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Seaport Adaptation to Climate Change Disasters: Subsidy Policy vs. Adaptation Sharing under Minimum Requirement

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Abstract

Many seaports around the world face serious threat of natural disasters related to climate change. They have been investing in adaptation measures to mitigate potential disaster damages. This paper proposes an economic model to examine the inter-port competition in adaptation investments when ports face asymmetric disaster losses. Specifically, we model the trading mechanism of the adaptation resources among different ports, and benchmark the outcomes with the widely used adaptation subsidy policies. Our analytical results suggest that with adaptation trading under the minimum requirement policy, the port facing the low disaster loss sells adaptation resources to the port facing the high disaster loss, allowing the latter to cover all its disaster loss. Subsidy policy is pro-competitive and intensifies inter-port competition in adaptation investment and output. In comparison, adaptation trading facilitates inter-port coordination, possibly leading to port collusion. When disaster damages are low, adaptation trading brings higher social welfare than the subsidy policy despite possible port collusion, leading to a Pareto improvement. When the magnitudes of disaster damages are high, the subsidy policy is preferred in terms of social welfare and port adaptation. Our model results reveal the strengths of alternative adaptation policies, and call for evaluation beyond competition effects when examining port coordination in adaptation.

Keywords: Port adaptation investment; Regulation; Sharing; Subsidy; Minimum requirement

1. Introduction

Climate changes have caused more extreme weather events and natural disasters (National Academies of Science, 2016). Seaports ('ports' hereafter) are highly vulnerable to climate-change related natural disasters such as hurricanes, storm surges, floods, and long-term sea-level rise (SLR). However, unlike production and capacity investments, adaptation projects often provide benefits only in the case of disasters, while they render little value otherwise. This tends to reduce port operators' incentives to implement adaptation projects (e.g., Ng et al., 2013, 2015, Yang et al., 2018, Panahi et al., 2020). This often calls for the governments to intervene with regulatory measurements to promote the port adaptation investments. Subsidy policy and minimum requirement are two common regulatory options that can be used to promote port adaptation investment (Zheng et al., 2021). Under a subsidy policy, the government provides the ports with direct financial support for the adaptation investment (Gong et al., 2020). For example, the US Federal government established the Hazard Mitigation Grant Program to offer financial support for port adaptation.[1] In other cases, countries stipulate a minimum requirement for the port adaptation level. In the Netherlands, the National Water Law specifies the minimum standards for levee construction.[2] As a result, key economic areas such as ports, power plants and gas supply infrastructures receive a higher protection level.

The same disaster can impose asymmetric damages on the ports in the same region. Due to heterogeneous landscapes and infrastructure facilities, some ports are better protected from natural hazards or have lower adaptation investment cost than others. For example, in 2020, Typhoon Hagupit hit Yangtze River Delta of China. Port of Shanghai was less affected as it is located in the inner section of Huangpu River. In comparison, the neighboring Port of Yangshan was much more severely damaged, as it was built on the reclaimed land around islands in order to accommodate mega containerships. Along the Hamburg-Le Havre port range in North Europe, some ports are more vulnerable to SLR than the others (Wang and Zhang, 2018). In particular, Port of Rotterdam and Port of Amsterdam in the Netherlands lie below the sea level and could be submerged if no effective adaptation measures are adopted. Therefore, SLR imposes more serious threat to the ports in the Netherlands than in Germany or France. In addition to the heterogeneous landscapes, the ports can also have quite different resilience to recover from the same disaster interruptions, which may be attributed to asymmetric disaster damages among ports.[3] Despite the significant heterogeneity across ports in the same catchment area, virtually all existing analytical studies on port adaptation assume the ports to have symmetric disaster occurrence probability or the same level of disaster damage (e.g., Xiao et al., 2015; Wang and Zhang, 2018; Randrianarisoa and Zhang, 2019; Gong et al., 2020; Wang et al., 2020a; Zheng et al., 2021). This symmetric assumption greatly simplifies the model derivations so that clear-cut conclusions and strong

[1] Some international organizations, such as the World Bank and the United Nations (UN), also provide no-interest loans and subsidies for infrastructure adaptation, with the recipients being mostly developing countries (UN ESCAP, 2018). In developed countries, favorable commercial arrangements may be arranged. For example, the European Investment Bank provided long term loans to the expansion of the Port of Rotterdam, which are designed to adapt for climate change impacts (European Commission, 2013).

[2] The Netherlands Flood Protection Act of 1996 also regulates the safety levels in terms of the exceedance frequency of flood defenses according to the economic value of the area and the source of the flooding (e.g., Jonkman et al., 2018).

[3] For example, Typhoon Mangkut hit Port of Hong Kong and Port of Shenzhen in 2018. Both ports were forced to shut down. But Port of Hong Kong recovered much faster than Port of Shenzhen thanks to Hong Kong's more efficient port management skills and advanced logistics systems.

intuition can be obtained. Nevertheless, such deviation from the reality could lead to biased findings.

The nearby ports in a region could also consider sharing their adaptation resources upon disaster occurrences. Since the ports in the same region are differently affected by a common disaster, they could have different adaptation requirements and resources. If one port is less affected or has more adaptation resources, it can provide assistance to the less adapted ports during the disaster. As observed in practice, various adaptation sharing arrangements have been adopted among ports in a region. For example, before hurricane arrival, those less adapted ports might transfer some ships to the better adapted ports with reserved adaptive capacity.[4] The involved ports might negotiate a price (i.e., service charge) for the adaptive capacity reserved for the accommodation of such temporally transferred services.[5] Such adaptive capacity sharing might enhance the inter-port cooperation, leading to port's coordination not only on the adaptation measures but other competition decisions.[6]

In addition to capacity sharing, some adaptation facilities may be built and customized for the better connection of two competing ports. The European Commission (2018b) studied the Delta Programme in Netherland, one of the largest adaptation project in the world against climate change and the SLR. The case study noted that the design of certain seaways of the Delta Works were specially modified for the sake of shipping between the ports of Rotterdam and Antwerp. Meyer (2009) also noted that Delta Works involved closing all the estuary sea gates with dikes except those providing entrance to the port of Amsterdam and Antwerp. He further argued that despite the competition between the two of the most important ports in Europe, a consistent policy should be developed, because "*a comprehensive cross-national policy concerning seaport development is increasingly regarded as necessary. Officially the ports of Rotterdam and Antwerp are two competing port clusters. But the economic reality is that these ports, together with a number of smaller ports in the delta area (Vlissingen, Terneuzen, Gent, Dordrecht), are operating as one large port cluster. Port companies settled in Rotterdam also have terminals in Antwerp, and vice versa. Both ports and the smaller ports are connected with each other by navigation canals, pipelines, roads and railroads. Together they are the largest and most important port cluster of Europe (Wang et al., 2007). Considering the common economic interest and the common interest of the Netherlands and Belgium regarding flood defence and improving environmental qualities, a common, cross national approach for the south-west delta is inevitable*."

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[4] For instance, before Hurricane Harvey attacked the Port of Houston and other gulf US ports, these ports advised shipping carriers to reroute to alternative ports in Louisiana, Florida and Georgia. See for example the relevant report at the link: https://www.wsj.com/articles/texas-seaports-close-to-prepare-for-hurricane-harvey-1503682646.

[5] It should be noted that such transfer or rerouting of shipping service during disasters would be temporal. After the recovery, the transferred shipping services would return to the original ports under normal circumstances. A permanent switch of the shipping services due to natural disaster has been quite rare, because shippers/shipping lines often sign a long-term contract with one port. Shippers/shipping lines usually commit to particular ports for various long term considerations such as the integration and investment in hinterland transport, warehousing, and other forms of cooperation with port (Chang et al., 2008; Wiegmans et al., 2008; Tongzon, 2009; Franc and van der Horst, 2010). In many cases, terminals or ports are vertically integrated with certain shipping firms (Zhu et al. 2019; Jiang et al. 2021). Shipping lines' network configuration is often a strategic decision (Tu et al. 2018), and even ports sharing the common catchment area may be differentiated (Zhuang et al. 2014).

[6] It should be noted that port capacity sharing can be motivated absent adaptation consideration. Asadabadi and Miller-Hooks (2020) examined the interacting investment problems for the independent ports to improve their network resiliency and reliability in a co-opetitive way. Xu et al. (2021) studied capacity sharing and "co-opetition" practices in the maritime industry, and concluded that ports may share capacity in response to strengthened rival, although such a decision is also moderated by the synergy from the cooperation.

Indeed, as early as in 1976, Belgium and The Netherlands had signed a contract to regulate shipping operations between the two ports. Still, common adaptation policies over competing ports have not been many, and even fewer ports have developed formal mechanisms for adaptation resource sharing. This is in sharp contrast to information sharing and knowledge transfer, which has been promoted by the maritime industry for years and formally incorporated in government initiatives in general.[7] Analyzing company responses to climate change-related issues in Germany and Japan, Lee and Tkach-Kawasaki (2018) concluded that information-sharing and resource-sharing are complementary. However, information-sharing has lower level influence compared to resource-sharing, and information-sharing relations increase the resource-sharing relations. This would suggest more resource sharing for port adaptation subsequent to information sharing initiatives in the port industry. Therefore, the more adapted ports could also share other adaptation resources, such as the[8] evacuation, drainage and maintenance equipment and personnel to help the more damaged ports recover and resume normal operations quickly. Indeed, this is what happening in the airport industry. Airport-to-airport mutual aid programs have been formed in the US with several airports signing agreement to provide expert assistance and material support to those that have been affected by a natural disaster on a voluntary basis. Southeast Airports Disaster Operations Group (SADOG) was found in 2004 in the southeast US, under the leadership of Savannah-Hilton Head International Airport and Orland International Airport. The aim of SADOG is to organize the member airports to provide mutual aid (maintenance equipment and personnel) to help airports recover from hurricane damages. More than 20 airports have joined in SADOG and offered mutual aids to each other for hurricane relief. The adaptation sharing has also been recently practiced in the landside and urban flood risk management, such that the different entities or regions can share their transport and logistics equipment when a disaster strikes (Seddighi and Baharmand, 2020; Alam and Ray-Bennett, 2021).

Along with the underdevelopment of adaptation sharing in the port industry, the formal economic analysis of such mechanism on the ports and social welfare is absent. It is thus unclear how such sharing mechanism can be best designed to help the maritime industry and regional economy, and meanwhile obtain supports from stakeholders including ports competing with each other. Such a mechanism, depending on the specific designs, could have complex implications. On one hand, the adaptation sharing helps rationalize adaptation resources among ports in the same region, thus improving the overall adaptation utilization efficiency and saving adaptation cost. This should be conducive to the ports and social welfare. On the other hand, the adaptation sharing, as a form of inter-port cooperation, might weaken the market competition, leading to anti-trust concern. This is because a port's adaptation investment is often proportional to its output (Wang and Zhang, 2018; Wang et al, 2020). Through adaptation sharing, the competing ports might be able to implicitly collude with each other to reduce outputs and raise prices. Port users' surplus and social welfare could be harmed as a result.[9] The lack of understanding and under

[7] See, for example European Commission (2018a) and information available at the European Climate Adaptation Platform, a one stop information and knowledge sharing portal created for EU countries

[8] They pointed out that this is a common observation in collaborative governance, as "*information exchange and sharing are involved in relatively low-level collaboration, then, as the intensity of relationship and level of trust grow, the level of collaboration becomes higher to enact resource exchange and sharing (Ansell & Gash, 2008; Wanna, 2008)*"

[9] When referring to the literature on the port emission control, Homsombat et al. (2013) suggested that the inter-port coordination in setting an uniform emission tax would effectively solve for the pollution spill-over problem and alleviate the emission tax distortion under inter-port competition, which would help improve the social welfare. By contrast, Sheng et al. (2017) found that a uniform emission regulation with inter-port

development of adaptation sharing could lead to a chicken-and-egg problem, preventing the associated benefits to be realized. In 2013, more than 10 prominent maritime researchers classified port adaptation into two categories: hard interventions that involve engineering works and high capital investments; and soft interventions that involve decision-making, such as systematic and strategic management, financial incentives, and notably institutional changes (Beck et al., 2013). These researchers further suggested that "*ports can apply many low-cost intervention measures that can reduce climate risks and build a port's resilience before they resort to hard engineering works*". Considering the potential large benefits and low cost of setting up adaptation sharing mechanism, it is therefore important to conduct a formal economic analysis to clearly untangle and quantify the complex countervailing effects of port adaptation sharing on market outcomes. Such a study is expected to have important practical and policy implications, and contributes to an under-developed yet potentially very important literature of adaptation cooperation.

