma_1, \Gamma_2)$*, information is shared in one port only, and the PA with shared information must offer a compensation of* $\Delta E_i^{SN}(\pi)$ *(as defined by [27]) to the PO. That is, (not sharing, sharing) and (sharing, not sharing) are the equilibria; otherwise, if the externality of information sharing on welfare is sufficiently large so that* $\tau K \in [\Gamma_2, \infty]$*, information is shared in both ports, and both PAs must offer the compensations of* $\Delta E_i^{SS}(\pi)$ *(as defined by [25]) to the POs.*

From Proposition 3, we know that in the two ports case with Cournot competition, when $\tau K \in [\Gamma_2, \infty]$, we have $E_i^{SS}(SW) - E_i^{NS}(SW) \geq \Delta E_i^{SS}(\pi)$ and $E_i^{SN}(SW) - E_i^{NN}(SW) \geq \Delta E_i^{SN}(\pi)$, which means that PA *i* can afford the payment to PO *i* to satisfy the IR constraint regardless of PA *j*'s strategies. With symmetry, we can show that PO *j*'s IR constraint is satisfied by using a similar argument. Thus, both ports choose information sharing if $\tau K \in [\Gamma_2, \infty]$. When $\tau K \in [\Gamma_1, \Gamma_2)$, we have $E_i^{SS}(SW) - E_i^{NS}(SW) < \Delta E_i^{SS}(\pi)$ and $E_i^{SN}(SW) - E_i^{NN}(SW) > \Delta E_i^{SN}(\pi)$, which means that PO *i*'s IR constraint can be satisfied only if Port *j* does not share information (and vice versa). Therefore, in this case, only one port shares information at the equilibrium. When $\tau K \in [0, \Gamma_1)$, none of the POs' IR constraints can be satisfied. Thus, no information is shared.

3.5 A numerical example

To better understand and interpret the key analytical results, in this section, a numerical example is provided, which allows the solution properties to be more directly illustrated with figures. The parameters used are as follows: $a = 1$, $\tau_i = \tau_j = 0.1$, $K_i = K_j = 5$,

$c_i = c_j = 0.1$, $\sigma^2 = 1$, $\eta_i = \eta_j = 0.5$, $b \in [0.3, 0.7]$, $t_i = t_j = t \in [0.1, 0.5]$, and $Y_i = Y_j = Y \in [-1,1]$. These values are consistent with the modelling assumptions and are chosen for better graphical illustration. Figures 1, 2, and 3, respectively, characterize the impact on port throughput imposed by the signal Y_i, the port congestion cost t_i and the degree of port competition b under different information-sharing scenarios. The comparisons of the PO's expected profits and the expected local welfare are shown in Figures 4 and 5, respectively. The equilibria of the port information sharing game under different conditions are illustrated in Figure 6. We mainly investigate the effect of port congestion costs because it is related to one of our key contributions (elaborated in Section 1).

When different sets of parameter values are used, these figures remain consistent with the propositions and corollaries, albeit with slightly changed shapes. We refrain from making additional comments beyond the conclusions reported because numerical simulations are more illustrative but nevertheless less conclusive compared with analytical solutions.

It would also be helpful to link some of our analytical results to relevant discussions in the literature and interpret them in the context of actual industry practices. The need for and benefits of information sharing have long been recognized in the maritime industry. The former European Liner Affairs Association in 2006 proposed the creation of a formal regulatory instrument that covers exchange of information on a wide range of issues such as aggregated capacity utilization and market size data by trade, evaluations of commodity developments by trade, aggregate supply and demand data by trade/commodity; and forecasts of demand by trade and commodity (Marlow and Nair 2006). The OECD/International Transport Forum (2018) noted that "*The sharing of knowledge and information within liner shipping alliance networks could confer both common and private benefits*". Such a finding is consistent with operational studies that have concluded that full cooperation including demand information sharing can enhance partners' operational efficiency and reduce the waste of resources (e.g., Lei et al, 2008).

Few detailed cases of demand information sharing in concession agreements are available in the public domain, which is understandable because they would have revealed commercially sensitive information. Nevertheless, some insights concerning our analytical conclusions on long-term strategic arrangements may be indirectly obtained from certain operational arrangements observed in the maritime industry. For example, studies have documented the benefits and technologies of information sharing in the port and shipping sector, including those implemented in leading ports such as Singapore, Hamburg, Hong Kong, Rotterdam, and Busan (e.g. Kia et al. 2000; Yavuz 2011). Olesen et al. (2012) map the needs of information flow among key stakeholders including port, terminal, broker, shipping line, transporter, and customer, with a caution that the biggest challenge and focus of information sharing is trust. Our paper complements these empirical studies through precise analysis of the arrangements when each stakeholder aims to maximize her benefits. Notably, some of our results are broadly consistent

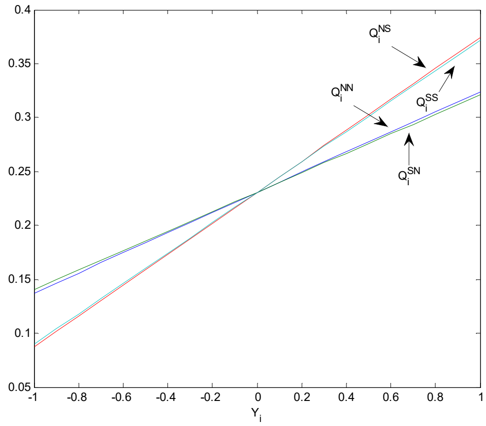

Figure 1 Comparisons of the port throughputs under different scenarios and signals ($b = 0.5$, $t = 0.5$)

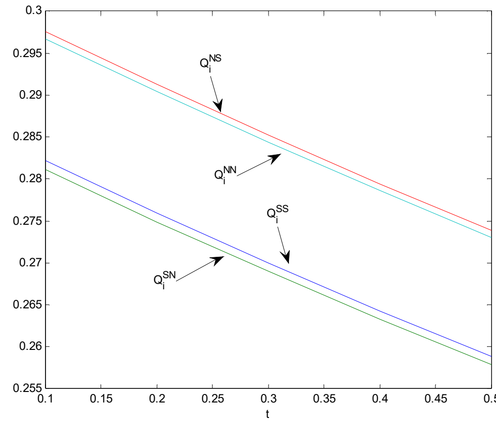

Figure 2 The impacts of the port congestion costs on the port throughputs under different scenarios ($b = 0.5$, $Y = 0.3$)

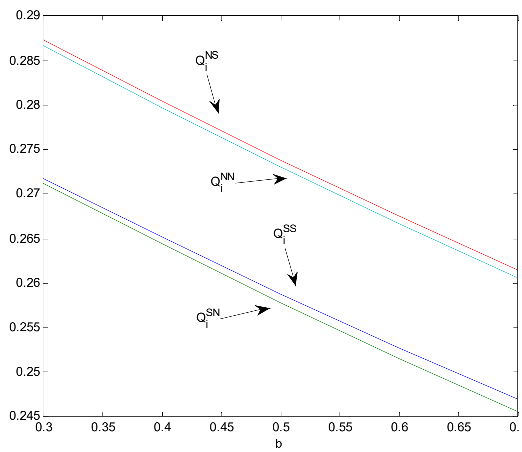

Figure 3 The impacts of the port competition on the port throughputs under different scenarios ($t = 0.5$, $Y = 0.3$)

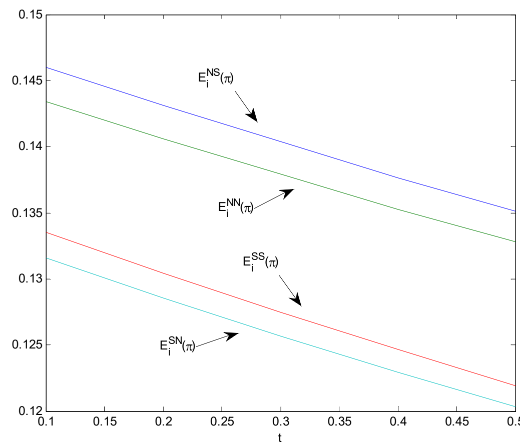

Figure 4 Comparisons of the PA's expected profits under different scenarios ($b = 0.5$)

