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Subsidy or Minimum Requirement? Regulation of Port Adaptation Investment under Disaster Ambiguity

Shiyuan Zheng[a], Kun Wang[b*], Zhi-chun Li[c], Xiaowen Fu[d], Felix T.S. Chan[d]

[a]*School of Transportation, Shanghai Maritime University, Shanghai, China*
[b]*School of International Trade and Economics, University of International Business and Economics, Beijing, China. Corresponding author E-mail: kunwang@uibe.edu.cn*
[c]*School of Management, Huazhong University of Science and Technology, Wuhan, China*
[d] *Department of Industrial and Systems Engineering, the Hong Kong Polytechnic University, Hong Kong, China*

Abstract

This paper models two commonly adopted regulatory polices (the minimum requirement regulation vs. subsidy) on port adaptation investment to mitigate the damage caused by climate change-related disasters. The ambiguity of the disaster occurrence probability and the decision makers' attitudes towards risk are explicitly modelled. It is found, under the minimum requirement regulation, ports balance the option of increasing their adaptation vs. reducing their economic activities. In comparison, subsidies promote adaptation without introducing any incentive for ports to reduce outputs, but they can be less efficient than minimum requirement regulations in addressing market failures, such as that caused by a spill-over externality. The ambiguity of disasters changes the optimal designs of minimum requirement regulation and subsidy policy but does not change their relative ranking qualitatively. Decision makers' risk attitudes also play important roles. Higher degrees of pessimism (more risk aversion) lead to lower port outputs but can also increase the level of port adaptation to achieve full insurance against disaster loss. Higher degrees of pessimism also make the government more conservative to intervene in the ports' adaptation and thus less likely to impose the two regulatory policies. Our analysis also explains why it is justified for the government to withhold intervention under ambiguity, and also shows that the ambiguity does not necessarily bring worse expected social welfare.

Keywords: Port adaptation investment; Climate change-related disaster; Disaster ambiguity; Regulation; Subsidy; Minimum requirement

1. Introduction and Background

Located along the coastal lines, seaports ('ports' hereafter) are highly vulnerable to natural disasters such as hurricanes, storm surges, floods, and long-term sea-level rise (SLR). It is of critical importance for ports to mitigate their damage and secure their resilience through adaptation, together with government regulators, if necessary (Jiang et al. 2020). 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. Therefore, the issue of how to promote and regulate port adaptation investment is urgent and important for public policymakers as well as the transport sector.

One promising regulatory tool is minimum requirement regulation (i.e., minimum standard), which has been adopted in the regulation of infrastructure adaptation and disaster prevention in many sectors. The evolution of the related decision-making can be illustrated using the flood prevention example that has been present in the Netherlands over the past century. In the early days, engineers simply chose the height of a dike to ensure that it was safe against the highest flood that had been observed at that place. Over time, the probability measurement of risk was introduced, with the distribution of sea level heights being empirically estimated in the late 1930s (van Dantzig, 1956). The Delta Commission, created after the disastrous 1953 flood in the Netherlands, formally recognized that dike height corresponds to a positive "exceedance probability", i.e., the chance at which the water would overtop the dike and cause damage. Hence, flood probabilities were formally used to make choices regarding the legal minimum safety standards of dikes by water management authorities. The minimum standards for levee construction and other adaptation measures are included in the National Water Law of the Netherlands. Over time, the minimum requirements have also incorporated economic damage in addition to the simple probability of flooding. The Netherlands Flood Protection Act of 1996 specified the safety levels in terms of the exceedance frequencies of flood defences according to the economic value of the area and the source of the flooding (coast or river) (Jonkman et al., 2008). As a result, key economic areas such as ports, power plants and gas supply infrastructures receive a higher protection level.[1] Minimum standard regulations have long been used in many other industries and occasions. For example, the construction industry has extensively used minimum safety standards against earthquakes and fires (Kartam, 1997; Behm, 2005).[2]

In addition to minimum requirement regulation, many governments employ a more proactive alternative by subsidizing port adaptation. For example, the US federal

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[1] Formally, three types of risks are considered, namely, individual risk, societal risk, and economic risk. The first two types are mainly determined by fatality, whereas the third type involves the economic cost and benefits related to flood prevention (Jonkman et al., 2018). For a non-technical interpretation, see, for example, the report at https://www.dutchwatersector.com/news/dutch-parliament-adopts-unique-risk-standards-for-flood-protection.