To address such industry and research needs, this study establishes an integrated economic model to examine the implications of adaptation sharing mechanism among ports with asymmetric disaster damages and levels of adaptation resources. We consider adaptation sharing implemented with formal financial arrangements, resembling a trading scheme. Moreover, we also model such adaptation trading to be jointly implemented with government's minimum requirement on port adaptation level. That is, the government first specifies a minimum adaptation standard for all ports, then allows them to trade the adapted capacity through a market mechanism. We also benchmark the analysis with adaptation subsidy, a policy widely used and in principle similar to the emission control taxation regulation. It should be noted that, adaptation trading is unlikely to be jointly implemented with the government subsidy policy. Ports may free-ride government's subsidy by trading the subsidized adaptation resources. That is, some ports could be motivated to acquire excessive subsidies by over-investing in adaptation, and subsequently sell the extra capacity to other ports to make "windfall profit" brought by regulation (Arguedas and Soest, 2009).

Specifically, we aim to answer the following research questions in this study: (1). Under what conditions would adaptation trading occur under the minimum requirement policy? (2). Whether the subsidy policy or adaptation trading under the minimum requirement can promote or alleviate the inter-port competition (compared to the case without any regulatory policy)? (3). What are the socially optimal levels of subsidy and minimum requirement with adaptation trading, respectively? (4). Which of the two policies is socially optimal (i.e. leading to higher social welfare) and how would the result be affected by factors notably port asymmetry in disaster damage and adaptation cost?

Whereas our study focuses on the port industry, it is expected to contribute to the economics of adaptation in general. The potential of using economic instruments and market mechanism in adaptation is well recognized.[10] However, Chambwera et al. (2014) concluded that there is relatively little literature on the use of economic instruments for adaptation with the exception of insurance- and trade- related instruments. Wang et al. (2020b) reviewed climate

cooperation would be more effective to reduce emissions than a unilateral regulation, but it could weaken the inter-port competition, harming the shipper's surplus and social welfare as a result. Park et al. (2018) discussed the port emission control under a duopoly market.

[10] See for example, discussions on economic instruments for climate change and adaptation by Kohn (1996), proposal of establishing "Adaptation Market Mechanism" in Braeuninger et al. (2011), the roles that can be played by market including market-based policy in Aldy and Stavines (2011), Ergas (2012), Meckling and Jenner (2016), and general discussions on economics of adaptations in Chambwera et al. (2014).

adaptation of transportation systems based on 100 papers published in 65 journals between 2005 and 2018. Among the major research gaps identified, they highlighted that "*Many adaptation tools or frameworks are not explicitly designed for the transportation sector … and the high uncertainty in adaptation for climate change risks poses a significant challenge for planners*." Our quantitative analysis directly contributes to the study of these identified research gaps.

The rest of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 sets up the basic economic model and investigates the market outcomes under the subsidy policy vs. the case of adaptation trading under minimum requirement policy. Section 4 examines the impacts of the government's policies on the social welfare and the port industry's profit. Section 5 concludes the main results and points out the possible future extensions.

2. Literature Review

This study is relevant to three streams of literature. The first is about economic analyses on port adaptation and regulatory policies. Xiao et al. (2015) modeled the port adaptation investment with information updating on the disaster uncertainty. Wang and Zhang (2018) extended the analysis to a two-port region and complicates the disaster uncertainty as "Knightian uncertainty", such that the inter-port competition/coordination and the disaster ambiguity can also be accounted for. Wang et al. (2020) examined the impact of the downstream terminal operator market structure on the inter-port competition/coordination on port adaptation. Randrianarisoa and Zhang (2019) considered the randomness of adaptation effectiveness and showed how such uncertain could also affect port adaptation. Jiang et al. (2020) established an economic model to incorporate both port's adaptation and mitigation decisions, and compare their relative effects on the market outcomes. The economic analysis on the regulatory policies on port adaptation is, however, relatively few. Zheng et al. (2021) established an integrated economic model to benchmark the outcomes of subsidy and minimum requirement policies. The social welfare comparisons depend on the degree of disaster uncertainty and also the relative magnitude of the potential disaster damage. Overall, the subsidy outperforms the minimum requirement policy as the subsidy is more pro-competitive to increase port output. Moreover, the government intervention under disaster ambiguity might damage social welfare compared to doing nothing. However, all abovementioned studies assumed the ports to have symmetric disaster damage. This could be a very strong assumption as ports can have very heterogenous disaster damage as explained in introduction. In addition, previous studies all ignored possible market mechanism for ports to share adaptation resources, and benchmarked the performance with currently adopted regulatory policies. Our economic analysis thus fills such research.

The second relevant stream of literature is for some qualitative studies to promote port cooperation to jointly deal with climate change-related disasters. In general, cooperation and resource sharing in climate change adaptation has been recognized as a top priority beyond the transport industry, across different levels of governments and national borders. Glicksman (2010) investigated the optimal policy structure to facilitate climate change adaptation of all levels of government from a legal perspective. He concluded that in the US, all levels of governments are required to play rules under existing laws such as the Clean Air Act, and "*the federal environmental laws identify these kinds of information and resource-sharing efforts as critical statutory purpose*". Agrawala and Fankhauser (2008) concluded that climate change adaptation has implications beyond national boundaries, and thus countries need to develop transboundary policies toward shared ecosystems and water resources. For example, co-operative management of shared river systems, such as the Mekong and the Nile, is of critical importance to adaptation and social development of multiple countries. The Mekong River Commission[11] collaborated with the Global Change System for Analysis, Research and Training to address climate change issues related to the Mekong river basin. The United Nations Economic Commission for Europe (UNECE, 2009), together with multiple governments and more than 80 experts, published the Guidance on Water and Adaptation to Climate Change because "*only concerted and coordinated action will enable countries to deal with the uncertainties of climate change and to tackle its impacts effectively*". The European Commission (2018a) has been financing quite a number of Cross-border Cooperation Programme for promoting climate adaptation, risk prevention and management involving EU countries and Turkey, Bulgaria in recent years.

Last, our economic study on port adaptation trading is also related to existing economic measures on emission control in the shipping industry. Specifically, the adaptation trading under the minimum requirement policy is somewhat analogous to the "cap-and-trade" policy in emission control, namely the emission trading scheme (ETS) (Wang et al., 2015; Dai et al., 2018). While the ETS specifies the maximum (i.e., the upper bound) emissions for individual port, the minimum requirement policy regulates the lower bound of port adaptation level. Similar to endogenously determined price of emission permits, the trading price of adaptation resources is determined by market force without direct government intervention. On the other hand, the subsidy on port adaptation could be analogous to emission tax to directly change ports' financial to deal with environmental threat. There is a well-developed literature using analytical models to examine and benchmark the economic mechanisms of emission control of shipping industry (e.g. ETS vs. tax). Findings obtained from these previous studies can serve as useful references for comparable policies on port adaptation. For example, Wang et al. (2015) modelled the emission trading between the container and dry bulk shipping sectors. They found that the container shipping sector would purchase emission permits from the dry bulk sector, while the equilibrium trading price would be determined by the market competition and cost structures of the two shipping sectors. Brueckner and Zhang (2010) analytically investigated the impact of an airline emission tax on market equilibrium of a duopoly airline competition. The airlines raise airfares but reduce flight frequency, which lead to increased load factor, fuel efficiency and social welfare. Many studies also tried to evaluate the performances of different economic regulations to cope with the climate-change related disasters for the shipping sector (e.g., Psaraftis and Kontovas, 2010; Yang et al., 2012; Lee et al. 2013; Cullinane and Bergqvist, 2014; Lee et al. 2016a, b; Dai et al., 2018; Afenyo et al. 2019). However, they mainly focused on the emission control (i.e., the mitigation) instead of adaptation. In addition, an integrated modeling framework is yet to be developed to directly benchmark the two types of regulatory policies (i.e., adaptation subsidy vs. the adaptation trading under minimum requirement). Our paper thus helps fill this research gap.

3. Economic Model

In this section, we first establish the economic model, and then the ports' output and

[11] The Commission is an intergovernmental organization created in 1995 by the governments of Cambodia, Lao PDR, Thailand, and Vietnam.

adaptation investment decisions under the subsidy and the adaptation trading with minimum requirement policies are examined.

3.1 Basic model specification

Two ports provide the substitutable services and their demand functions are:

$$P_i = a - Q_i - bQ_j, \forall i, j = 1,2 \tag{1}$$

where Q_i is port i's output, P_i is port i's charge and $b \in (0,1]$ measures the service substitutability between the two ports, thus a larger b also indicates more intense inter-port competition. The two ports engage in a Cournot competition. Cournot competition is commonly used in the port literature, e.g., Van Reeven (2010), Kaselimi et al. (2011), Wan and Zhang (2013), Yip et al. (2014), Chen and Liu (2016), Zheng et al. (2020), especially for the ports under government regulations. It has been proven that in a competition when capacity is first determined and then price is set, this multi-stage game is equivalent to a Cournot competition. That is, if ports first determine capacity then price, it can be characterized by a Cournot competition. To rule out trivial cases of negative output and price, it is assumed that the market potential a is large enough. The two ports are heterogeneous in terms of natural conditions and geographic locations, and face different potential disaster loss in the future. We use D_H and D_L (with $D_H \geq D_L \geq 0$) to indicate the two ports' expected disaster loss, respectively. Without loss of generality (WLOG), we assume that Port 1 is subject to the high loss D_H (the port is hence referred as "Port H" hereinafter for easy reference), whereas Port 2 faces D_L ("Port L" hereinafter).[12] To reduce the disaster loss, a port can make an *ex-ante* adaptation investment. Port i's actual expected loss thus can be specified as $D_i(1-x_i)Q_i$, where $i = \{H, L\}$, and $x_i \in [0,1]$ is the percentage of the disaster loss reduction thanks to the adaptation investment. Port i's adaptation investment cost is $c_i(x_iQ_i)^2$, where c_i is a parameter in Port i's adaptation investment cost function. Here we consider the case in which the port's adaptation investment cost is an increasing quadratic function of the loss reduction quantity x_iQ_i. The increasing and convex cost function of adaptation is commonly used in the related studies (e.g., Wang and Zhang, 2018; Randrianarisoa and Zhang, 2019; Wang et al., 2020a; Zheng et al., 2021). The quadratic form captures the nonlinear nature of the adaptation cost, and meanwhile ensures the mathematical tractability. The ports' marginal operation costs are normalized to 0.[13] We focus on the port asymmetry in terms of different expected disaster loss, assuming that the two ports have the same investment efficiency (i.e. the coefficients in their cost functions of adaptation investment are the same thus $c_H = c_L = c$).

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[12] To simplify the model analysis and focus on the key conclusions, we use two discrete values to indicate the different levels of the disaster loss for the ports. Using the continuous value or function to indicate the ports' disaster losses cannot obtain more economic insights, but complicates the model analysis and even makes the model intractable. Such a simplification is common in the transport economic literature. In reality, each port's true expected disaster damage can be expressed as $D = \sum \delta_k Z_k$, where Z_k is its disaster damage under the different scenarios k and δ_k is the corresponding probability of the occurrence of scenarios k. Here the probability distribution δ_k is used to reflect the "disaster occurrence uncertainty", which is the same to all ports. Therefore, the differences of the expected disaster damage among the ports are only caused by each port's damages under the disaster, i.e., Z_k. To simplify the expressions, we omit δ_k and let the expected disaster damage indicate the asymmetry between the ports when they face the same disaster. Apparently, this will not change the modelling conclusions.

[13] Normalizing the ports' marginal operation costs is used to simplify the expressions of the model solutions. It has no impacts on the results qualitatively because one can simply add the marginal operation costs to the equilibrium prices under any scenarios, if they are considered. Such normalization is frequently used in the literature, e.g., Zheng et al. (2021).

Here we focus on modeling the ports' asymmetry on their disaster losses. Under this assumption and our model setting, we can obtain more clear-cut economic insights and better illustration of some basic characteristics of the port adaptation policies, especially the minimum requirement policy. In addition, the port adaptation technology is commonly accessible and thereby the adaptation cost is affected mainly by the port scale (or its outputs). This technical efficiency of adaptation investment can be reflected by the parameter c in its cost function. Meanwhile, in order to test the robustness of our models, we will relax this assumption in the numerical studies (Section 4.4.2) to investigate the influences of the ports' investment efficiency (i.e., the coefficients in their cost functions of adaptation investment).