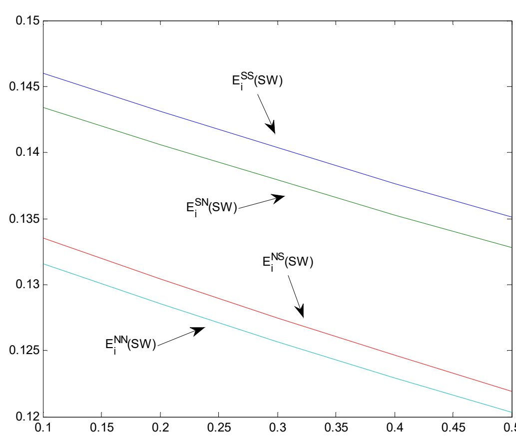

Figure 5 Comparisons of the expected local welfare under different scenarios ($b = 0.5$)

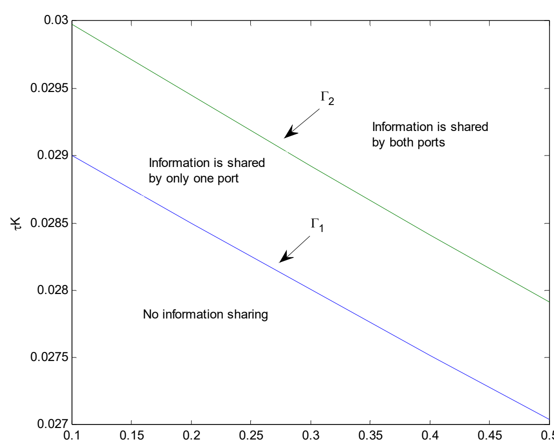

Figure 6 The equlibria of the port information sharing game under different conditions ($b = 0.5$)

with industry observations. For example, our analytical results suggest that the effects of information sharing are more significant when there is stronger inter-port competition and when port congestion is more costly. Notably, the Port of Singapore used to enjoy significant market power and experienced some congestion. Maersk would like to have its own terminal and ensure the port service received (much like a concession), but was turned down. The shipping line thus took a 30% stake in nearby Port in Tanjung Pelepas in 1999 through its own PO APM. With increased competition, the Port of Singapore subsequently started to work jointly with several shipping lines and their terminal operation subsidiary companies. Clearly, such joint ventures and vertical arrangements involve much information sharing, and other more in-depth cooperation. Similar observations in the maritime industry are broadly consistent with our modelling results.

4. Extension: when two ports engage in Bertrand competition

In Section 3, we consider demand information sharing when two ports engage in Cournot competition. However, in some circumstances, ports may compete in price instead. In this section, we examine information sharing when ports engage in Bertrand competition.

4.1 Market equilibria under different scenarios

Notably, the game involving the PAs and POs remains the same as in Section 3, except that the two POs compete in Bertrand in Stage Four. Using a similar approach to that in Section 3 (the detailed solution processes are presented in the Appendix), we obtain the market equilibria under different scenarios, which is summarized in the following table. Examining these equilibria, we can obtain conclusions similar to those obtained in Section 3.2. The PO's optimal port charge is a linear function of her demand signal, which only affects the slopes of the POs' charges. The port throughput, the PO's expected profit, and the PA i's unit-fee and her expected local welfare can also be divided into the "regular parts" and the "signal dependent parts" that have similar economic interpretations as in the case of Cournot competition.

Table 3 Market equilibria under different scenarios
when two POs engage in a Bertrand competition

Port i	Port j	
	Sharing	Not sharing
Sharing	$f_{iB}^{SS}=A_{iB}+B_{iB}^{SS}Y_i$ $r_{iB}^{SS}=\Omega_i[(m_j-b)a+bA_{jB}-m_jc_i$ $+(m_j-b+bB_{jB}^{SS})E(\theta\mid Y_i)]$ $Q_{iB}^{SS}=(m_j-b)a+bA_{jB}-m_jc_i$ $+(m_j-b+bB_{jB}^{SS})E(\theta\mid Y_i)$	$f_{iB}^{SN}=A_{iB}+B_{iB}^{SN}Y_i$ $r_{iB}^{SN}=\Omega_i[(m_j-b)a+bA_{jB}-m_jc_i$ $+(m_j-b+bB_{jB}^{NS})E(\theta\mid Y_i)]$ $Q_{iB}^{SN}=(m_j-b)a+bA_{jB}-m_jc_i$ $+(m_j-b+bB_{jB}^{NS})E(\theta\mid Y_i)$

	$E_{iB}^{SS}(\pi)=\frac{1-m_j\Omega_i}{2m_j}\{[(m_j-b)a+bA_{jB}$ $-m_jc_i]^2+(m_j-b+bB_{jB}^{SS})^2\delta\}$ $E_{iB}^{SS}(SW)=(\frac{1}{2}+\Omega_i)\{[(m_j-b)a+bA_{jB}$ $-m_jc_i]^2+(m_j-b+bB_{jB}^{SS})^2\delta\}+\tau_iK_i$	$E_{iB}^{SN}(\pi)=\frac{1-m_j\Omega_i}{2m_j}\{[(m_j-b)a+bA_{jB}$ $-m_jc_i]^2+(m_j-b+bB_{jB}^{NS})^2\delta\}$ $E_{iB}^{SN}(SW)=(\frac{1}{2}+\Omega_i)\{[(m_j-b)a+bA_{jB}$ $-m_jc_i]^2+(m_j-b+bB_{jB}^{NS})^2\delta\}+\tau_iK_i$
Not sharing	$f_{iB}^{NS}=A_{iB}+B_{iB}^{NS}Y_i$ $r_{iB}^{NS}=\Omega_i[(m_j-b)a+bA_{jB}-m_jc_i]$ $Q_{iB}^{NS}=(m_j-b)a+bA_{jB}-m_jc_i+$ $\frac{4m_im_j-m_j-4b^2}{2m_im_j-2b^2}(m_j-b+bB_{jB}^{SN})$ $E(\theta\|Y_i)$ $E_{iB}^{NS}(\pi)=\frac{1-m_j\Omega_i}{2m_j}[(m_j-b)a+bA_{jB}$ $-m_jc_i]^2+\frac{(4m_im_j-m_j-4b^2)(1+m_j\Omega_i)}{4m_j(m_im_j-b^2)}$ $(m_j-b+bB_{jB}^{SN})^2\delta$ $E_{iB}^{NS}(SW)=(\frac{1}{2}+\Omega_i)[(m_j-b)a+bA_{jB}$ $-m_jc_i]^2+\frac{(4m_im_j-m_j-4b^2)^2}{8(m_im_j-b^2)^2}$ $(m_j-b+bB_{jB}^{SN})^2\delta$	$f_{iB}^{NN}=A_{iB}+B_{iB}^{NN}Y_i$ $r_{iB}^{NN}=\Omega_i[(m_j-b)a+bA_{jB}-m_jc_i]$ $Q_{iB}^{NN}=(m_j-b)a+bA_{jB}-m_jc_i+$ $\frac{4m_im_j-m_j-4b^2}{2m_im_j-2b^2}(m_j-b+bB_{jB}^{NN})$ $E(\theta\|Y_i)$ $E_{iB}^{NN}(\pi)=\frac{1-m_j\Omega_i}{2m_j}[(m_j-b)a+bA_{jB}$ $-m_jc_i]^2+\frac{(4m_im_j-m_j-4b^2)(1+m_j\Omega_i)}{4m_j(m_im_j-b^2)}$ $(m_j-b+bB_{jB}^{NN})^2\delta$ $E_{iB}^{NN}(SW)=(\frac{1}{2}+\Omega_i)[(m_j-b)a+bA_{jB}$ $-m_jc_i]^2+\frac{(4m_im_j-m_j-4b^2)^2}{8(m_im_j-b^2)^2}$ $(m_j-b+bB_{jB}^{NN})^2\delta$

Note: (1) The subscript "B" indicates the case of Bertrand competition. (2) Definitions of the related parameters are presented in Appendix.