[2] For example, the Japanese Law on Building Standards mandate minimum standards for buildings and infrastructures in flood-prone areas. After the 2011 Tohoku earthquake and tsunami, the Japanese government's Central Disaster Management Council further tightened the minimum requirements to address future tsunami and typhoon threats. The new requirements include mandatory measures such as raising the ground level, enhancing the drainage system, preparing evacuation sites, *etc*. in high-risk areas.

government established the Hazard Mitigation Grant Program (HMGP) to offer financial support to public infrastructures for their adaptations to flood and other climate change-related disasters. The programme is application based and provides up to 75% of the total cost of disaster adaptation projects. The adaptation investments of many ports in the US have been financed by the HMGP. For instance, the Port of Neches received more than $1.5 million to improve its adaptations after being damaged by Hurricane Rita in 2007, which greatly helped the same port defend itself against the more serious Hurricane Ike in 2008. After Hurricane Harvey in 2017, the Port of Beaumont and other heavily affected ports received HMGP funds to enhance their adaptations for future disasters. Relatedly, Canada has set up a Disaster Mitigation and Adaptation Fund (DMAF), which has earmarked 2 billion Canadian dollars each year from 2017 to 2027 to directly subsidize public infrastructures for adaptation to climate change-related disasters.[3] 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).

Despite the important roles played by minimum requirement regulation and subsidy policy on port adaptation, to the best of our knowledge, few studies have analytically benchmarked these two alternatives. This is a serious deficiency in the literature. Although more than 70% of ports indicated that they had been impacted by weather or climate change-related events in a recent survey by the United Nations Conference on Trade and Development (UNCTAD, 2017), few ports have committed sizable adaptation funds (TRB, 2014; Ng et al., 2015). In fact, insufficient adaptation investment is a general challenge that extends beyond the maritime sector to the extent that "we need to make an almost existential change" (United Nations, 2018; Yeo, 2019). As the shortage of adaptation resources is expected to persist in the foreseeable future, it is imperative to thoroughly investigate the implications of alternative adaptation options so that maximum benefits and protection can be secured subject to resource constraints. Because adaptation requirements and market structures differ significantly across ports and markets, it is necessary to develop analytical models that depict basic industry structures yet allow for the abstraction of market-specific characteristics. This is not a trivial task. Therefore, in addition to bringing fresh insights concerning adaptation policies, this paper also seeks modelling contributions with the following specifications.

Ambiguity and risk attitude. One major challenge related to port adaptation decisions is the significant amount of uncertainty involved (e.g., Weitzman, 2009; Becker et al., 2013; Ng et al., 2013, 2015; Yang et al., 2018).[4] The Transportation Research Board (2012) notes several types of uncertainty present in adaptation, namely,

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[3] For more details about the fund, see, for example: https://www.infrastructure.gc.ca/dmaf-faac/dmaf-guide-faac-eng.html

[4] In addition to the uncertainty related to climate change-related disasters, ports also face significant demand uncertainty. There is a rich literature on the impact of demand uncertainty on port or airport capacity investment (e.g., Meersman, 2005; Czerny, 2010; Allahviranloo and Afandizadeh, 2008; Yeo et al., 2014; Xiao et al. 2013, 2017; Zheng and Negenborn, 2017; Balliauw et al., 2019a, 2019b, 2020; Balliauw, 2020). A recent study by Gong et al. (2020) considers the disaster and demand uncertainties simultaneously, but the port regulation and disaster ambiguity are missing in the discussions.

the natural variability of the environment, data uncertainty, knowledge uncertainty, and model uncertainty. A few recent studies on adaptation have attempted to formally capture the effects of uncertainty using alternative specifications (Xiao et al., 2015; Randrianarisoa and Zhang, 2019). However, the United Nations Conference on Trade and Development (UNCTAD, 2017) finds that even the majority of ports previously impacted by extreme climate events do not have sufficient information for effective risk assessment and adaptation planning. Conclusions obtained under the assumption of a particular distribution of uncertain factors may offer rich insights. However, it is unclear to what extent these conclusions continue to hold when the actual probability distribution is different from that being modelled. One possible solution for such a problem is to consider a Knightian uncertainty (Knight, 1921) to capture the "ambiguity" (unknown disaster occurrence probability) (Wang and Zhang, 2018; Wang et al., 2020). More importantly, adaptation choices are dependent on the decision-makers' attitudes towards the risks, which have yet been formally modelled in transport adaptation studies. Ng et al. (2018) conduct surveys and interviews, which find that different ports and stakeholders can have different risk-attitudes towards disaster risk and the effectiveness of port adaptation. In this study, we model port adaptation decisions with ambiguity, and decision-makers' risk attitudes being explicitly considered with reference to the degree of pessimism. Such an analysis allows us to evaluate and benchmark practical policies used in the industry while introducing a new dimension in adaptation modelling.