In order to regulate the ports' adaptation investment, the government has the options of the following two policies: subsidy vs. minimum requirement with adaptation trading between the ports. Under the subsidy policy, the government provides a subsidy δ for each unit of adaptation investment made by the ports. The two ports thus face the following problems respectively:

$$\max_{Q_H, 0 \le x_H \le 1} \pi_H = P_H Q_H - D_H(1 - x_H)Q_H - c(x_H Q_H)^2 + \delta(x_H Q_H) \tag{2a}$$

$$\max_{Q_L, 0 \le x_L \le 1} \pi_L = P_L Q_L - D_L(1 - x_L)Q_L - c(x_L Q_L)^2 + \delta(x_L Q_L) \tag{2b}$$

Under the minimum requirement policy, the government regulates an upper limit of the expected disaster loss for each port. Meanwhile, the two ports can trade their surplus adaptation materials, or share their surplus adaptive capacities, based on a trading price negotiated between them. Under the minimum requirement policy, the two ports face the following problems respectively:

$$\max_{Q_H \ge 0, 0 \le x_H \le 1, x_{HB}} \pi_H = P_H Q_H - D_H(1 - x_H - x_{HB})Q_H - c(x_H Q_H)^2 - t(x_{HB} Q_H) \tag{3a}$$

$$\text{s.t. } D_H(1 - x_H - x_{HB})Q_H \le R_H \tag{3b}$$

$$0 \le x_H + x_{HB} \le 1 \tag{3c}$$

$$\max_{Q_L \ge 0, 0 \le x_L \le 1, x_{LB}} \pi_L = P_L Q_L - D_L(1 - x_L - x_{LB})Q_L - c(x_L Q_L)^2 - t(x_{LB} Q_L) \tag{4a}$$

$$\text{s.t. } D_L(1 - x_L - x_{LB})Q_L \le R_L \tag{4b}$$

$$0 \le x_L + x_{LB} \le 1 \tag{4c}$$

where R_H (or R_L, respectively) is the upper limit of the disaster loss for Port H (or Port L, respectively). Here $x_{HB}Q_H$ and $x_{LB}Q_L$ are the traded adaptation, with a positive (or negative, respectively) adaptation trading indicates the purchase (or sale, respectively) from the other. t is the trading price agreed between the two ports, and clears the adaptation trading market (i.e., $x_{HB}Q_H + x_{LB}Q_L = 0$).

The social welfare of this two-port region can be defined as:

$$\begin{aligned} SW = a(Q_H + Q_L) - Q_H^2/2 - Q_L^2/2 - bQ_H Q_L - c(x_H Q_H)^2 - c(x_L Q_L)^2 \\ - D_H(1 - x_H)Q_H - D_L(1 - x_L)Q_L \end{aligned} \tag{5}$$

where $a(Q_H + Q_L) - Q_H^2/2 - Q_L^2/2$ is the port users' surplus, $c(x_H Q_H)^2 + c(x_L Q_L)^2$ is the adaptation investment costs of the two ports, and $D_H(1 - x_H)Q_H + D_L(1 - x_L)Q_L$ is the expected disaster loss at the two ports.

The game structure can be described as follows:

Stage 1. The government designs the optimal policy (R_H^* and R_L^*, or δ^*) to maximize the expected social welfare;

Stage 2. Ports simultaneously decide their outputs and adaptation investments to maximize their own expected profits. Specifically, under the subsidy policy, the subsidy is offered to the ports. Under the minimum requirement policy, the ports can trade their surplus adaptation resource (adaptation materials or adaptive capacity) based on the negotiated trading price.

The game is solved by backward induction. Stage 2 of the inter-port interaction is first solved given the government's subsidy or minimum requirement policies, reported in subsection 2.2 and 2.3, respectively. Under minimum requirement policy, the equilibrium of adaptation trading is also derived. Then, Stage 1 is solved to obtain the government's optimal subsidy or minimum requirement specification for social welfare maximization. The detailed derivations of the government decisions are presented in Section 3.

3.2 Ports' decisions under the subsidy

Solving Problem (2a) and (2b) simultaneously, we obtain the ports' equilibrium outputs and adaptation investments under the subsidy policy, which are summarized in the following proposition.

Proposition 1. Under the subsidy policy, the ports' output and adaptation investment decisions depend on the subsidy δ. *Let* $\delta_1 = \frac{2ac(2-b)-(4+4c-b^2)D_H+2bcD_L}{4-b^2}$, $\delta_2 = \frac{2ac-(2+b+2c)D_L}{2+b}$. *Specifically,*

(i) if $\delta \in [0, \delta_1]$, *two ports' outputs are* $Q_H = \frac{a(2-b)-2D_H+bD_L}{4-b^2}$ *and* $Q_L = \frac{a(2-b)+bD_H-2D_L}{4-b^2}$, *with* $Q_H < Q_L$. *Their adaptation decisions are* $x_H = \frac{D_H+\delta}{2cQ_H}$ *and* $x_L = \frac{D_L+\delta}{2cQ_L}$, *with* $x_H > x_L$*;*

(ii) if $\delta \in (\delta_1, \delta_2)$, *two ports' outputs are* $Q_H = \frac{a(2-b)+2\delta+bD_L}{4-b^2+4c}$ *and* $Q_L = \frac{a(2+2c-b)-2(1+c)D_L-b\delta}{4-b^2+4c}$, *with* $Q_H < Q_L$. *Their adaptation decisions are* $x_H = 1$ *and* $x_L = \frac{D_L+\delta}{2cQ_L}$, *with* $x_H > x_L$*;*

(iii) if $\delta \in [\delta_2, \infty)$, *two ports have the same outputs and adaptation decisions, i.e.,* $Q_H = Q_L = \frac{a+\delta}{2+b+2c}$, $x_H = x_L = 1$.

Proposition 1 shows that the government's subsidy has different impacts on the ports' output and adaptation investments decisions. When the subsidy is low, it has no impacts on the two ports' output decisions and only promotes adaptation to reduce disaster loss. Port H installs more adaptation to reduce more disaster loss than Port L. At the same time, as shown in Figure 1a, due to the competition disadvantage of Port H (because it faces higher disaster loss D_H), Port H's output is lower than Port L's. As the subsidy increases, Port H first reaches its highest disaster loss reduction with $x_H = 1$ (i.e., full coverage), and the subsidy begins promoting its output as well.

Meanwhile, Port L still uses the subsidy to increase adaptation to reduce disaster loss but it does not contribute to output increase. Because two ports compete in Cournot, Port H's output increase squeezes Port L's output. When the subsidy is high enough, both ports make the full adaptation investment thus that they are fully covered against all possible disaster damage. Subsidy leads to output increases instead of further adaptation. Because disaster losses are fully covered, outputs are the same at the two ports.

Proposition 1 reveals the evolving effects of the subsidy to asymmetric ports. As shown in Figure 1b, when the subsidy is low, the ports use it for adaptation investment. When subsidy is high, it also promotes port outputs and "neutralize" port competitive difference, in the sense that it benefits the port having a competitive disadvantage (i.e. facing the higher disaster loss). Proposition 1 has important policy implications which is elaborated in Section 3.

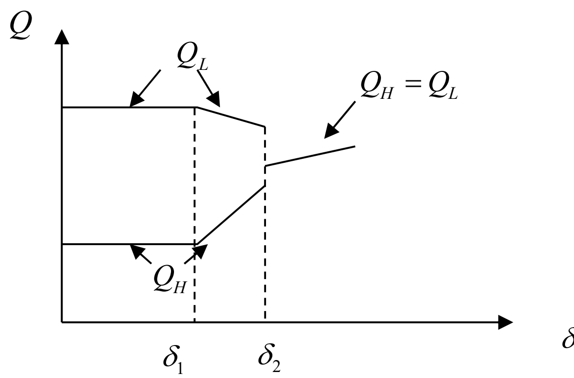

Figure 1a Ports' outputs under the subsidy policy

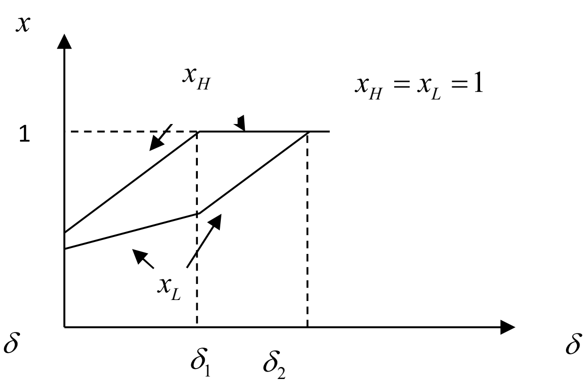

Figure 1b Ports' adaptation decisions under the subsidy policy

3.3 Ports' decisions under the minimum requirement

Solving Problem (3a)-(3c) and (4a)-(4c) simultaneously, we obtain the ports' equilibrium outputs and adaptation investments under the minimum requirement policy. We first investigate the conditions under which the adaptation trading can be achieved, which are summarized as in Proposition 2. Proposition 3 discusses the case in which no trading happens.

Proposition 2. Under the minimum requirement policy, whether the adaptation trading between the ports can be achieved depends on the adaptation investment cost and the minimum requirement of Port L, i.e., c *and* R_L*. Specifically,*

(i) when $c \in [\frac{(2+b)D_L}{a-D_L}, \frac{(4-b)^2 D_H}{(2-b)a-2D_H+bD_L}]$ *and* $R_L \geq \frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}$*, the adaptation trading can be achieved and ports' outputs and adaptation investments are* $Q_H = \frac{a(2-b)+bD_L-2t}{4-b^2}$*,* $Q_L = \frac{a(2-b)-2D_L+bt}{4-b^2}$*,* $x_H = \frac{t}{2cQ_H}$*,* $x_L = \frac{t}{2cQ_L}$*. The trading price is* $t = \frac{c(2a-ab+bD_L)}{2(2+c)-b^2}$ *and Port L sells all adaptation to Port H, i.e.,* $x_{LB} = -x_L < 0$ *and Port H achieves the full adaptation finally, i.e.,* $x_H + x_{HB} = 1$*, with* $x_{HB} > 0$.

(ii) when $R_L \in [0, \frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}]$ *and* $c \in [\frac{(2+b)D_L^2}{2(a-D_H)D_L-(2+b)R_L}, \frac{(2+b)D_H D_L}{2(a-D_L)D_L-(2+b)R_L}]$ *, the*

adaptation trading can be achieved and the ports' outputs and adaptation investments are $Q_H = Q_L = \frac{a-t}{2+b}$*,* $x_H = \frac{t}{2cQ_H}$*,* $x_L = \frac{t}{2cQ_L}$*. The trading price is* $t = \frac{c[2aD_L-(2+b)R_L]}{(2+b+2c)D_L}$ *and the trading adaptation is* $x_{LB}Q_L$*, where* $x_{LB} = x_L + \frac{R_L}{D_LQ_L} - 1 < 0$*. Port H achieves the full adaptation finally, i.e.,* $x_H + x_{HB} = 1$*, with* $x_{HB} > 0$*.*

Proposition 2 provides some interesting implications on the ports' adaptation investment and trading decisions. From Port H's profit function (3a), we know that its marginal benefit and marginal cost from buying a unit of adaptation resource is D_H and t, respectively. Only when $t \leq D_H$, Port H is willing to buy the adaptation resource from Port L. On the other side, from (4a) we know that Port L's marginal benefit and marginal cost from selling a unit of adaptation resource is t and D_L, respectively. Only when $t \geq D_L$, Port L is willing to sell its surplus adaptation resource to Port H. The trading condition $D_L \leq t \leq D_H$ and the market clearance condition (i.e., $x_{HB}Q_H + x_{LB}Q_L = 0$) confine the scope of the parameter of the adaptation cost function, i.e., c. Furthermore, only Port L sells its surplus adaptation resource to Port H, and Port H always makes the full adaptation investment to cover all its disaster loss (with its own adaptation investment and purchase from Port L). The reason is that the relative high trading price (to Port L) makes it profitable to prepare the adaptation first and then sell to Port H (after satisfying Port L's minimum requirement). Because Port H can find the "low price" of adaptation (from Port L), which is lower than its marginal benefit, it is always better to make the full adaptation investment to cover all its disaster loss. Furthermore, if the adaptation trading between the ports can be achieved, the minimum requirement for Port H is unnecessary and the minimum requirement for Port L affects the usage of the adaptation investment made by Port L, i.e., whether it is used for its own disaster coverage. If Port L's minimum requirement is loose (not binding and so $R_L \geq \frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}$), it sells all its adaptation to Port H (and Port L does not use its adaptation investment at all). If Port L's minimum requirement is strict, i.e., $R_L \leq \frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}$, Port L uses its adaptation investment partially on itself and sells the remaining proportion to Port H. From Proposition 2 we have the following Corollary 1, which has the important policy implications.

Corollary 1. If the adaptation trading between two ports can be achieved, Port H will buy adaptation resources from Port L to achieve full coverage against the disaster loss. Then, the minimum requirement for Port H is unnecessary.

Corollary 1 suggests that, if the adaptation trading can happen between the asymmetric ports, the government only needs to focus on the minimum requirement of the ports with the lower disaster loss (i.e., Port L). The trading mechanism between the ports can realize the effective use of the adaptation investment. Therefore, it seems that the adaptation trading between ports should be encouraged in terms of disaster recovery. However, whether the trading will benefit the social welfare needs further investigation, which is discussed in the next section.

To make the analysis complete, we obtain the below proposition to describe the ports' decisions under the minimum requirement policy if the adaptation trading cannot be achieved.