4.2 Comparisons across different scenarios

Due to the complexity of the equilibrium expressions under the Bertrand competition, it is difficult to compare analytical solutions in general. Therefore, we focus on a symmetric case, namely, when $K_i=K_j=K$, $c_i=c_j=c$, $\eta_i=\eta_j=\eta$, and $m_i=m_j=m$. The following results can be obtained.

Proposition 4. *In a symmetric case, namely,* $K_i=K_j=K$, $c_i=c_j=c$, $\eta_i=\eta_j=\eta$, *and*

$m_i = m_j = m$ *, when two ports engage in Bertrand competition and their congestion costs are sufficiently large,* $2m^2 - m - 2b^2 > 0$ *holds, given the positive signal* Y_i *, and the port charges under the different scenarios have the following orders:* $f_{iB}^{NN} < f_{iB}^{SN} < f_{iB}^{SS}$ *and* $f_{iB}^{NN} < f_{iB}^{NS} < f_{iB}^{SS}$ *; the port throughputs have the following orders:* $Q_{iB}^{SN} < Q_{iB}^{SS} < Q_{iB}^{NS}$ *and* $Q_{iB}^{SN} < Q_{iB}^{NN} < Q_{iB}^{NS}$ *; and the unit-fees have the following orders:* $r_{iB}^{NN} = r_{iB}^{NS} < r_{iB}^{SN} < r_{iB}^{SS}$ *. Given the negative signal* Y_i *, these variables under the different scenarios have the opposite directions to the aforementioned orders. The expected PO's operating profits always have the following orders:* $E_{iB}^{SN}(\pi) < E_{iB}^{SS}(\pi) < E_{iB}^{NS}(\pi)$ *and* $E_{iB}^{SN}(\pi) < E_{iB}^{NN}(\pi) < E_{iB}^{NS}(\pi)$ *, regardless of the sign of signal* Y_i *. The expected local social welfare has the following orders:* $E_{iB}^{SN}(SW) < E_{iB}^{SS}(SW)$ *and* $E_{iB}^{NN}(SW) < E_{iB}^{NS}(SW)$ *, regardless of the sign of signal* Y_i *. However, no definite comparison results can be obtained for* $E_{iB}^{SS}(SW)$ *and* $E_{iB}^{NS}(SW)$ *,* $E_{iB}^{SN}(SW)$ *and* $E_{iB}^{NN}(SW)$ *.*

From Proposition 4, we find that most comparison results under the Bertrand competition are the same as under the Cournot competition (when the port congestion cost is sufficiently large), except for the local welfare. In the Cournot competition, a PA always benefits from the shared information, whether the competing port shares information or not. However, in the Bertrand competition, although one port's information sharing still benefits the local welfare of the competing port, the impact on her own local welfare is uncertain. In other words, a PO's information sharing may not benefit her corresponding PA for sure. The reason for this is related to the different characteristics of the two competition modes. In the Cournot competition, two POs' strategies (throughput decisions) are complementary to each other, and their strategies (port charge decisions) are substitutes for each other in the Bertrand competition. We know that demand information sharing makes the POs' throughputs less responsive in the Cournot competition, whereas the POs' prices are more responsive in the Bertrand competition, to the demand signal. This finding means that demand information sharing softens port competition in the Cournot game, whereas it increases competition in the Bertrand game. Therefore, the PA's local welfare may be reduced by the demand information because of intensified competition in the Bertrand game.

Next, we investigate the impacts of the congestion cost and port competition. The results are summarized in the following corollary.

Corollary 3. *In a symmetric case, namely,* $K_i = K_j = K$ *,* $c_i = c_j = c$ *,* $\eta_i = \eta_j = \eta$ *, and* $m_i = m_j = m$ *, when two ports engage in Bertrand competition and their congestion costs are* *sufficiently big, namely,* $2m^2 - m - 2b^2 > 0$ *holds, we have the following conclusions. As the port congestion becomes more costly, (i) port throughputs and port charges are more responsive to the demand signal in all scenarios, regardless of whether there is information sharing in the competing port; and (ii) the unit concession fee is more responsive (has no responses, respectively) to the demand signal when information is shared (not shared, respectively), regardless of whether there is information sharing in the competing port. As services at the two ports become more substitutable and thus inter-port competition is more intense, (i) port throughputs and charges are always less responsive to the demand signal so long as information is shared in at least one port; and (ii) unit concession fee at Port i is less responsive (has no responses, respectively) to the demand signal when PO i shares (does not share, respectively) her demand information with PA i, regardless of whether there is information sharing in the competing port.*

Corollary 3 suggests that most conclusions on the impacts of the congestion cost and port competition are consistent across the cases of Bertrand competition and Cournot competition (when the port congestion cost is sufficiently big), except for the impact of the port congestion cost on port throughput. As the port congestion becomes more costly, port throughputs are less responsive under the Cournot competition, whereas they are more responsive under the Bertrand competition, to the demand signal. Facing a similar situation, namely, as the port congestion becomes more costly and there is a positive demand signal, a PO tends to increase her throughput less to alleviate port congestion in the Cournot competition, making the throughput less responsive. However, in the Bertrand competition, a PO incorporates the increasing cost to the port charge, which makes the port charges more responsive.

4.3 PAs' decisions on demand information sharing

If information is shared at rival port *j*, the decrease in PO *i*'s operating profit due to information sharing is

$$\begin{aligned}\Delta E_{iB}^{SS}(\pi) = E_{iB}^{NS}(\pi) - E_{ib}^{SS}(\pi) = \delta_i[&\frac{(4m_i m_j - m_j - 4b^2)(1 + m_j\Omega_i)}{4m_j(m_i m_j - b^2)}(m_j - b + bB_{jB}^{SN})^2 \\ &- \frac{1 - m_j\Omega_i}{2m_j}(m_j - b + bB_{jB}^{SS})^2]\end{aligned} \tag{29}$$

To make information sharing sustainable, PA *i* must pay PO *i* $\Delta E_{iB}^{SS}(\pi)$, in which case the "net" local welfare with information sharing can be calculated as

$$\begin{aligned}E_{iB}^{SS}(SW) - \Delta E_{iB}^{SS}(\pi) &= \tau_i K_i + (\frac{1}{2} + \Omega_i)[(m_j - b)a + bA_{jB} - m_j c_i]^2 \\ &+ \delta_i[\frac{1 + (m_j + 1)\Omega_i}{2m_j}(m_j - b + bB_{jB}^{SS})^2 - \frac{(4m_i m_j - m_j - 4b^2)(1 + m_j\Omega_i)}{4m_j(m_i m_j - b^2)}(m_j - b + bB_{jB}^{SN})^2]\end{aligned} \tag{30}$$

Without information sharing, the net local welfare at port *i* is $E_{iB}^{NS}(SW)$.

Similarly, if information is not shared in port *j*, PO *i*'s loss in operating profit due to information sharing is

$$\Delta E_{iB}^{SN}(\pi) = E_{iB}^{NN}(\pi) - E_{iB}^{SN}(\pi) = \delta_i[\frac{(4m_i m_j - m_j - 4b^2)(1+m_j\Omega_i)}{4m_j(m_i m_j - b^2)}(m_j - b + bB_{jB}^{NN})^2 - \frac{1-m_j\Omega_i}{2m_j}(m_j - b + bB_{jB}^{NS})^2] \tag{31}$$

Therefore, PA *i* must offer an equivalent payment to PO *i*, thus, the "net" local welfare with information sharing is

$$E_{iB}^{SN}(SW) - \Delta E_{iB}^{SN}(\pi) = \tau_i K_i + (\frac{1}{2} + \Omega_i)[(m_j - b)a + bA_{jB} - m_j c_i]^2 + \delta_i[\frac{1+(m_j+1)\Omega_i}{2m_j}(m_j - b + bB_{jB}^{NS})^2 - \frac{(4m_i m_j - m_j - 4b^2)(1+m_j\Omega_i)}{4m_j(m_i m_j - b^2)}(m_j - b + bB_{jB}^{NN})^2]. \tag{32}$$

Absent information sharing, the local welfare is $E_{iB}^{NN}(SW)$. Similar calculations can be performed for PA *j* under different scenarios. The results are summarized in Table 4.