Two-way relationship between adaptation and production. Disaster prevention policy should anticipate future risks instead of reacting to problems as they occur (Brouwer and Kind, 2005). As a port's throughput increases, the port thus offers more economic contributions. However, this also increases the port's potential loss in the case of a natural disaster.[5] Therefore, it is necessary to consider port production and adaptation planning in one integrated framework. Whereas it is common sense to invest in adaptations to protect operation and economic activities, relatively less attention has been given to the option of controlling economic activities in response to high levels of disaster risk. It should be noted that this option has been adopted in practice for an extended period of time. The Netherlands uses detailed Geographical Information System for regional planning and disaster prevention. If the flood risk in a region is high, then the options for future development in that region may include refraining from building new housing, shifting investments to higher elevated areas, and the offensive protection of the economic core.[6] However, few studies have analytically modelled the two-way relationship between adaptation and economic production, and few public

[5] This is a general consideration for disaster prevention. For example, the Netherlands Scientific Council for Government Policy (WRR) indicated that economic growth is a central source of future flood damage, whereas urban planning determines the amount of value that is protected by dikes. Formally, the risk of a natural disaster is defined as the multiplication of the disaster probability and the expected damage. This implies that disaster risk increases with economic activity. Since the term "risk" has been used loosely in (policy) discussions as equivalent to probability, this expression is not used extensively in our paper.

[6] See, for example, the following discussion in OECD (2009): "*… In the trend scenario, the bulk of future urban development will occur in the flood-prone area of Randstad Holland. Some alternative development scenarios were identified. These entail mainly refraining from building new housing in dike rings with high flood probabilities, shifting investment to higher elevated areas in the Netherlands (predominantly to the east of the country), and offensive protection of the economic core in Randstad Holland by extending the coastline 5 kilometres westward (MNP, 2007).*"

policies have formally incorporated such an issue in regulation (OECD 2014).[7] To address this research gap, in our model, the total loss from a disaster is modelled as being proportional to the port output. As shown in the modelling section, such a specification not only characterizes the interdependence between disaster loss and economic activities but also mandates the decision-makers to align the costs and benefits of port operation and adaptation investments.

In addition to the two abovementioned methodological contributions, our study also carefully controls the complicating factor, namely, the market structure that affects port adaptation investments, such as the inter-port competition and possible free-riding of port adaptation effort among different ports (Xiao et al., 2015; Wang and Zhang, 2018; Wang et al., 2020). Thus, in this study, we consider a region with several competing ports that is consistent with industry realities, such as the famous Hamburg-Le Havre (HLH) Port Region in Europe or the Pearl River Delta (PRD) in China. The potential positive externality of one port's adaptation on other ports is accounted for, in that for ports that are nearby one another, one port's adaptation, such as building levees in the sea or enhancing the common hinterland expressway drainage system for flood protection, can also benefit other ports. As a result, the impacts of inter-port competition and the spill-over effect of adaptations under different regulation schemes can be formally analysed together with their interactions with disaster ambiguity.

This study also complements the existing environmental economics literature that benchmarks the standard and tax policy instruments to mitigate emissions. Our minimum requirement regulation and subsidy on adaptation resemble the standard and tax policies on emission reductions, respectively. The relative performances of standard and tax in emission control are determined by the market structure (perfect competition vs. oligopoly), firm entry and exit barrier and uncertainty in abatement cost (see Weitzman, 1974; Baumol and Oates, 1988; Stavins, 1996; Helfand, 1991, 1999; Lahari and Ono, 2007; Heuson, 2010 etc.).[8] Our study focuses on the ranking of standard vs. tax policies on port adaptation efforts, instead of mitigating emissions. In addition, we not only consider the disaster uncertainty, but also examine the ambiguity and decision makers' risk-attitudes, together with their impacts on policy performances. This paper also supplements the international shipping research on the economic regulations used

[7] Although the OECD (2014) rated the Netherlands' water management highly, it cautioned that "…*economic incentives to efficiently manage water are sometimes weak. For instance, water management and spatial development are closely connected, but the actors who benefit from spatial development, such as municipalities and property developers, do not necessarily bear the additional costs related to water management; as a consequence, ongoing spatial development at times increases exposure to flood risk, leading to the escalation of the costs of water management, today and in the future. This raises equity issues.... Economic incentives could be strengthened and made consistent with water policy objectives. In particular, they can ensure that those who generate liabilities with regards to water management also bear the costs*."