Proposition 3. Under the minimum requirement policy, if the adaptation trading between the ports cannot be achieved, the ports' decisions depend on their minimum requirements. Let $R_H^0 = \frac{D_H[2ac(2-b)-(4+4c-b^2)D_H+2bcD_L]}{2c(4-b^2)}$ *and* $R_L^0 = \frac{D_L[2ac(2-b)-(4+4c-b^2)D_L+2bcD_H]}{2c(4-b^2)}$*. Specifically,*

(i) When $R_H \geq R_H^0$ *and* $R_L \geq R_L^0$,

$Q_H = \frac{a(2-b)-2D_H+bD_L}{4-b^2}$, $Q_L = \frac{a(2-b)-2D_L+bD_H}{4-b^2}$, $x_H = \frac{D_H}{2cQ_H}$, $x_L = \frac{D_L}{2cQ_L}$;

(ii) When $R_H < R_H^0$ *and* $R_L < R_L^0$,

$Q_H = \frac{a[2(1+c)-b]D_HD_L+4c(1+c)D_LR_H-2bcD_HR_L}{[4(1+c)^2-b^2]D_HD_L}$, $Q_L = \frac{a[2(1+c)-b]D_HD_L+4c(1+c)D_HR_L-2bcD_LR_H}{[4(1+c)^2-b^2]D_HD_L}$, $x_H = \frac{a[2(1+c)-b]D_HD_L-(4+4c-b^2)D_LR_H-2bcD_HR_L}{a[2(1+c)-b]D_HD_L+4c(1+c)D_LR_H-2bcD_HR_L}$, $x_L = \frac{a[2(1+c)-b]D_HD_L-(4+4c-b^2)D_HR_L-2bcD_LR_H}{a[2(1+c)-b]D_HD_L+4c(1+c)D_HR_L-2bcD_LR_H}$

(iii) When $R_H < R_H^0$ *and* $R_L \geq R_L^0$,

$Q_H = \frac{[a(2-b)+bD_L]D_H+4cR_H}{[4(1+c)-b^2]D_H}$, $Q_L = \frac{aD_H[2(1+c)-b]-2(1+c)D_HD_L-2bcR_H}{[4(1+c)-b^2]D_H}$, $x_H = 1-\frac{R_H}{D_HQ_H}$, $x_L = \frac{D_L}{2cQ_L}$

(iv) When $R_H \geq R_H^0$ *and* $R_L < R_L^0$,

$Q_H = \frac{aD_L[2(1+c)-b]-2(1+c)D_HD_L-2bcR_L}{[4(1+c)-b^2]D_L}$, $Q_L = \frac{[a(2-b)+bD_H]D_L+4cR_L}{[4(1+c)-b^2]D_L}$, $x_H = \frac{D_H}{2cQ_H}$, $x_L = 1-\frac{R_L}{D_LQ_L}$

Proposition 3 indicates that each port's output and adaptation investment decisions only depend on its minimum requirement without adaptation trading. When the minimum requirement is loose enough, i.e., larger than R_H^0 or R_L^0, output decision is only determined by the port competition. When minimum requirement is strict, i.e., less than R_H^0 or R_L^0, port adaptation investment is determined by minimum requirement whereas its output is constrained by its adaptation investment as well as the port competition. Moreover, compared to the adaptation trading, Port H's full adaptation may not be achieved and its minimum requirement does matter and is necessary.

4. Welfare Analysis

This section solves for Stage 1 of the game by investigating the government's optimal subsidy and minimum requirement policies. For the minimum requirement policy, we focus on the case where the adaptation trading between the ports can be achieved. By benchmarking the social welfares, we explore the conditions where either the subsidy or the adaptation trading with minimum requirement is more welfare-improving. In addition, the impact on the port profit is examined to show whether the subsidy policy and adaptation trading promotes or discourages the inter-port competition.

4.1 Subsidy policy

Substituting the ports' outputs and adaptation investments under the subsidy policy into (2a), (2b) and (5), we obtain the ports' profits and social welfare under different values of δ. Investigating the impacts of δ on the ports' outputs, adaptation investments and profits, we obtain the following proposition.

Proposition 4. When the subsidy is low, i.e., $\delta \in [0, \delta_1]$*, it has no impacts on the ports' outputs, but increases the adaptation investment to reduce disaster loss. The subsidy increases the profits of both ports. When the subsidy is intermediate, i.e.,* $\delta \in (\delta_1, \delta_2)$*, it increases Port H's output while decreases Port L's output. Subsidy still helps Port L reduce disaster loss, while Port H achieves full adaptation to disaster loss. Port H's profit is increased while Port L's profit is decreased. When the subsidy is high, i.e.,* $\delta \in [\delta_2, \infty)$*, it has no impacts on the ports' disaster loss reduction (with both their disaster losses fully covered) but increases their outputs. Moreover, subsidy increases the profits of both ports.*

The derivation and the expression of optimal subsidy leading to the maximum social welfare are complicated. However, it is possible to prove the unique existence and show some properties of the optimal subsidy, which are as summarized in Corollary 2.

Corollary 2. When the subsidy is low, i.e., $\delta \in [0, \delta_1]$*, the subsidy leads to lower social welfare than no subsidy. When* $\delta > \delta_1$*, the social welfare is concave with respect to* δ*. Let* δ^* *be the optimal subsidy to maximize the social welfare. If* $SW(\delta^*) > SW(0)$*, we have* $\delta^* \geq \delta_1$*.*

Proposition 4 and Corollary 2 indicate the different impacts of the subsidy on the ports and social welfare. When the subsidy is low ($\delta \in [0, \delta_1]$), its main function is to reduce the ports' disaster loss and thereby improve their profits. However, it harms the social welfare. The explanations are as follows. The marginal contributions of the subsidy to social welfare is $\frac{\partial SW}{\partial \delta} = \frac{\partial SW}{\partial Q_H} \cdot \frac{\partial Q_H}{\partial \delta} + \frac{\partial SW}{\partial x_H} \cdot \frac{\partial x_H}{\partial \delta} + \frac{\partial SW}{\partial Q_L} \cdot \frac{\partial Q_L}{\partial \delta} + \frac{\partial SW}{\partial x_L} \cdot \frac{\partial x_L}{\partial \delta}$. Because $\frac{\partial Q_H}{\partial \delta} = \frac{\partial Q_L}{\partial \delta} = 0$, $\frac{\partial x_H}{\partial \delta} > 0$, $\frac{\partial x_L}{\partial \delta} > 0$, $\frac{\partial SW}{\partial x_H} = -2cx_H Q_H^2 + D_H Q_H < 0$ and $\frac{\partial SW}{\partial x_L} = -2cx_L Q_L^2 + D_L Q_L < 0$, we have $\frac{\partial SW}{\partial \delta} < 0$. When the subsidy is low, it does not promote the port output, while its benefit to reduce the damage loss is smaller than the increasing adaptation cost. The social welfare is thus damaged as a result.

When the subsidy is intermediate, i.e., $\delta \in (\delta_1, \delta_2)$, it has different impacts on the two ports. For Port H (or Port L, respectively), the subsidy increases (or decreases, respectively) its output and thereby its profit. When the subsidy is high ($\delta \in [\delta_2, \infty)$),both ports have achieved the full adaptation investments to cover all disaster loss. The subsidy increases the profits of both ports. In terms of social welfare, it is concave with respect to the subsidy when $\delta > \delta_1$. Such concavity can be explained as below. At the beginning, the subsidy brings more output and adaptation to reduce disaster loss. However, such marginal benefits diminish compared to an increasing marginal cost in adaptation investment (i.e., a convex adaptation investment cost function). As a result of this concavity of social welfare with respect to δ, the optimal subsidy always uniquely exists and should be higher than a threshold ($\delta > \delta_1$) to promote the port output.

4.2 Adaptation trading under minimum requirement

Substituting the ports' outputs and adaptation investments under the minimum requirement policy (when the adaptation trading can be achieved) into (1), (2) and (5), we obtain the ports' profits and social welfare under different R_L. Investigating the impacts of R_L on the ports' outputs, adaptation investments, profits and the social welfare, we obtain the following proposition.

Proposition 5. Under minimum requirement policy with adaptation trading between the ports (i.e., $R_L \leq \frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}$), a stricter minimum requirement for Port L raises the trading price and increases the adaptation investment for both ports. Meanwhile, it decreases the ports' outputs. Moreover, its marginal contributions to Port H's profit increase, while its marginal contributions to Port L's profit and the social welfare decrease.

Proposition 5 means that if the minimum requirement increases (i.e., looser), Port H's marginal profit increases, while both Port L's marginal profit and the social welfare decrease, i.e., $\frac{\partial^2 \pi_H}{\partial R_L^2} > 0$, $\frac{\partial^2 \pi_L}{\partial R_L^2} < 0$, $\frac{\partial^2 SW}{\partial R_L^2} < 0$. The reason that the social welfare is concave on R_L is as follows. From Part (ii) of Proposition 2, we know that R_L has the linear effects on *t*, and *t* has the linear effects on Q_H and Q_L. Therefore, $\frac{\partial^2 t}{\partial R_L^2} = \frac{\partial^2 Q_H}{\partial R_L^2} = \frac{\partial^2 Q_L}{\partial R_L^2} = 0$. Moreover, we know that $\frac{\partial^2 x_H}{\partial R_L^2} = \frac{\partial^2 x_L}{\partial R_L^2} = 0$. From the proofs of Proposition 5, we know that $\frac{\partial^2 \pi_H}{\partial R_L^2} = \frac{[(2+b)^2+4c]c}{2(2+b+2c)^2 D_L^2} > 0$, $\frac{\partial^2 \pi_L}{\partial R_L^2} = \frac{-[(2+b)^2+4(1+b)c]c}{2(2+b+2c)^2 D_L^2} < 0$, and $\frac{\partial^2 \pi_H}{\partial R_L^2} + \frac{\partial^2 \pi_L}{\partial R_L^2} < 0$. From the definition of the social welfare, i.e., (5), we know that it consists of two parts: the port users' benefits and the ports' profits. The port users' benefits rely on their consumptions on the port services, i.e., Q_H and Q_L. Because the effects of R_L on the port users' marginal benefits are 0, and the effects of R_L on the ports' marginal profits are negative too, the total effects of R_L on the marginal social welfare are negative, or equivalently the social welfare is concave on R_L.

We obtain the following implications from Proposition 5. First, a stricter minimum requirement for Port L is not conducive to the adaptation trading between the ports, because it raises the trading price and reduces the trading volume. Second, a stricter minimum requirement for Port L inhibits the outputs and encourages own adaptation investment for both ports. These results are sensible. Meanwhile, the minimum requirement of Port H has no impacts on the ports' outputs, profits and social welfare with the trading available, because Port H always buys enough adaptation from Port L to make the full coverage against disaster damage. Third, the impacts of the minimum requirement for Port L on the profits of the two ports are different. Relaxing R_L reduces the trading price, and thereby decreases Port H's adaptation purchasing cost and Port L's adaptation selling revenue. Therefore, relaxing R_L increases Port H's profit more quickly than Port L's profit. Fourth, the social welfare is concave with respect to R_L. which provides an implication that the optimal minimum requirement can maximize the social welfare, if the trading between the ports can be achieved. We obtain the following corollary to summarize the optimal minimum requirement under adaptation sharing, if the regulation is necessary.

Corollary 3. Let R_L^* *be the optimal minimum requirement under adaptation sharing for Port L, we have* $R_L^* = min(\frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}, \frac{2acD_L(3+b+2c)-(2+b+2c)^2D_L^2}{(2+b)^2c+2(1+b)c^2})$.

Corollary 3 indicates that the optimal minimum requirement under adaptation sharing to maximize Port L's profit is the smaller one of two thresholds: $\frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}$ and $\frac{2acD_L(3+b+2c)-(2+b+2c)^2D_L^2}{(2+b)^2c+2(1+b)c^2}$. From Proposition 2 we know that if $R_L \geq \frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}$, the minimum requirement has no impacts on Port L's profit. Therefore, the optimal R_L never exceeds this level. If the minimum requirement can affect Port L's profit, $\frac{2acD_L(3+b+2c)-(2+b+2c)^2D_L^2}{(2+b)^2c+2(1+b)c^2}$ is the optimal R_L, but it should be lower than the threshold $\frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}$.

The direct analytical comparison on social welfare under the optimal subsidy and minimum requirement is very complicated, such that we need to rely on numerical simulations for clearer insights. Still, the following Corollary 4 on the choice of policy (subsidy vs. minimum requirement) can be obtained.

Corollary 4. When the government has a tight budget constraint, such that it cannot provide a sufficiently high subsidy, it is better to provide no subsidy. Alternatively, the minimum requirement with adaptation trading is recommended.