Table 4 PAs' net local welfare in different scenarios
when two ports engage in Bertrand competition

PA *i*	PA *j*: Sharing	PA *j*: Not sharing
Sharing	$E_{iB}^{SS}(SW) - \Delta E_{iB}^{SS}(\pi), E_{jB}^{SS}(SW) - \Delta E_{jB}^{SS}(\pi)$	$E_{iB}^{SN}(SW) - \Delta E_{iB}^{SN}(\pi), E_{jB}^{SN}(SW)$
Not sharing	$E_{iB}^{NS}(SW), E_{jB}^{NS}(SW) - \Delta E_{jB}^{NS}(\pi)$	$E_{iB}^{NN}(SW), E_{jB}^{NN}(SW)$

Note: in each cell, the first and second expressions are the net local welfare of port *i* and *j*, respectively.

Next, we investigate a case with two symmetric ports and find conclusions similar to those under the Cournot competition. The following proposition summarizes them.

Proposition 5. *In a symmetric case in which* $\tau_i = \tau_j = \tau$, $K_i = K_j = K$, $c_i = c_j = c$, $\eta_i = \eta_j = \eta$, $m_i = m_j = m$, $\Omega_i = \Omega_j = \Omega$, $B_{iB}^{SS} = B_{jB}^{SS} = B_B^{SS}$, $B_{iB}^{SN} = B_{jB}^{SN} = B_B^{SN}$, *and* $B_{iB}^{NS} = B_{jB}^{NS} = B_B^{NS}$, $B_{iB}^{NN} = B_{jB}^{NN} = B_B^{NN}$, *when two ports engage in Bertrand competition and their congestion costs are sufficiently large, namely,* $2m^2 - m - 2b^2 > 0$ *holds, define*

$$\Gamma_{1B}=\delta\{\frac{4m^2-m-4b^2}{4(m^2-b^2)}[\frac{1+m\Omega}{m}+\frac{4m^2-m-4b^2}{2(m^2-b^2)}](m-b+bB_B^{NN})^2-\frac{1+(m+1)\Omega}{2m}(m-b+bB_B^{NS})^2\},$$

$$\Gamma_{2B}=\delta\{\frac{4m^2-m-4b^2}{4(m^2-b^2)}[\frac{1+m\Omega}{m}+\frac{4m^2-m-4b^2}{2(m^2-b^2)}](m-b+bB_B^{SN})^2-\frac{1+(m+1)\Omega}{2m}(m-b+bB_B^{SS})^2\},$$

it can be concluded that: if the externality of information sharing on welfare is small so that $\tau K\in[0,\Gamma_{1B})$*, no information is shared (in either port); if the externality of information sharing on welfare is moderate so that* $\tau K\in[\Gamma_{1B},\Gamma_{2B})$*, information is shared in one port only and the PA who receives the shared information must offer a compensation of* $\Delta E_{iB}^{SN}(\pi)$ *(defined by [31]) to the PO. That is, (not sharing, sharing) and (sharing, not sharing) are the equilibria; otherwise, if the externality of information sharing on welfare is sufficiently large so that* $\tau K\in[\Gamma_{2B},\infty]$*, information is shared in both ports, and both POs must offer the compensation of* $\Delta E_{iB}^{SS}(\pi)$ *(defined by [29]) to the POs.*

5. Conclusions

Many investments in the port sector are capital intensive, and port operations are subject to the influences of significant market dynamics and volatilities. Port investments, operations, and concessions often involve multiple stakeholders, and all call for improved collaboration and information sharing. Despite the strong will to promote information sharing by government agencies and industry associations, few studies have systematically examined the implications of information sharing on stakeholders and social welfare. It is unclear whether and how sustainable information sharing arrangements can be made for the port industry.

This paper investigates the effects of demand information sharing on concession arrangements and resultant market equilibria at ports governed under the landlord port model. Port authorities are assumed to maximize local welfare, whereas POs maximize their profits. A multi-stage game is analyzed, in which the authority and operator at a port first decide whether to share demand information and the corresponding concession arrangements, after which POs compete à la *Cournot*. Alternative scenarios are considered and compared so that the effects of information sharing and market structure can be identified. Our analytical results suggest that information sharing can be an important source of welfare improvements and that such effects are more significant when the positive externality of information sharing on welfare is larger, when there is stronger inter-port competition, and when port congestion is more costly. However, absent compensation, POs are reluctant to share their private information because this is likely to lead to higher concession unit-fees, disadvantages a PO in inter-port competition, and lowers the POs' expected operating profits. Therefore, transfer payments are necessary to motivate POs to engage in information sharing. With this information sharing – payment arrangements and when ports' costs and services are symmetric, one PO prefers to share information when the externality on welfare is larger than a threshold. When the positive externality on welfare is sufficiently large, both port authorities prefer to share information. When ports compete in price, most conclusions are similar such as under quantity competition, except that a PO's information sharing may not always benefit her corresponding PA.

Our study provides fresh management insights and policy implications as follows:

(i) With information sharing, the PAs can set concession fees more strategically, which transfers the power and benefits from a PO to the corresponding PA. The concession unit-fee should be designed as two parts: the regular part (unrelated to the PO's shared information), and the signal dependent part (positively related to the signals supplied by the PO), which varies across different scenarios (whether the port and its competitor share demand information).

(ii) With information sharing, a PO's output is less responsive to a demand signal but more responsive to a rival port's output. Combined with (i), we demonstrate that a PO's operating profit is reduced by information sharing, and she may be put in a disadvantaged position in her competition with rival ports. Therefore, although information sharing tends to promote social welfare, which is consistent with the PA's objective, POs only share information when they are sufficiently compensated. As a result, information sharing is sustainable only if the positive externality of information sharing on welfare is sufficiently large.

(iii) The demand information sharing between the PO and PA is more likely to be sustainable in markets where congestion is more costly, when the demand signal is more accurate, and the demand is less variable.

(iv) Different competition modes between ports, such as the price competition and quantity competition considered in our study, may have different impacts on information-sharing decisions and market outcomes. Although the PA always benefits from information sharing under quantity competition, we identified cases in which information sharing harms both the PA and the PO under price competition. Therefore, policymakers and industry stakeholders must consider market structure and competition in specific markets before committing to information sharing.

Although we attempted to capture the key features of the maritime industry, for modeling tractability our analysis assumed particular function forms for the specifications of demand, information signal, and competition type. Further research could consider more general function forms in a less restrictive setting. In addition, the assumption that the PO truthfully reveals her private demand information to the PA does not always hold in reality. Further research may consider using the principal-agent framework or the "cheap talk" mechanism (Crawford and Sobel, 1982) to prevent cheating. Moreover, other possible cooperation (in addition to the compensation payment discussed in this paper) between the PA and the PO can be considered to promote information sharing. For example, in some landlord or quasi-landlord ports, POs can participate in port infrastructure investments and share profits through joint ventures with PAs (Zhang, 2016). Because the POs share the investments and profits with PAs already, they may be willing to share information even without a separate payment from the PAs. Finally, although POs are more likely to have better information than PAs for the reasons discussed in the introduction section, in theory, we cannot rule out the possibility that PAs may have better information than POs. It would be useful to check if our conclusions still hold qualitatively in such a case.[31] All these are promising topics for further research.

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Appendix. Analytical solutions and proofs

A.1 Definitions of the parameters in Table 1

$A_i = \dfrac{(a-c_i)(4m_j-1)-b(a-c_j)}{(4m_i-1)(4m_j-1)-b^2}$, $B_i^{SS} = \dfrac{T_i(4m_j-1-bT_j)}{(4m_i-1)(4m_j-1)-b^2T_iT_j}$,

$B_i^{NN} = \dfrac{T_i(2m_j-bT_j)}{4m_im_j-b^2T_iT_j}$, $B_i^{SN} = \dfrac{T_i(2m_j-bT_j)}{2m_j(4m_i-1)-b^2T_iT_j}$, $B_i^{NS} = \dfrac{T_i(4m_j-1-bT_j)}{2m_i(4m_j-1)-b^2T_iT_j}$,

$m_i = 1+\dfrac{t_i}{K_i}$, $T_i = \dfrac{\eta_i\sigma^2}{1+\eta_i\sigma^2}$, and $\delta_i = E([E(\theta|Y_i)]^2) = \dfrac{\eta_i\sigma^4}{1+\eta_i\sigma^2}$, where superscript "SS" denotes the case in which both POs share information with their respective PAs, superscript "NN" denotes the case in which neither PO shares a private demand signal, and superscript "SN" (or "NS") denotes the case in which PO *i* (or PO *j*) shares (or does not share) information with PA *i* (or PA *j*) but the other PO *j* (or PO *i*) does not share (or share) information with PA *j* (or PA *i*).

A.2 Solution for the equilibrium outcomes in Section 3.2

A.2.1 Information sharing at both ports

We first analyze the optimal output of PO *i*, whose objective is specified as

$$\max_{Q_i} E(\pi_i) = E[(f_i - c_i - r_i)Q_i]. \tag{33}$$

Let $m_i = 1 + t_i / K_i$. From (22) and $p_i = f_i + t_iQ_i / K_i$, we have

$$f_i = a + \theta - m_iQ_i - bQ_j. \tag{34}$$

Substituting (34) into (33), the FOC of PO *i*'s objective function (33) implies that

$$Q_i = \frac{a + E(\theta | Y_i) - bE(Q_j | Y_i) - c_i - r_i}{2m_i}. \tag{35}$$

Notably, PA *i*'s objective function is

$$\max_{r_i} E(SW_i) = E[1/2Q_i^2 + r_iQ_i + \tau_iK_i] \tag{36}$$

Substituting (35) into (36), the corresponding FOC of (36) is

$$r_i^{SS} = \frac{(2m_i-1)}{4m_i-1}[a + E(\theta | Y_i) - bE(Q_j | Y_i) - c_i], \tag{37}$$

Substituting (37) into (35), we have

$$Q_i^{SS} = \frac{a + E(\theta | Y_i) - bE(Q_j^{SS} | Y_i) - c_i}{4m_i - 1} \tag{38}$$

The same logic applies for PO *j*'s optimal throughput decision as

$$Q_j^{SS} = \frac{a + E(\theta \mid Y_j) - bE(Q_i^{SS} \mid Y_j) - c_j}{4m_j - 1} \tag{39}$$

We assume that PO i's optimal throughput Q_j^{SS} *is a linear function on her signal* Y_i, namely,

$$Q_i^{SS} = A_i^{SS} + B_i^{SS} Y_i, \tag{40}$$

We have $E(Q_j^{SS} \mid Y_i) = A_j^{SS} + B_j^{SS} E(Y_i \mid Y_i) = A_j^{SS} + B_j^{SS} E(\theta \mid Y_i)$ (41)

Substituting (23), (40), and (41) into (39), and making a rearrangement, we have

$$A_i^{SS} + B_i^{SS} Y_i = \frac{a - bA_j^{SS} + (1 - bB_j^{SS}) T_i Y_i - c_i}{4m_i - 1} \tag{42}$$

Using the same logic, we have

$$A_j^{SS} + B_j^{SS} Y_j = \frac{a - bA_i^{SS} + (1 - bB_i^{SS}) T_j Y_j - c_j}{4m_j - 1} \tag{43}$$

Then, the following four equations should hold simultaneously:

$$A_i^{SS} = \frac{a - bA_j^{SS} - c_i}{4m_i - 1} \tag{44}$$

$$B_i^{SS} = \frac{1 - bB_j^{SS}}{4m_i - 1} T_i \tag{45}$$

$$A_j^{SS} = \frac{a - bA_i^{SS} - c_j}{4m_j - 1} \tag{46}$$

$$B_j^{SS} = \frac{1 - bB_i^{SS}}{4m_j - 1} T_j \tag{47}$$

Solving (44)–(47), we obtain A_i^{SS}, B_i^{SS}, A_j^{SS}, and B_j^{SS}.

Substituting (41) into (37) and (34), we obtain each PA's optimal unit-fee and each PO's optimal charge as

$$r_i^{SS} = \frac{(2m_i - 1)}{4m_i - 1} [a - bA_j^{SS} + (1 - bB_j^{SS}) E(\theta \mid Y_i) - c_i] \tag{48}$$

$$f_i^{SS} = \frac{(3m_i - 1)}{4m_i - 1} [a - bA_j^{SS} + (1 - bB_j^{SS}) E(\theta \mid Y_i)] + \frac{m_i}{4m_i - 1} c_i \tag{49}$$

respectively. Substituting (40), (48), and (49) into (33), and (40), (48), into (36), we obtain each PO's optimal profit and each PA's optimal welfare when both ports have information sharing; thus,

$$E_i^{SS}(\pi) = \frac{m_i [(a - c_i - bA_j^{SS})^2 + (1 - bB_j^{SS})^2 \delta_i]}{(4m_i - 1)^2} \tag{50}$$

$$E_i^{SS}(SW) = \frac{(a - c_i - bA_j^{SS})^2 + (1 - bB_j^{SS})^2 \delta_i}{2(4m_i - 1)} + \tau_i K_i \tag{51}$$

A.2.2 Information sharing at neither port

If both POs do not share information with their respective PAs, (35) still applies. PA *i*'s decision now becomes

$$r_i^{NN} = \frac{(2m_i - 1)}{4m_i - 1}[a - bE(Q_j) - c_i] \tag{52}$$

Substituting (52) into (35), we have

$$Q_i^{NN} = \frac{a - c_i}{4m_i - 1} + \frac{E(\theta \mid Y_i) - bE(Q_j^{NN} \mid Y_i)}{2m_i} + \frac{(2m_i - 1)bE(Q_j^{NN})}{2m_i(4m_i - 1)} \tag{53}$$

The same logic applies to the PO *j*'s optimal throughput; thus,

$$Q_j^{NN} = \frac{a - c_j}{4m_j - 1} + \frac{E(\theta \mid Y_j) - bE(Q_i^{NN} \mid Y_j)}{2m_j} + \frac{(2m_j - 1)bE(Q_i^{NN})}{2m_j(4m_j - 1)} \tag{54}$$

Using the same logic as in A.1.1, we obtain A_i^{NN}, B_i^{NN} and other market outcomes.