From Proposition 4 and Corollary 2, we know that the subsidy should be larger than a threshold, otherwise a low subsidy would harm social welfare. On the other hand, the minimum requirement does not cost any financial resources. Therefore, the minimum requirement is more financially feasible than the subsidy. If the shadow price (opportunity cost) of the public fund is considered, the advantage of the minimum requirement policy could be more prevailing.

4.3 Impacts on port industry profits

In this subsection, we examine the impacts of the port adaptation policies on the port profits. Specifically, we discuss whether the subsidy policy and the minimum requirement policy can help the two ports collude with each other for joint profit maximization. We show whether the two ports' profits increase, and whether the total profit achieves or exceeds the case of full collusion but without regulation. The answer is important to address the concern whether the policy would lead to anti-trust issue by facilitating the two port's collusion for higher joint profit. For the subsidy policy, we have the following proposition.

Proposition 6. The subsidy policy can never help achieve the port industrial optimum profit. The difference between the ports' profits and the industrial optimum remains constant when the subsidy is low (i.e., $\delta \leq \delta_1$*) and increases when the subsidy is intermediate or high (i.e.,* $\delta > \delta_1$*).*

Proposition 6 points out that the subsidy policy does not facilitate the two ports to achieve collusive profits. Under the subsidy policy, we have $\pi_C \geq \pi_H + \pi_L$, where π_C is the total profits of two ports if they behave collusively. When $\delta \leq \delta_1$, $\frac{\partial(\pi_C - \pi_H - \pi_L)}{\partial \delta} = 0$. When $\delta > \delta_1$, $\frac{\partial(\pi_C - \pi_H - \pi_L)}{\partial \delta} > 0$. From Proposition 4 we know that the subsidy either has no impacts on the ports' outputs (when $\delta \leq \delta_1$) or increases the ports' outputs (when $\delta > \delta_1$). Therefore, it cannot inhibit the ports' incentive to overproduce and thereby cannot reach the collusive pricing. On the contrary, the subsidy intensifies the inter-port competition on both adaptation investment and output, as it lowers the cost to install the competitive "weapons" (i.e., adaptation investment) for the two ports to compete. Thus, the subsidy policy is pro-competitive and has no anti-trust issue.

For the adaptation trading under the minimum requirement policy, we know that the two ports can coordinate their adaptation investments and benefit each other through adaptation sharing. From Proposition 5, Port H might reduce its own adaptation investment and Port L would reduce the output. Thus, the two ports can achieve profit increase and is likely to reach the collusive profits. As a result, the adaptation trading could be anti-competitive. However, it is difficult to examine this issue analytically, such that we need to use the numerical simulation in the following subsection to show it clearly.

4.4 Numerical simulations

In order to obtain additional insights which are not easily examined by the theoretical analysis, we use the numerical simulations in this subsection for illustrations. Specifically, we use the numerical simulations examine some issues related to the social welfare, which is difficult to show analytically. We benchmark the social welfare under the subsidy vs. adaptation trading under minimum requirement. For the verification of the theoretical results, because the analytical results have been obtained, the impacts of the parameter values on the model outcomes can be predicted and thereby the choice of their values would not qualitatively change the conclusions. For the social welfare examination, the parameter values are set to satisfy their required constraints in the theoretical models, e.g., non-negativity. In addition, for some critical parameters, e.g., b, δ and R_L, we illustrate all their possible and meaningful values, and investigate their impacts on the model outcomes. For the other parameters, we set their values to keep all important thresholds in the theory holding. Moreover, we set different c to Port H and Port L to investigate the impacts of the ports' different investment efficiencies in Section 4.4.2. The parameter values are chosen as follows, which satisfy all non-negative conditions and achieve the adaptation trading: $a = 30$, $D_H = \{3,4,5\}$, $D_L = \{1,2,3\}$, $c_H = \{0.2,0.3,0.4\}$, $c_L = \{0.2,0.3,0.4\}$, $b \in [0,1]$, $\delta \in [0,18]$, $R_L \in [0,36]$.

4.4.1 Social welfare analysis

Table 1 shows that the policies (subsidy vs. adaptation trading under minimum requirement) can be equivalent in terms of social welfare outcomes, with different degrees of inter-port competition (i.e., different values of b). Thus, although the achieved social welfare may not be optimal, it is feasible to replace one policy with the other to reach the same level of social welfare (of course, the welfare division between the port user's surplus and profits of two ports could be different under two policies).

Table 1 The equivalence of the two policies under different b

b	Regulation policies	Social Welfare
0.3	$\delta = 3.3$	$SW = 479.69$
	$R_L = 10.2$	
0.5	$\delta = 5.7$	$SW = 437.87$
	$R_L = 9.6$	
0.7	$\delta = 8.4$	$SW = 401.98$
	$R_L = 7.8$	

Note: $D_H = 3,\ D_L = 1,\ c_H = c_L = 0.3$.

Second, we compare the performances of two policies by answering the following two questions: (1) which policy can bring higher social welfare (i.e., socially optimal policy)? (2) whether subsidy or adaptation trading under the minimum requirement bring anti-trust concern (i.e. the total port profit reaches the collusive profit)? If the total port profit reaches the collusive profit, whether one policy can lead to a Pareto improvement (i.e. the social welfare or port user's surplus also increase)?

For above question (1), Figure 2 shows that the optimal social welfare comparison depends on the magnitude of disaster damage levels (i.e., the magnitude of D_H and D_L). When D_H and D_L are low (in the cases of $D_H = 3,\ D_L = 1$ and $D_H = 4,\ D_L = 2$), adaptation trading under minimum requirement improves welfare more than the subsidy policy. This is because the former policy adequately takes the advantage of the market mechanism to guarantee the efficiency of the adaptation investment. When D_H and D_L are high (in the cases of $D_H = 5,\ D_L = 3$), the subsidy policy leads to higher social welfare than the adaptation trading under minimum requirement. When the levels of disaster damage are high, the ports need to make more adaptation investment to achieve social optimal outcomes. Compared to the minimum requirement policy, the subsidy policy is more effective to promote port adaptation investment in that it provides the ports with direct financial incentives and stimulates the inter-port competition on adaptation investment and output. Such an effect of promoting adaptation investment and output through subsidy is more important than the efficiency gain by the adaptation trading under minimum requirement. Thus, the subsidy policy is better in terms of social welfare.

Moreover, as shown in Figure 2, the social welfare decreases with increased port competition and substitutability (i.e., an increasing b). The explanations are provided as follows. In the case of Cournot competition, if the firms provide homogeneous products or services, more firms in the market lead to increasing competition. At equilibrium the output of each firm decreases, while the total output in the whole market increases. Therefore, social welfare is promoted by increased competition. However, if the firms provide the heterogeneous products or services, such as the case of linear demand function as considered in our study, increasing substitutability among the products or services indicates increasing competition and reduced product differentiation. Note in the extreme of full product differentiation there are n totally different products/markets. In the extreme case of total loss of product differentiation, there is only 1 products/market. In the linear demand case we considered, increased competition leads to the decline of outputs of each firm and the whole market, and the consumers have fewer alternatives and product to choose. As a result, the social welfare is reduced. In addition, in our model, the ports not only compete in outputs, but also in adaptation investment, which is positively correlated with their outputs. As their outputs decreases, their adaptation investments also decrease, which result in the reduction of the social welfare. Previous industrial organization literature on the differentiated Cournot competition can provide support to our conclusions. According to the classical paper by Singh and Vives (1984), with differentiated products, the social welfare is still increasing and concave with the total market output. A higher degree of product substitutability would discourage the firms' total output, and thus decreases the social welfare. Ritz (2014) shows that, with n symmetric firms, equilibrium welfare declines at the order $1/n^4$, and thus vanishes quickly with the number of firms. This is also because the firms' total output increases with the number of firms under Cournot competition.

For question (2), Figure 3 shows that the total port profit $\pi_H + \pi_L$ increases with the subsidy (i.e., $\frac{d(\pi_H+\pi_L)}{d\delta} > 0$). However, it never reaches the collusive profit π_C. Moreover, the social welfare can be reduced by a higher subsidy as shown in Figure 3. Therefore, the subsidy will not bring a Pareto improvement for the entire port industry and the society. It will never help two ports to achieve the outcome of full integration or collusion. The social welfare is consisted of two parts, namely the total port profit and port user's surplus. The port user's surplus decreases with the subsidy. This suggests that the ports would not pass all benefit of subsidy to the port users through lower port charges. In contrast, an increasing adaptation investment motivated by the subsidy indicates better service quality, which enables the ports to raise port charge so as to extract more port user's surplus. In particular, when the subsidy is large enough (i.e., $\delta = 4.1$), the lines of port total profit and social welfare intersect, implying zero port user's surplus as shown in Figure 3. That is, the ports would absorb all port user's surplus as port profits. When the subsidy is further increased, the port users could even stop use the port service to avoid a negative surplus.

On the contrary, Figure 4 shows that the adaptation trading under minimum requirement can lead to a Pareto improvement for the entire port industry and society. As exhibited in Figure 4, when R_L is high (a less strict minimum requirement), the total port profit $\pi_H + \pi_L$ can achieve the level of the collusive total profit π_C, and the social welfare also increases at the same time. Although the inter-port competition is moderated by the adaptation trading as the two port can coordinate their adaptation investment and output, the social welfare has also been improved. This is because the adaptation trading improves the overall efficiency in adaptation investment, and such efficiency gain outweighs the possible negative effect of port coordination on the ship users' surplus. Indeed, as shown in Figure 4, within some range of R_L, the social welfare increases faster than the total port profit, suggesting an improvement in the port user's surplus as well. Therefore, adaptation trading can lead to a Pareto improvement for all stakeholders.

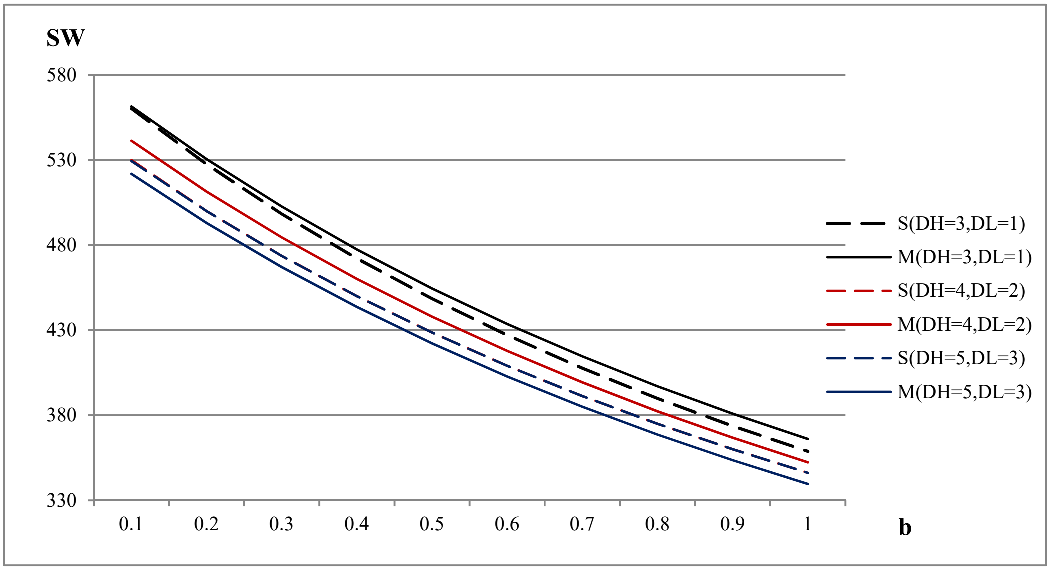

Figure 2 Comparisons of the optimal social welfare under two policies

Note: (1) In the legend, "S" and "M" indicate the cases under the subsidy policy and the minimum requirement policy, respectively. The optimal social welfare under the subsidy when $D_H = 5$, $D_L = 3$ and $D_H = 4$, $D_L = 2$ are almost the same (except the case when $b = 0.1$), because the optimal subsidy under these two scenarios are greater than δ_2, which leads to the same Q_H, Q_L, x_H and x_L, thus the same social welfare.

(2) $c_H = c_L = 0.3$.

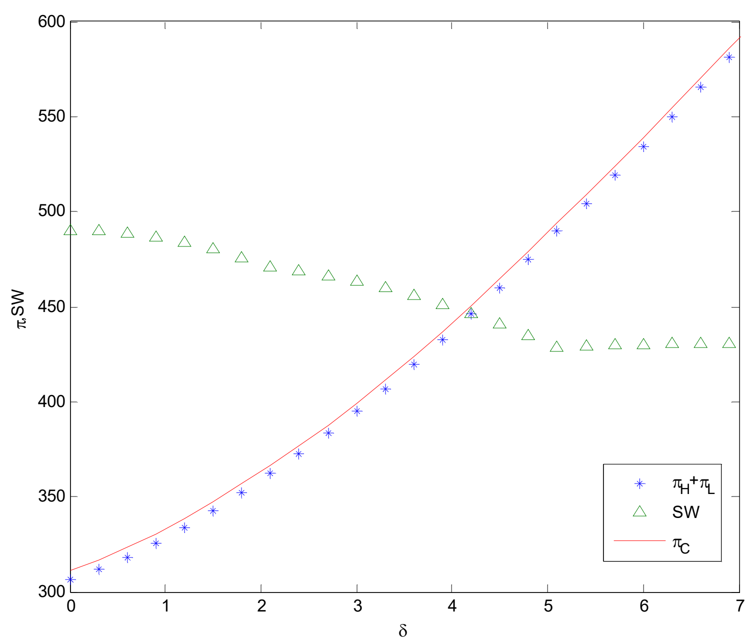

Figure 3 The ports' profits and social welfare if the subsidy policy is used

Note: $b = 0.3$, $D_H = 3$, $D_L = 1$, $c_H = c_L = 0.3$.