A.2.3 Information sharing in one port only

When PO *i* shares information with PA *i* but PO *j* does not, PO *i*'s optimal throughput should satisfy the following equation based on the logic in A.1.1:

$$Q_i^{SN} = \frac{a + E(\theta \mid Y_i) - bE(Q_j^{NS} \mid Y_i) - c_i}{4m_i - 1} \tag{55}$$

Additionally, using the same logic as in A.1.2, PO *j*'s optimal throughput decision is

$$Q_j^{NS} = \frac{a - c_j}{4m_j - 1} + \frac{E(\theta \mid Y_j) - bE(Q_i^{SN} \mid Y_j)}{2m_j} + \frac{(2m_j - 1)bE(Q_i^{SN})}{2m_j(4m_j - 1)} \tag{56}$$

Using the same logic as in A.1.1, we obtain A_i^{SN}, A_i^{NS}, B_i^{NN}, B_i^{NS}, and other market outcomes. □

A.3 Proof of Proposition 2

Because $m_i > 1$, $m_j > 1$, $0 < T_i < 1$, $0 < T_j < 1$, and $0 < b \le 1$, it is easy to find that $A_i^{SS} = A_i^{NN} = A_i^{SN} = A_i^{NS}$, $B_i^{SN} < B_i^{NN}$, and $B_i^{SS} < B_i^{NS}$. Moreover,

$$\frac{B_i^{NS}}{B_i^{NN}} = \frac{(4m_j - 1 - bT_j)(4m_i m_j - 1 - b^2 T_i T_j)}{[2m_i(4m_j - 1) - b^2 T_i T_j](2m_j - bT_j)}.$$

Because $(4m_j - 1 - bT_j)(4m_i m_j - 1 - b^2 T_i T_j) > [2m_i(4m_j - 1) - b^2 T_i T_j](2m_j - bT_j) > 0$, we know that $B_i^{NN} < B_i^{NS}$. On the other side, $\frac{B_i^{SS}}{B_i^{SN}} = \frac{(4m_j - 1 - bT_j)[2m_i(4m_j - 1) - b^2T_iT_j]}{[(4m_i - 1)(4m_j - 1) - b^2T_iT_j)(2m_j - bT_j)}$. Because $(4m_j - 1 - bT_j)[2m_i(4m_j - 1) - b^2T_iT_j] > [(4m_i - 1)(4m_j - 1) - b^2T_iT_j)(2m_j - bT_j) > 0$, we know that $B_i^{SN} < B_i^{SS}$.

Therefore, we have $B_i^{SN} < B_i^{SS} < B_i^{NS}$ and $B_i^{SN} < B_i^{NN} < B_i^{NS}$. The aforementioned equalities and inequalities are used to compare port throughputs in different scenarios.

Comparing port charges in different scenarios, it is easy to find that $f_i^{SN} < f_i^{SS}$ and $f_i^{NN} < f_i^{NS}$ when $Y_i > 0$, and the opposite holds when $Y_i < 0$. Moreover, $\frac{1 - bB_j^{NN}}{2} = \frac{m_i(2m_j - bT_j)}{4m_im_j - b^2T_iT_j}$ and $\frac{3m_i - 1}{4m_i - 1}(1 - bB_j^{NS}) = \frac{(3m_i - 1)(2m_j - bT_j)}{2m_j(4m_i - 1) - b^2T_iT_j}$. Comparing the right sides of the aforementioned two equalities, we know that $\frac{1 - bB_j^{NN}}{2} < \frac{3m_i - 1}{4m_i - 1}(1 - bB_j^{NS})$. Therefore, $f_i^{NN} < f_i^{SN}$ when $Y_i > 0$, and the opposite holds when $Y_i < 0$. On the other side, $\frac{1 - bB_j^{SN}}{2} = \frac{m_i(4m_j - 1 - bT_j)}{2m_i(4m_j - 1) - b^2T_iT_j}$ and $\frac{3m_i - 1}{4m_i - 1}(1 - bB_j^{SS}) = \frac{(3m_i - 1)(4m_j - 1 - bT_j)}{(4m_i - 1)(4m_j - 1) - b^2T_iT_j}$. Comparing the right sides of the aforementioned two equalities, we know that $\frac{1 - bB_j^{SN}}{2} < \frac{3m_i - 1}{4m_i - 1}(1 - bB_j^{SS})$. Therefore, $f_i^{NS} < f_i^{SS}$ when $Y_i > 0$, and the opposite holds when $Y_i < 0$. These results form our conclusions on the relationships between port charges in different scenarios.

The comparison of unit concession fees across different scenarios can be proven in a similar fashion.

Comparing the expected profit of PO i in different scenarios, it is easy to find that $E_i^{SN}(\pi) < E_i^{SS}(\pi)$ and $E_i^{NN}(\pi) < E_i^{NS}(\pi)$. Moreover, $\frac{m_i(1 - bB_j^{SS})^2}{(4m_i - 1)^2} = \frac{m_i(4m_j - 1 - bT_j)^2}{[(4m_i - 1)(4m_j - 1) - b^2T_iT_j]^2}$ and $\frac{(1 - bB_j^{SN})^2}{4m_i} = \frac{m_i(4m_j - 1 - bT_j)^2}{[2m_i(4m_j - 1) - b^2T_iT_j]^2}$. Comparing the right sides of the aforementioned two equalities, we know that $\frac{m_i(1 - bB_j^{SS})^2}{(4m_i - 1)^2} < \frac{(1 - bB_j^{SN})^2}{4m_i}$. Therefore, $E_i^{SS}(\pi) < E_i^{NS}(\pi)$. On the other side,

$$\frac{m_i(1-bB_j^{NS})^2}{(4m_i-1)^2}=\frac{m_i(2m_j-bT_j)^2}{[2m_j(4m_i-1)-b^2T_iT_j]^2} \quad \text{and} \quad \frac{(1-bB_j^{NN})^2}{4m_i}=\frac{m_i(2m_j-bT_j)^2}{(4m_im_j-b^2T_iT_j)^2}.$$

Comparing the right sides of the aforementioned two equalities, we know that $\frac{m_i(1-bB_j^{NS})^2}{(4m_i-1)^2}<\frac{(1-bB_j^{NN})^2}{4m_i}$. Therefore, $E_i^{SN}(\pi)<E_i^{NN}(\pi)$. The results form our conclusions on the relationships between a PO's expected operating profits across different scenarios.

Comparing expected local welfare in different scenarios, it is easy to find that $E_i^{SN}(SW)<E_i^{SS}(SW)$ and $E_i^{NN}(SW)<E_i^{NS}(SW)$. Moreover,

$$\frac{(1-bB_j^{SS})^2}{2(4m_i-1)}=\frac{(4m_i-1)(4m_j-1-bT_j)^2}{2[(4m_i-1)(4m_j-1)-b^2T_iT_j]^2} \quad \text{and} \quad \frac{(1-bB_j^{SN})^2}{8m_i^2}=\frac{(4m_j-1-bT_j)^2}{2[2m_i(4m_j-1)-b^2T_iT_j]^2}.$$

Comparing the right sides of the aforementioned two equalities, we know that $\frac{(1-bB_j^{SN})^2}{8m_i^2}<\frac{(1-bB_j^{SS})^2}{2(4m_i-1)}$. Therefore, $E_i^{NS}(SW)<E_i^{SS}(SW)$. On the other side,

$$\frac{(1-bB_j^{NS})^2}{2(4m_i-1)}=\frac{(4m_i-1)(2m_j-bT_j)^2}{2[2m_j(4m_i-1)-b^2T_iT_j]^2} \quad \text{and} \quad \frac{(1-bB_j^{NN})^2}{8m_i^2}=\frac{(2m_j-bT_j)^2}{2(4m_im_j-b^2T_iT_j)^2}.$$

Comparing the right sides of the aforementioned two equalities, we know that $\frac{(1-bB_j^{NN})^2}{8m_i^2}<\frac{(1-bB_j^{NS})^2}{2(4m_i-1)}$. Therefore, $E_i^{NN}(SW)<E_i^{SN}(SW)$. These results form our conclusions on the relationships between the expected local welfare in different scenarios. □

A.4 Proof of Corollary 2:

It is easy to verify that $\partial B_i^{SS}/\partial m_i<0$, $\partial B_i^{NN}/\partial m_i<0$, $\partial B_i^{SN}/\partial m_i<0$, and $\partial B_i^{NS}/\partial m_i<0$. Notably, the sensitivity of r_i^{SS} to the demand signal is captured by the coefficient of $E[\theta|Y_i]$, which is $\frac{(2m_i-1)(1-bB_j^{SS})}{4m_i-1}$. Clearly, $\partial[\frac{(2m_i-1)(1-bB_j^{SS})}{4m_i-1}]/\partial m_i>0$. The same results hold for r_i^{SN}. However, by checking the equilibrium solutions of r_i^{NN} and r_i^{NS}, they are clearly not affected by demand signal. The sensitivity of f_i^{SS} (the unit concession fee) to the demand signal is captured by the coefficient of $E[\theta|Y_i]$, which is $\frac{(3m_i-1)(1-bB_j^{SS})}{4m_i-1}$. Direct calculations lead to

$\partial[\frac{(3m_i-1)(1-bB_j^{SS})}{4m_i-1}]/\partial m_i>0$. The same results can be found in f_i^{SN}. However, the opposite results hold for f_i^{NN} and f_i^{NS}.

In a symmetric case in which $T_i=T_j=T$ and $m_i=m_j=m$, we can show that $\partial B_i^{SS}/\partial b<0$, $\partial B_i^{NN}/\partial b<0$, $\partial B_i^{SN}/\partial b<0$, and $\partial B_i^{NS}/\partial b<0$. Clear, the sensitivity of r_i^{SS} to the demand signal is captured by the coefficient of $[\theta|Y_i]$, which is $\frac{(2m_i-1)(1-bB_j^{SS})}{4m_i-1}$. Clearly, $\partial[\frac{(2m_i-1)(1-bB_j^{SS})}{4m_i-1}]/\partial b<0$, and the same result holds for r_i^{SN}. However, for the case of no information sharing in either port, the demand signal has no relation with r_i^{NN} and r_i^{NS}. Similarly, the sensitivity of f_i^{SS} (the unit concession fee) to the demand signal is captured by the coefficient of $E[\theta|Y_i]$, which is $\frac{(3m_i-1)(1-bB_j^{SS})}{4m_i-1}$. Direct calculations lead to $\partial[\frac{(3m_i-1)(1-bB_j^{SS})}{4m_i-1}]/\partial b<0$. The same results hold for f_i^{SN}, f_i^{NN} and f_i^{NS}. □

A.5 Proof of Proposition 3:

When $\tau K<\Gamma_1$, $E_i^{SS}(SW)-\Delta E_i^{SS}(\pi)<E_i^{NS}(SW)$ and $E_i^{SN}(SW)-\Delta E_i^{SN}(\pi)<E_i^{NN}(SW)$ because $B_i^{SN}<B_i^{NN}$ and $B_i^{SS}<B_i^{NS}$. Not sharing is the dominant strategy for PA *i.* Based on the same logic, not sharing is the dominant strategy for PA *j* too. Therefore, both ports have no information sharing. When $\tau K>\Gamma_2$, sharing is the dominant strategy for PA *i* and *j*. Both ports choose information sharing. When $\tau K\in[\Gamma_1,\Gamma_2)$, $E_i^{SS}(SW)-\Delta E_i^{SS}(\pi)<E_i^{NS}(SW)$ and $E_i^{SN}(SW)-\Delta E_i^{SN}(\pi)>E_i^{NN}(SW)$. Given that PA *j* chooses sharing, PA *i*'s best response is not sharing. Given that PA *j* chooses not sharing, PA *i*'s best response is sharing. The same results apply to PA i. Therefore, (not sharing, sharing) and (sharing, not sharing) are the equilibria. □

A.6 Definitions of the parameters in Table 3

$$A_{iB}=\frac{b\Phi_j[c_jm_i(b^2-m_im_j)+a\Phi_i(b-m_i)]+\Delta_i[c_im_j(b^2-m_im_j)+a\Phi_j(b-m_j)]}{b^2\Phi_i\Phi_j-\Delta_i\Delta_j},$$

$$B_{iB}^{SS}=\frac{T_i\Phi_j[bT_j(b-m_i)\Phi_i+(b-m_j)\Delta_i]}{b^2T_iT_j\Phi_i\Phi_j-\Delta_i\Delta_j}, \quad B_{iB}^{NN}=\frac{T_i[b^2T_j-bm_i(T_j-2)-2m_im_j]}{b^2T_iT_j-4m_im_j},$$

$$B_{iB}^{SN}=\frac{T_i\Phi_j[b^2T_j-bm_i(T_j-2)-2m_im_j]}{b^2T_iT_j\Phi_j-2m_i\Delta_j}, \quad B_{iB}^{NS}=\frac{T_i[bT_j(b-m_i)\Phi_i+(b-m_j)\Delta_i]}{b^2T_iT_j\Phi_i-2m_j\Delta_i},$$

$\Phi_i=3m_im_j-m_i-3b^2$, $\Delta_i=m_i(4m_im_j-m_i-4b^2)$ and $\Omega_i=\dfrac{(2m_im_j-m_j-2b^2)}{m_j(4m_im_j-m_j-4b^2)}$

A.7 Solution for the equilibrium outcomes in Section 4.1

A.7.1 Information sharing at both ports

From (34) we have

$$Q_i=\frac{(m_j-b)(a+\theta)-m_jf_i+bf_j}{m_im_j-b^2}. \tag{57}$$

Substituting (57) into (33), the FOC of PO i's objective function under the Bertrand competition implies that

$$f_i=\frac{(m_j-b)[a+E(\theta\,|\,Y_i)]+m_j(c_i+r_i)+bE(f_j\,|\,Y_i)}{2m_j}. \tag{58}$$

Substituting (58) into (57), we obtain

$$Q_{iB}=\frac{(m_j-b)[a+E(\theta\,|\,Y_i)]-m_j(c_i+r_i)+bf_j}{2(m_im_j-b^2)}. \tag{59}$$

Substituting (59) into PA i's objective function (36), we obtain the corresponding FOC as

$$r_{iB}^{SS}=\frac{(2m_im_j-m_j-2b^2)}{m_j(4m_im_j-m_j-4b^2)}\{(m_j-b)[a+E(\theta\,|\,Y_i)]+bE(f_j\,|\,Y_i)-m_jc_i\}, \tag{60}$$

Using a similar approach as in A.1, PO j's optimal port charge f_{jB}^{SS} is a linear function of her signal Y_j. Then, we know that for PO i,

$$E(f_{jB}^{SS}\big|Y_i)=A_{jB}^{SS}+B_{jB}^{SS}E(Y_j\big|Y_i)=A_{jB}^{SS}+B_{jB}^{SS}E(\theta\big|Y_i) \tag{61}$$

We further have

$$A_{iB}^{SS}+B_{iB}^{SS}Y_i=\frac{\begin{array}{c}[(m_j-b)a+bA_{jB}^{SS}](3m_im_j-m_j-3b^2)+m_j(m_im_j-b^2)c_i\\+(3m_im_j-m_j-3b^2)(m_j-b+bB_{jB}^{SS})T_iY_i\end{array}}{m_j(4m_im_j-m_j-4b^2)}. \tag{62}$$

Using the same logic as in A.1, we obtain the coefficients A_{iB}^{SS} and B_{iB}^{SS}. Using A_{iB}^{SS}, B_{iB}^{SS} and Substituting f_{jB}^{SS} into (59) and (60), r_{iB}^{SS} and Q_{iB}^{SS} can be obtained. Based on f_{jB}^{SS}, r_{iB}^{SS} and Q_{iB}^{SS}, we obtain $E_{iB}^{SS}(\pi)$ and $E_{iB}^{SS}(SW)$.

A.7.2 Information sharing at neither port

If both POs do not share their information with their PAs, (58) and (59) still apply. PA i's decision now becomes

$$r_{iB}^{SS} = \frac{(2m_i m_j - m_j - 2b^2)}{m_j(4m_i m_j - m_j - 4b^2)}[(m_j - b)a + bE(f_j) - m_j c_i] \tag{63}$$

Substituting (63) into (58), and using similar logic as in A.5.1, we have

$$\begin{aligned} A_i^{NN} + B_i^{NN} Y_i = & \frac{[(m_j - b)a + bA_j^{NN}](3m_i m_j - m_j - 3b^2) + m_j(m_i m_j - b^2)c_i}{m_j(4m_i m_j - m_j - 4b^2)} \\ & + \frac{[m_j + (B_j^{NN} - 1)b]T_i Y_i}{2m_j} \end{aligned}. \tag{64}$$

Then, we obtain the coefficients A_{iB}^{NN} and B_{iB}^{NN}. Using A_{iB}^{NN}, B_{iB}^{NN} and Substituting f_{jB}^{NN} into (59) and (63), we obtain r_{iB}^{NN} and Q_{iB}^{NN}. Based on f_{jB}^{NN}, r_{iB}^{NN} and Q_{iB}^{NN}, we obtain $E_{iB}^{NN}(\pi)$ and $E_{iB}^{NN}(SW)$.