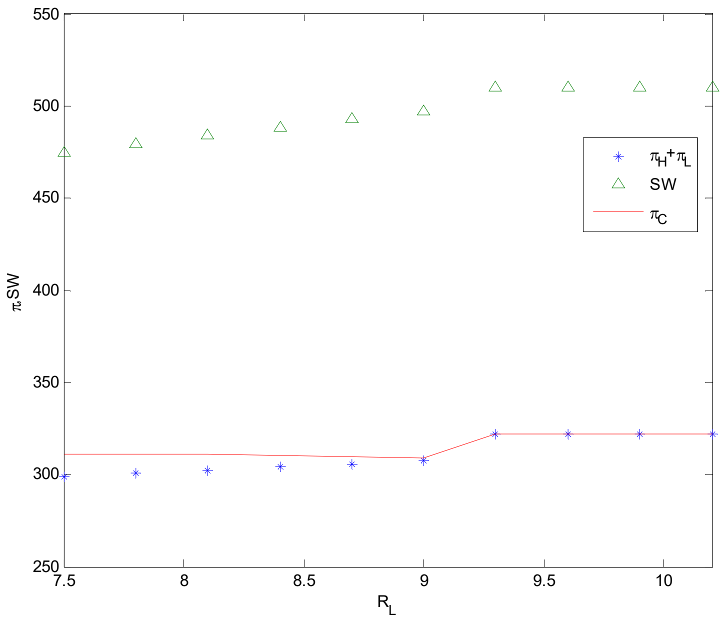

Figure 4 The ports' profits and social welfare with adaptation trading under minimum requirement
Note: $b = 0.3$, $D_H = 3$, $D_L = 1$, $c_H = c_L = 0.3$.

4.4.2 Ports having different adaptation investment efficiencies

To investigate the influences of the ports' investment efficiency, we let $c_H \neq c_L$ in the numerical studies in this section. For the subsidy policy, most basic conclusions still hold, e.g., when the subsidy is low, it has no impacts on the two ports' output decisions; when the subsidy is high enough, both ports make the full adaptation investment and the subsidy leads to output increases instead of further adaptation. Meanwhile, some new observations can be found as follows. When their adaptation investment efficiencies are the same, i.e., $c_H = c_L$, we have $Q_H \leq Q_L$ and $x_H \geq x_L$ (recalling Figure 1 in Section 3.2). However, when $c_H \neq c_L$, these may not hold and Q_H may be greater than Q_L, if the subsidy is high (see Figure 5 and 6). The reason is that the ports' outputs are affected by their actual disaster loss, which is their disaster loss with adaptations. In the case of symmetric adaptation investment efficiency, their actual disaster losses are completely determined by their expected losses (D_H or D_L, because their adaptation outcomes are the same). In the case of asymmetric adaptation investment efficiency, their actual disaster losses are determined by their expected losses (D_H or D_L) as well as their adaptation efficiencies.

For the minimum requirement policy, most basic conclusions still hold, e.g., if the adaptation trading between the ports can be achieved, the port with high disaster loss (Port H) will buy adaptation resources from the port with low disaster loss (Port L) to achieve its full coverage against the disaster loss, and Port L sells all adaptation to Port H. The minimum requirement for Port H is unnecessary. Moreover, some new observations can also be found in the case of asymmetric adaptation investment efficiency. This asymmetry only affects the ports' adaptation investments when R_L is low (see Figure 7- Figure 9). When R_L is low, we still have $Q_H = Q_L$, which is the same as in the case of symmetric adaptation investment efficiency. However, $x_H \neq x_L$ because their different adaptation efficiencies.

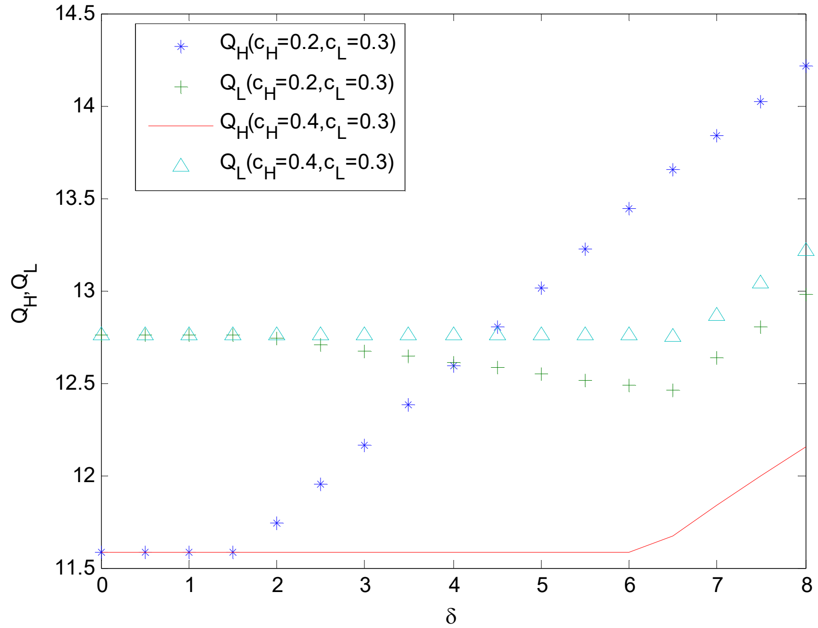

Figure 5 The ports' outputs under subsidy when
they have different adaptation investment efficiencies

Note: $b = 0.3, \; D_H = 3, \; D_L = 1.$

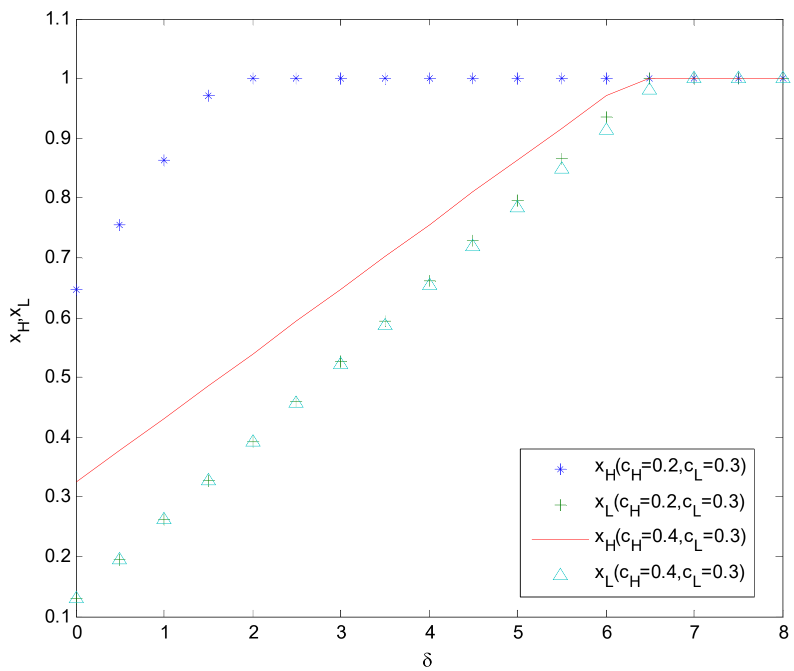

Figure 6 The ports' adaptation investments under subsidy
when they have different adaptation investment efficiencies

Note: $b = 0.3, \; D_H = 3, \; D_L = 1.$

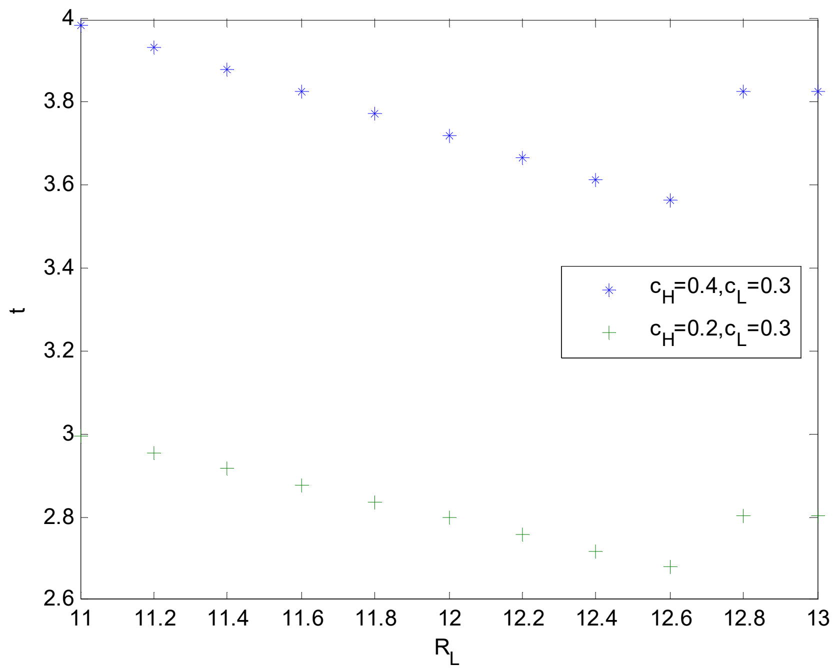

Figure 7 The adaptation trading price under minimum requirement when the ports have different adaptation investment efficiencies

Note: $b = 0.3,\ D_H = 4,\ D_L = 1.$

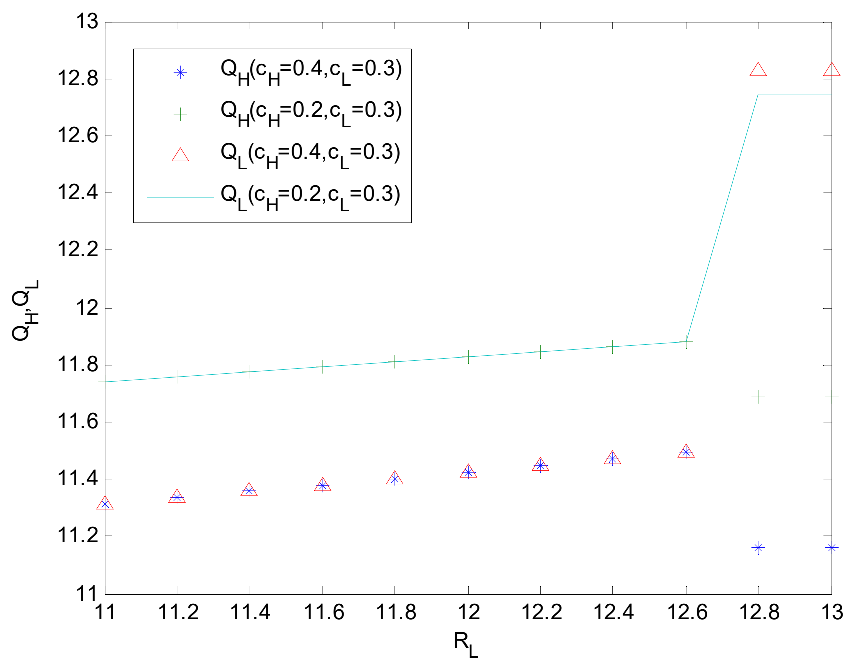

Figure 8 The ports' outputs under minimum requirement when the they have different adaptation investment efficiencies

Note: $b = 0.3,\ D_H = 4,\ D_L = 1.$

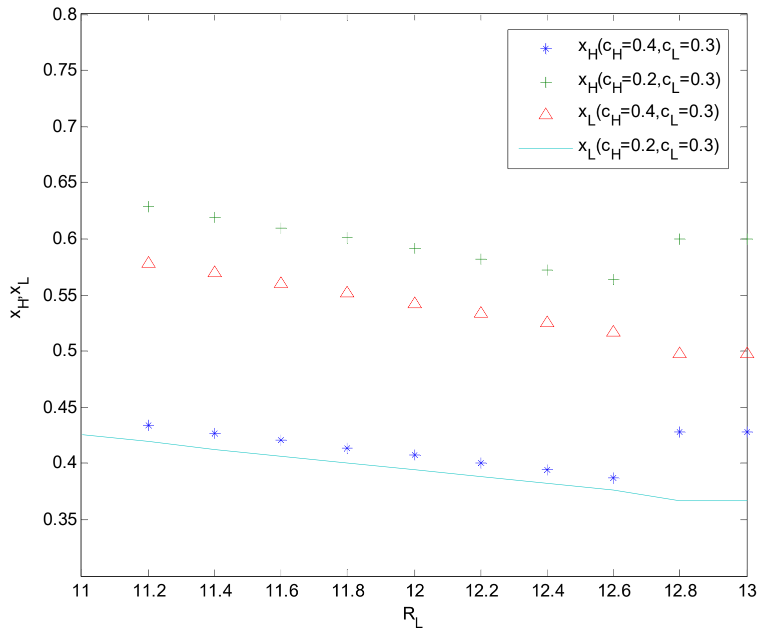

Figure 9 The ports' adaptation investments under minimum requirement when the they have different adaptation investment efficiencies

Note: $b = 0.3,\ D_H = 4,\ D_L = 1.$

4.4.3 Discussions

Although the simulation results depend on the parameter values, some of them can be generalized, e.g.,

(i) The policies (subsidy vs. adaptation trading under minimum requirement) can be equivalent in terms of social welfare.

(ii) The comparison of social welfare under the subsidy and the minimum requirement depends on the magnitude of disaster damage levels.

(iii) The subsidy will not bring a Pareto improvement for the entire port industry and the society.

(iv) The adaptation trading under minimum requirement can lead to a Pareto improvement for the entire port industry and society.

(v) When the subsidy is low, it has no impacts on the two ports' output decisions. When the subsidy is high enough, both ports make the full adaptation investment and the subsidy leads to output increases instead of further adaptation. These conclusions still hold even when the ports have asymmetric adaptation investment efficiencies.

(vi) If the adaptation trading between the ports can be achieved, the port with high disaster loss (Port H) will buy adaptation resources from the port with low disaster loss (Port L) to achieve its full coverage against the disaster loss, and Port L sells all adaptation to Port H. The minimum requirement for Port H is unnecessary. These conclusions still hold even when the ports have asymmetric adaptation investment efficiencies.

However, the numerical simulation inevitably has some limitations, because the conclusions of the following questions depend on the specific parameter values and thereby may not be generalized:

(i) The question which policy is the better choice in terms of social welfare may not have a certain conclusion, because it depends on D_H , D_L, c_H and c_L.

(ii) The question which port has more output when the subsidy is high and $c_H \neq c_L$ may not have a certain conclusion, because it depends on D_H , D_L, c_H and c_L.

(iii) The question which port has the higher adaptation investment when R_L is low and $c_H \neq c_L$ may not have a certain conclusion, because it depends on D_H , D_L, c_H and c_L.

5. Conclusions

In this paper, we establish an integrated economic model to analyze adaptation investments of competing ports with asymmetric disaster losses. Two regulatory policies have been modeled, namely the subsidy policy vs. the minimum requirement policy. Under the minimum requirement policy, the trading of adaptation resources (adaptation materials and adapted capacities) between the two ports is allowed after the disaster occurs. Both the asymmetry of disaster losses among nearby ports and the effects of adaptation sharing have not been examined by previous studies, although they have important implications in terms of industrial policy and modelling results. Our analyses reveal different impacts of subsidy and adaptation trading under minimum requirement on the port adaptation and output. Specifically, when the subsidy is low, the ports compete on adaptation investment and their outputs are the same; when the subsidy is high, the ports compete on outputs and their adaptation investment are the same (to fully cover the disaster loss). If the adaptation trading can be achieved, the port facing the low disaster loss (Port L) sells all (or partial, respectively) adaptation to the port facing the high disaster loss (Port H), when Port L's minimum requirement is low (or high, respectively). Comparisons of social welfare suggest that the social welfare optimum under different polices can be achieved only when the subsidy is large enough, or the minimum requirement for Port L is properly set such that the adaptation trading can be achieved. When comparing the two policies' effect on inter-port competition, it is found that the subsidy policy is pro-competitive, which intensifies inter-port competition in adaptation investment and output. But adaptation trading facilitates inter-port coordination, possibly leading to port collusion. Finally, it is found that the relative social welfare ranking between the two policies depend on the magnitudes of disaster damage. When the magnitudes of disaster damage are low, the adaptation trading under minimum requirement brings higher social welfare than the subsidy policy. The investment efficiency gain from adaptation trading outweighs potential negative impact on port users' surplus, leading to a Pareto improvement for the port industry and society. When the magnitudes of disaster damages are high, the subsidy policy leads to higher welfare improvements, as it is more effective in stimulating port adaptation investments. All these results suggest that adaptation trading can be an important source of welfare improvements. Regulators need to think beyond competition effects when examining port coordination involving adaptation market mechanisms.

This is one of the first studies formally modeling the ports' asymmetry in disaster damage and the adaptation trading behaviors. To derive the most important and clear insights, several simplifying assumptions have been imposed on the analytical model, which can be removed or extended in future studies for more comprehensive investigations in a general setting. For example, the vertical structure of the port industry was not explicitly considered. Many ports are governed by the landlord model with upstream port authority and downstream terminal operators. The concession contract in the vertical structure could also affect the adaptation investment behaviors. In addition, the existing model does not account for the ambiguity of the disaster occurrence probability and the possibly different risk attitudes of different ports and government on such uncertainty. Last, although the ports have asymmetry disaster damage, such information is assumed to be common knowledge among all parties (the ports and the government). The disaster damage information might be private information for some parties. For example, one port could have better knowledge on the potential disaster damage on its own than others. This requires the modeling of incomplete information. All these are very meaningful extensions, although out of the scope of the current paper.

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Appendix

A.1 Proof of Proposition 1

Maximizing (1) with respect to Q_H and x_H, we obtain the first order conditions (FOCs) as follows:

$$a - 2Q_H - bQ_L - D_H(1 - x_H) - 2cx_H^2 Q_H + \delta x_H = 0 \tag{6}$$

$$D_H - 2cx_H Q_H + \delta = 0 \tag{7}$$

Maximizing (2) with respect to Q_H and x_H, we obtain the FOCs as follows:

$$a - 2Q_L - bQ_H - D_L(1 - x_L) - 2cx_L^2 Q_L + \delta x_L = 0 \tag{8}$$

$$D_L - 2cx_L Q_L + \delta = 0 \tag{9}$$

If $D_H + \delta \leq 2cx_H Q_H$ and $D_L + \delta \leq 2cx_L Q_L$, we obtain the following outcomes by solving (6) – (9) simultaneously.

$Q_H = \dfrac{(2-b)a - 2D_H + bD_L}{4-b^2}$, $Q_L = \dfrac{a(2-b) + bD_H - 2D_L}{4-b^2}$, $x_H = \dfrac{D_H + \delta}{2cQ_H}$ and $x_L = \dfrac{D_L + \delta}{2cQ_L}$. Substituting Q_H and x_H into the following equation,

$$D_H + \delta = 2cx_H Q_H \tag{10}$$

we obtain $\delta = \delta_1$. Substituting Q_L and x_L into the following equation,

$$D_H + \delta = 2cx_H Q_H \tag{11}$$

we obtain $\delta = \delta_3$. It can be proved that $\delta_1 < \delta_3$, $Q_H < Q_L$ and $x_H > x_L$. Thus, we prove Part (i).

If $D_H + \delta > 2cx_H Q_H$ and $D_L + \delta \leq 2cx_L Q_L$, we have $x_H = 1$. Substituting $x_H = 1$ into (6), (8) and (9), and solving them simultaneously, we obtain $Q_H = \dfrac{a(2-b) + 2\delta + bD_L}{4 - b^2 + 4c}$, $Q_L = \dfrac{a(2+2c-b) - 2(1+c)D_L - b\delta}{4 - b^2 + 4c}$ and $x_L = \dfrac{D_L + \delta}{2cQ_L}$. Substituting Q_L and x_L into (11), we obtain $\delta = \delta_2$. It can be proved that $Q_H < Q_L$ and $x_H > x_L$. Thus, we prove Part (ii).

If $D_H + \delta > 2cx_H Q_H$ and $D_L + \delta > 2cx_L Q_L$, we have $x_H = x_L = 1$. Substituting

$x_H = x_L = 1$ into (6) and (8), and solving them simultaneously, we prove Part (iii). □

A.2 Proof of Proposition 2

Observing the objective function (3), we find that it is an increasing function with respect to the decision variable x_{HB}. The coefficient of x_{HB} in (3) is $D_H Q_H - tQ_H$. Thus, x_{HB} reaches its maximum (or minimum, respectively) value, if $D_H \geq t$ (or $D_H \leq t$, respectively). The same logic can be applied to x_{LB} and we know that x_{LB} reaches its maximum (or minimum, respectively) value, if $D_L \geq t$ (or $D_L \leq t$, respectively). Therefore, the trading or sharing of the adaptation between the ports can be achieved only when $D_L \leq t \leq D_H$, where x_{HB} (or x_{LB}, respectively) reaches its maximum (or minimum, respectively) value. Thus, we have

$$x_H + x_{HB} = 1 \tag{12}$$

and Constraint (3b) is surplus.

If R_L is large enough to make Constraint (4b) hold strictly in the optimum, we have

$$x_L + x_{LB} = 0 \tag{13}$$

and Constraint (4c) is surplus.

Substituting (12) and (13) into (3a) and (3b), and maximizing them with respect to Q_H, x_H, Q_L and x_L, we obtain the following FOCs

$$a - 2Q_H - bQ_L - 2cx_H^2 Q_H - t(1 - x_H) = 0 \tag{14}$$

$$t - 2cx_H Q_H = 0 \tag{15}$$

$$a - 2Q_L - bQ_H - D_L - 2cx_L^2 Q_L + tx_L = 0 \tag{16}$$

$$t - 2cx_H Q_H = 0 \tag{17}$$

Solving (14) – (17) simultaneously, we obtain $Q_H = \dfrac{a(2-b) + bD_L - 2t}{4 - b^2}$, $Q_L = \dfrac{a(2-b) - 2D_L + bt}{4 - b^2}$, $x_H = \dfrac{t}{2cQ_H}$ and $x_L = \dfrac{t}{2cQ_L}$. From (12) and (13) we have $x_{HB} = 1 - x_H$ and $x_{LB} = -x_L$. Substituting them into the market clearance condition

$x_{HB}Q_H + x_{LB}Q_L = 0$, we have $t = \frac{c(2a - ab + bD_L)}{2(2+c) - b^2}$. Substituting t into Constraint (4b), we know that it hold strictly if $R_L \geq \frac{[a(2+c-b) - (2+c)D_L]D_L}{2(2+c) - b^2}$. Meanwhile, Substituting t into the inequality $D_L \leq t \leq D_H$, we obtain $c \in [\frac{(2+b)D_L}{a - D_L}, \frac{(4-b)^2 D_H}{(2-b)a - 2D_H + bD_L}]$. Moreover, substituting t into x_H and x_L, it can be proved that $x_H < 1$ and $x_L < 1$. Thus, we prove Part (i).

If R_L is small to make Constraint (4b) binding in the optimum, we have

$$x_L + x_{LB} = 1 - \frac{R_L}{D_L Q_L} \tag{18}$$

Substituting (12) and (18) into (3a) and (3b), and maximizing them with respect to Q_H, x_H, Q_L and x_L, we obtain (14), (15), (17) and the following FOC

$$a - 2Q_L - bQ_H - 2cx_L^2 Q_L + t(1 - x_L) = 0 \tag{19}$$

Solving (14), (15), (17) and (19) simultaneously, we obtain $Q_H = Q_L = \frac{a-t}{2+b}$, $x_H = \frac{t}{2cQ_H}$ and $x_L = \frac{t}{2cQ_L}$. From (12) and (18) we have $x_{HB} = 1 - x_H$ and $x_{LB} = 1 - \frac{R_L}{D_L Q_L} - x_L$. Substituting them into the market clearance condition $x_{HB}Q_H + x_{LB}Q_L = 0$, we have $t = \frac{c[2aD_L - (2+b)R_L]}{(2+b+2c)D_L}$. Meanwhile, Substituting t into the inequality $D_L \leq t \leq D_H$, we obtain $c \in [\frac{(2+b)D_L^2}{2(a - D_H)D_L - (2+b)R_L}, \frac{(2+b)D_H D_L}{2(a - D_L)D_L - (2+b)R_L}]$. Moreover, substituting t into x_H and x_L, it can be proved that $x_H < 1$ and $x_L < 1$. Thus, we prove Part (ii). □

A.3 Proof of Corollary 1

From Proposition 2 we know that $x_{HB} = 1 - x_H$ for any cases. Therefore,

$D_H(1-x_H-x_{HB})Q_H=0$ and any R_H can be satisfied under adaptation sharing. □

A.4 Proof of Proposition 3

Without sharing, Problem (3a) – (3c) becomes:

$$\max_{Q_H\geq 0, 0\leq x_H\leq 1} \pi_H = P_H Q_H - D_H(1-x_H)Q_H - c(x_H Q_H)^2 \tag{20a}$$

$$\text{s.t. } D_H(1-x_H)Q_H \leq R_H \tag{20b}$$

Problem (4a) – (4c) becomes:

$$\max_{Q_L\geq 0, 0\leq x_L\leq 1} \pi_L = P_L Q_L - D_L(1-x_L)Q_L - c(x_L Q_L)^2 \tag{21a}$$

$$\text{s.t. } D_L(1-x_L)Q_L \leq R_L \tag{21b}$$

(i) When both R_H and R_L are large enough, Constraint (20b) and (21b) are slack. Optimizing (20a) and (21a) simultaneously with respect to Q_H, x_H, Q_L and x_L, we obtain the following FOCs:

$$a-2Q_H-bQ_L-D_H(1-x_H)-2cx_H^2Q_H=0 \tag{22}$$

$$D_H-2cx_HQ_H=0 \tag{23}$$

$$a-2Q_L-bQ_H-D_L(1-x_L)-2cx_L^2Q_L=0 \tag{24}$$

$$D_L-2cx_LQ_L=0 \tag{25}$$

Solving (22) – (25) simultaneously, we obtain Q_H, x_H, Q_L and x_L. It can be proved that $0\leq x_H\leq 1$ and $0\leq x_L\leq 1$. Substituting them into Constraint (20b) and (21b), we obtain R_H^0 and R_L^0. Thus, we prove Part (i) of Proposition 3.