A.7.3 Information sharing in one port only

Using the same logic as in A.1.3, we obtain A_{iB}^{SN}, A_{iB}^{NS}, B_{iB}^{SN}, B_{iB}^{NS}, f_{jB}^{SN}, f_{jB}^{NS}, r_{iB}^{SN}, r_{iB}^{NS}, Q_{iB}^{SN}, Q_{iB}^{NS}, $E_{iB}^{SN}(\pi)$, $E_{iB}^{NS}(\pi)$, $E_{iB}^{SN}(SW)$, and $E_{iB}^{NS}(SW)$. □

A.8 Proof of Proposition 4

When $2m_i m_j - m_j - 2b^2 > 0$, it is easy to prove that $\Phi_i > 0$, $\Delta_i > 0$, and $\Omega_i > 0$. Moreover, we find that $\frac{\Delta_j}{\Phi_j} = \frac{m_j(4m_i m_j - m_j - 4b^2)}{3m_i m_j - m_j - 3b^2} < 2m_j$. Therefore, we know that $B_{iB}^{SS} > 0$, $B_{iB}^{NS} > 0$, $B_{iB}^{SN} > 0$, and $B_{iB}^{NN} > 0$. We can show with comparisons that $B_{iB}^{SS} > B_{iB}^{NS}$ and $B_{iB}^{SN} > B_{iB}^{NN}$ in general. In a symmetric case, when $2m^2 - m - 2b^2 > 0$ or $m \geq (1+\sqrt{17})/4$, we have $B_{iB}^{SS} > B_{iB}^{SN}$ and $B_{iB}^{NS} > B_{iB}^{NN}$.

For a positive Y_i, we can show that $f_{iB}^{NN} < f_{iB}^{SN} < f_{iB}^{SS}$ and $f_{iB}^{NN} < f_{iB}^{NS} < f_{iB}^{SS}$. From $m_j - b + bB_{jB}^{SS} > m_j - b + bB_{jB}^{NS} > 0$, we know that $r_{iB}^{NN} = r_{iB}^{NS} < r_{iB}^{SN} < r_{iB}^{SS}$. From $B_{iB}^{SS} > B_{iB}^{NS}$ and $B_{iB}^{SN} > B_{iB}^{NN}$, we know that $Q_{iB}^{SN} < Q_{iB}^{SS}$ and $Q_{iB}^{NN} < Q_{iB}^{NS}$. When $2m^2 - m - 2b^2 > 0$, both $m - b + bB_B^{SS} > \frac{4m^2 - m - 4b^2}{2m^2 - 2b^2}(m - b + bB_B^{SN})$ and

$m-b+bB_B^{NS} > \frac{4m^2-m-4b^2}{2m^2-2b^2}(m-b+bB_B^{NN})$ hold. Therefore, we have $Q_{iB}^{NS} < Q_{iB}^{SS}$ and $Q_{iB}^{NN} < Q_{iB}^{SN}$. Finally, we have $Q_{iB}^{SN} < Q_{iB}^{SS} < Q_{iB}^{NS}$ and $Q_{iB}^{SN} < Q_{iB}^{NN} < Q_{iB}^{NS}$. Using a similar logic, we can prove the comparisons under a negative Y_i.

Because $\frac{1-m_j\Omega_i}{2m_j} > 0$, it is easy to show that $E_{iB}^{SN}(\pi) < E_{iB}^{SS}(\pi)$ and $E_{iB}^{NN}(\pi) < E_{iB}^{NS}(\pi)$. When $2m^2-m-2b^2>0$, both $\frac{1-m\Omega}{2m}(m-b+bB_B^{SS})^2 < \frac{(4m^2-m-4b^2)(1+m\Omega)}{4m(m^2-b^2)}(m-b+bB_B^{SN})^2$ and $\frac{1-m\Omega}{2m}(m-b+bB_B^{NS})^2 < \frac{(4m^2-m-4b^2)(1+m\Omega)}{4m(m^2-b^2)}(m-b+bB_B^{NN})^2$ hold. Therefore, we have $E_{iB}^{SS}(\pi) < E_{iB}^{NS}(\pi)$ and $E_{iB}^{SN}(\pi) < E_{iB}^{NN}(\pi)$. Finally, we have $E_{iB}^{SN}(\pi) < E_{iB}^{SS}(\pi) < E_{iB}^{NS}(\pi)$ and $E_{iB}^{SN}(\pi) < E_{iB}^{NN}(\pi) < E_{iB}^{NS}(\pi)$.

It is easy to show that $E_{iB}^{SN}(SW) < E_{iB}^{SS}(SW)$ and $E_{iB}^{NN}(SW) < E_{iB}^{NS}(SW)$. However, for the comparisons of $E_{iB}^{SS}(SW)$ and $E_{iB}^{NS}(SW)$, $E_{iB}^{SN}(SW)$ and $E_{iB}^{NN}(SW)$, different results are obtained with different parameters. Therefore, their comparisons are uncertain. □

A.9 Proof of Corollary 3

In a symmetric case, when $2m^2-m-2b^2>0$, we can prove that $\frac{\partial B_B^{SS}}{\partial m}>0$, $\frac{\partial B_B^{SN}}{\partial m}>0$, $\frac{\partial B_B^{NS}}{\partial m}>0$, $\frac{\partial B_B^{NN}}{\partial m}>0$, $\frac{\partial B_B^{SS}}{\partial b}<0$, $\frac{\partial B_B^{SN}}{\partial b}<0$, $\frac{\partial B_B^{NS}}{\partial b}<0$, $\frac{\partial B_B^{NN}}{\partial b}<0$, $\frac{\partial(m-b+bB_B^{SS})}{\partial m}>0$, $\frac{\partial(m-b+bB_B^{SN})}{\partial m}>0$, $\frac{\partial(m-b+bB_B^{NS})}{\partial m}>0$, $\frac{\partial(m-b+bB_B^{NN})}{\partial m}>0$, $\frac{\partial(m-b+bB_B^{SS})}{\partial b}<0$, $\frac{\partial(m-b+bB_B^{SN})}{\partial b}<0$, $\frac{\partial(m-b+bB_B^{NS})}{\partial b}<0$, $\frac{\partial(m-b+bB_B^{NN})}{\partial b}<0$, $\frac{\partial}{\partial m}[\frac{4m^2-m-4b^2}{2m^2-2b^2}(m-b+bB_B^{SS})]>0$, $\frac{\partial}{\partial m}[\frac{4m^2-m-4b^2}{2m^2-2b^2}(m-b+bB_B^{SN})]>0$, $\frac{\partial}{\partial m}[\frac{4m^2-m-4b^2}{2m^2-2b^2}(m-b+bB_B^{NS})]>0$, $\frac{\partial}{\partial m}[\frac{4m^2-m-4b^2}{2m^2-2b^2}(m-b+bB_B^{NN})]>0$, $\frac{\partial}{\partial b}[\frac{4m^2-m-4b^2}{2m^2-2b^2}(m-b+bB_B^{SS})]<0$,

$\frac{\partial}{\partial b}[\frac{4m^2 - m - 4b^2}{2m^2 - 2b^2}(m - b + bB_B^{SN})] < 0$, $\frac{\partial}{\partial b}[\frac{4m^2 - m - 4b^2}{2m^2 - 2b^2}(m - b + bB_B^{NS})] < 0$, and $\frac{\partial}{\partial b}[\frac{4m^2 - m - 4b^2}{2m^2 - 2b^2}(m - b + bB_B^{NN})] < 0$. □

A.10 Proof of Proposition 5

Using a similar logic as in the proof of Proposition 3, and because $\Gamma_{1B} < \Gamma_{2B}$ when $2m^2 - m - 2b^2 > 0$, Proposition 5 can be obtained. □