(ii) When both R_H and R_L are small, i.e., $R_H<R_H^0$ and $R_L<R_L^0$, Constraint (20b) and (21b) are binding. Substituting the binding (20b) and (21b) into (20a) and (21a), respectively, and optimizing them simultaneously with respect to Q_H and Q_L, we obtain the following FOCs:

$$a-2Q_H-bQ_L-2cx_HQ_H=0 \tag{26}$$

$$a-2Q_L-bQ_H-2cx_LQ_L=0 \tag{27}$$

Solving binding (20b) and (21b), and (26) – (27) simultaneously, we obtain Q_H, x_H, Q_L and

x_L. It can be proved that $0 \le x_H \le 1$ and $0 \le x_L \le 1$. Thus, we prove Part (ii) of Proposition 3.

(iii) When R_H is small and R_L is large, i.e., $R_H < R_H^0$ and $R_L > R_L^0$, Constraint (20b) is binding and (21b) is slack. Substituting the binding (20b) into (20a), and optimizing (20a) and (21a) simultaneously with respect to Q_H, Q_L and x_L, we obtain the (24) - (26). Solving the binding (20b) and (24) – (26) simultaneously, we obtain Q_H, x_H, Q_L and x_L. It can be proved that $0 \le x_H \le 1$ and $0 \le x_L \le 1$. Thus, we prove Part (iii) of Proposition 3.

(iv) When R_H is large and R_L is small, i.e., $R_H > R_H^0$ and $R_L < R_L^0$, Constraint (20b) is slack and (21b) is binding. Substituting the binding (21b) into (21a), and optimizing (20a) and (21a) simultaneously with respect to Q_H, Q_L and x_H, we obtain the (22), (23) and (27). Solving the binding (21b) and (22), (23) and (27) simultaneously, we obtain Q_H, x_H, Q_L and x_L. It can be proved that $0 \le x_H \le 1$ and $0 \le x_L \le 1$. Thus, we prove Part (iv) of Proposition 3.

□

A.5 Proof of Proposition 4 and Corollary 2

(i) When $\delta \in [0, \delta_1]$, $\frac{\partial Q_H}{\partial \delta} = \frac{\partial Q_L}{\partial \delta} = 0$, $\frac{\partial x_H}{\partial \delta} > 0$, $\frac{\partial x_L}{\partial \delta} > 0$. Substituting Q_H, x_H, Q_L and x_L into (1), (2) and (5), respectively, we obtain

$$\pi_H = \frac{4a^2c(2-b)^2 + [(4-b^2)^2 + 16c]D_H^2 + 4b^2cD_L^2 - 16bcD_HD_L - 8ac(2-b)(2D_H - bD_L) + (4-b^2)^2(\delta^2 + 2D_H\delta)}{4c(4-b^2)^2}$$

$$\pi_L = \frac{4a^2c(2-b)^2 + 16(1+c)D_L^2 + 4b^2cD_H^2 - 16bcD_HD_L - 8ac(2-b)(2D_L - bD_H) + b^2(b^2-8)(D_L+\delta)^2 + 16\delta(2D_L+\delta)}{4c(4-b^2)^2}$$

$$SW = \frac{4ac(2-b)^2(3+b)(a - D_H - D_L) + [(4-b^2)^2 + 2c(12-b^2)](D_H^2 + D_L^2) - 4bc(8-b^2)D_HD_L - 2(4-b^2)^2\delta^2}{4c(4-b^2)^2}$$

We know that $\frac{\partial \pi_H}{\partial \delta} > 0$, $\frac{\partial \pi_L}{\partial \delta} > 0$ and $\frac{\partial SW}{\partial \delta} < 0$.

(ii) When $\delta \in (\delta_1, \delta_2]$, $\frac{\partial Q_H}{\partial \delta} > 0$, $\frac{\partial Q_L}{\partial \delta} < 0$, and $\frac{\partial x_L}{\partial \delta} > 0$. Substituting Q_H, x_H, Q_L and x_L into (1), (2) and (5), respectively, we obtain

$$\pi_H = \frac{(1+c)[a(2-b) + bD_L + 2\delta]^2}{[4(1+c) - b^2]^2},$$

$$\pi_L = \frac{\begin{array}{c}4a^2c[2(1+c)-b]^2 + [b^4 - 8b^2(1+c) + 16(1+c)^3]D_L^2 + 2[b^4 + 8b(1+c)(c-b) + \\ 16(1+c)^2]D_L\delta + [b^4 - 4b^2(2+c) + 16(1+c)^2]\delta^2 - 8ac[2(1+c)-b][2(1+c)D_L + b\delta]\end{array}}{4c[4(1+c)-b^2]^2}$$

$$SW = \frac{\begin{array}{c}4a^2c[(2-b)^2(3+b) + (2-b)(8+b)c + 6c^2] + [b^4 + 8(1+c)^2(2+3c) - \\ 2b^2(4+5c+2c^2)]D_L^2 + 8bc(2+c)D_L\delta - [b^4 - 2b^2(4+7c) + 8(2+5c+4c^2)]\delta^2 \\ -4ac[(2-b)^2(3+b) + 2(12-3b-b^2)c + 12c^2]D_L + 4ac[(2-b)^2 - 2bc]\delta\end{array}}{4c[4(1+c)-b^2]^2}$$

We know that $\frac{\partial \pi_H}{\partial \delta} > 0$, $\frac{\partial \pi_L}{\partial \delta} < 0$ and $\frac{\partial^2 SW}{\partial \delta^2} < 0$.

(iii) When $\delta \in (\delta_2, \infty)$, $\frac{\partial Q_H}{\partial \delta} > 0$ and $\frac{\partial Q_L}{\partial \delta} > 0$. Substituting Q_H, x_H, Q_L and x_L into (1), (2) and (5), respectively, we obtain

$$\pi_H = \pi_L = \frac{(1+c)(a+\delta)^2}{(2+b+2c)^2}, \quad SW = \frac{(a+\delta)[a(3+b+2c) - (1+b+2c)\delta]}{(2+b+2c)^2}.$$

We know that $\frac{\partial \pi_H}{\partial \delta} > 0$, $\frac{\partial \pi_L}{\partial \delta} > 0$ and $\frac{\partial^2 SW}{\partial \delta^2} < 0$. □

A.6 Proof of Proposition 5 and Corollary 3

When $R_L \leq \frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}$, we know that $\frac{\partial t}{\partial R_L} < 0$, $\frac{\partial Q_H}{\partial R_L} = \frac{\partial Q_L}{\partial R_L} > 0$, $\frac{\partial x_H}{\partial R_L} = \frac{\partial x_L}{\partial R_L} < 0$. Substituting Q_H, x_H, Q_L, x_L and t into (3a), (4a) and (5), respectively, we obtain $\pi_H = \frac{4a^2(1+c)D_L^2 - 4abcD_LR_L + [(2+b)^2 + 4c]cR_L^2}{4(2+b+2c)^2 D_L^2}$,

$$\pi_L = \frac{4a^2(1+c)D_L^2 + [8ac(1+c) + 2(2+b+2c)^2(1-2D_L)]D_LR_L - [(2+b)^2 + 4(1+b)c]cR_L^2}{4(2+b+2c)^2 D_L^2}$$

$$SW = \frac{2a^2(3+b+2c)D_L^2 + [4ac(3+b+2c) - 2(2+b+2c)^2 D_L]D_L R_L - [(2+b)^2 + 2(1+b)c]cR_L^2}{2(2+b+2c)^2 D_L^2}$$

We know that $\frac{\partial^2 \pi_H}{\partial R_L^2} > 0$, $\frac{\partial^2 \pi_L}{\partial R_L^2} < 0$ and $\frac{\partial^2 SW}{\partial R_L^2} < 0$.

Moreover, from $\frac{\partial SW}{\partial \delta} = 0$ we have $R_L^* = \frac{2acD_L(3+b+2c)-(2+b+2c)^2 D_L^2}{(2+b)^2 c + 2(1+b)c^2}$. Because $R_L \leq \frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}$, we know that $R_L^* = min(\frac{[a(2+c-b)-(2+c)D_L]D_L}{2(2+c)-b^2}, \frac{2acD_L(3+b+2c)-(2+b+2c)^2 D_L^2}{(2+b)^2 c + 2(1+b)c^2})$. □

A.7 Proof of Corollary 4

It can be directly obtained from Corollary 2 and corollary 3. □

A.8 Proof of Proposition 6

(i) When $\delta \in [0, \delta_1]$, Maximizing $\pi_C = \pi_H + \pi_L$ with respect to Q_H, x_H, Q_L and x_L,

$Q_{H,C} = \frac{(1-b)a - D_H + bD_L}{2-2b^2}$, $Q_{L,C} = \frac{a(1-b) + bD_H - D_L}{2-2b^2}$, $x_{H,C} = \frac{D_H + \delta}{2cQ_H}$ and $x_{L,C} = \frac{D_L + \delta}{2cQ_L}$. Substituting $Q_{H,C}$, $x_{H,C}$, $Q_{L,C}$ and $x_{L,C}$ into π_C, we have

$$\pi_C - \pi_H - \pi_L = \frac{b^2[2a(2-b)^2(1-b)(a - D_H - D_L) - 2b(8+b^2)D_H D_L + (4+5b^2)D_L^2]}{4(4-b^2)^2(1-b^2)}$$

and $\frac{\partial(\pi_C - \pi_H - \pi_L)}{\partial \delta} = 0$.

(ii) When $\delta \in (\delta_1, \delta_2]$, Maximizing $\pi_C = \pi_H + \pi_L$ with respect to Q_H, x_H, Q_L and x_L,

$Q_{H,C} = \frac{(1-b)a + bD_L + \delta}{2-2b^2+2c}$, $Q_L = \frac{a(1-b+c) - (1+c)D_L - b\delta}{2-2b^2+2c}$, $x_H = 1$ and $x_L = \frac{D_L + \delta}{2cQ_L}$.

Substituting Q_H, x_H, Q_L and x_L into π_C, we have

$$\pi_C - \pi_H - \pi_L = \frac{\begin{array}{l} b^2[a^2(4(1+c)(2+c) + 5b^2(2+c) - 2b^3 - 16b(1+c)) + 2a(b^3 + 8b(1+c) \\ -5b^2(1+c) - 4(1+c)^2)D_L + (1+c)(4+5b^2+4c)D_L^2 + 2a((2-b)^2(1-b) \\ +4(1-2b)c)\delta + 2b(8+b^2+8c)D_L\delta + (4+5b+4c)\delta^2] \end{array}}{4[4(1+c) - b^2]^2(1+c-b^2)}$$

and $\frac{\partial(\pi_C - \pi_H - \pi_L)}{\partial \delta} > 0$.

(iii) When $\delta \in (\delta_2, \infty)$, Maximizing $\pi_C = \pi_H + \pi_L$ with respect to Q_H, x_H, Q_L and x_L, $Q_H = Q_L = \dfrac{a+\delta}{2(1+b+c)}$ and $x_H = x_L = 1$. Substituting Q_H, x_H, Q_L and x_L into π_C, we have $\pi_C - \pi_H - \pi_L = \dfrac{b^2(a+\delta)^2}{2(1+b+c)(2+b+2c)^2}$ and $\dfrac{\partial(\pi_C - \pi_H - \pi_L)}{\partial\delta} > 0$. □