[8] Weitzman (1974) shows that quantitative restrictions (i.e., standards) can sometimes be welfare-superior to price instruments in the presence of uncertainty. Our model considers both disaster uncertainty and the ambiguity, and also shows they affect ranking of policy performance. Helfand (1991) finds that a relative emission standard (defined as the ratio of total emission to total output) may raise pollution because firms can comply with a stricter emission standard by raising output rather than by lowering pollution. This resembles our findings about the minimum requirement on port adaptation in that the ports could reduce port outputs, instead of raising adaptation, to meet the requirement (standard). This would be welfare-harming compared to subsidy (price) policy. Heuson (2010) analyzes the optimal choice of emission control instruments under imperfect competition assuming uncertain abatement costs, and finds that taxes are more social welfare-conducive. Lahari and Ono (2007) also consider an imperfect competition and demonstrate that an emission standard leads to higher social welfare given a fixed number of firms, while the results become opposite when firms can freely enter and exit.

to cope with climate change-related threats (e.g., Psaraftis and Kontovas, 2010; Yang et al., 2012; Lee et al. 2013; Lee et al. 2016a, b; Afenyo et al. 2019). Previous literature, however, has focused on mitigation (i.e., emission reduction) regulations, while the adaptation regulatory policy discussions are missing in the international shipping field (e.g., Cullinane and Bergqvist, 2014; Wang et al., 2015; Sheng et al., 2017; Dai et al., 2018; Sheng et al., 2019). Our study thus fills in this apparent research gap.

The remainder of this paper is organized as follows. Section 2 establishes the model and investigates the benchmark case without disaster occurrence ambiguity. The optimal minimum requirement regulation and subsidy policy are solved and compared. In Section 3, the model is extended to examine port adaptations and regulations under ambiguity. Numerical simulation is conducted to verify the analytical results and further explore the impact of the ambiguity and regulation on the expected social welfare. The last section concludes the paper and identifies areas for future investigation. It is noted that constant marginal adaptation investment cost is assumed in our main model derivations and discussions. In Appendix 1, we conduct a robustness check by using the increasing marginal adaptation investment cost. Appendix 2 collates detailed proofs of the analytical results.

2. Adaptation Investment and Regulation Without Ambiguity

In this section, we first set up an analytical model to investigate port adaptation investment decisions in the absence of disaster occurrence ambiguity. Next, we discuss two regulatory tools on port adaptation, namely, the minimum requirement regulation and the subsidy policy, and benchmark the corresponding market outcomes and social welfare.

2.1 Model basics

We consider *N* identical ports that provide homogenous services in a region, whose demand can be specified as the following linear form:

$$P = a - b\sum_{i=1}^{N} q_i \tag{1}$$

In addition to homogeneous services, these ports are identical in the sense that they have the same constant marginal costs, which are normalized to zero. Such a simplified specification is necessary for modelling tractability to benchmark across different scenarios and to reveal the implications of important issues such as market competition, ambiguity and risk attitude. Ports face the risk of natural disasters but can reduce the level of damage experienced through *ex-ante* disaster prevention investment (i.e., adaptation investment). The actual loss of port i is therefore $L_i = (Dq_i - \gamma I_i - \varphi\gamma \sum_{j\neq i}^{N} I_j)^+$, where I_i represents the adaptation investments of port i, and the adaptation effectiveness is represented by $\gamma > 0$.[9] Here, $(x)^+ = max(x, 0)$. As

[9] With this specification, the adaptation investment is considered as a continuous measurement which reduces the damage in proportion to the level of investment. This is reasonable for the adaptation measures such as elevation

introduced in Section 1, we allow for the case where there is the positive externality of one port's disaster prevention investment on its neighbouring competitor, which is captured by φ. As a port's own investment is likely to be more effective than such a spill-over effect, we focus on the case where $\varphi \in [0,1]$. D is the average disaster loss for each unit of output, which can be represented as D_H (with the probability of ρ, $0 < \rho < 1$) or D_L (with probability of $1-\rho$), and $D_H > D_L$.[10] To exclude the trivial case of a negative price, it is assumed that $a > max(D_H/\gamma, 3D_H)$. Note that the adaptation investment cannot reduce the damage "probability" as the disaster probability ρ is exogenous. This is because the disaster occurrence probability is mainly determined by the events out of the control of individual ports, e.g., the global climate change. We first consider the case where the port adaptation investment cost is linear and then normalize its marginal cost to 1. In this case, the parameter γ can be interpreted as the relative adaptation benefit or effectiveness compared to the constant unit of adaptation investment cost. The value of γ is higher either when the adaptation effectiveness is larger or when the adaptation investment cost is lower. For example, several studies have suggested that adaptation effectiveness can vary significantly across ports, which is attributed to the nature or types of disasters and the technology available, while the adaptation cost can also differ among ports owing to different landscapes and capital costs (e.g., Ng et al., 2015; Randrianarisoa and Zhang, 2019). Thus, the parameter γ can play an important role in port adaptation investment decisions. Some studies have also suggested an increasing marginal adaptation cost (e.g., Wang and Zhang, 2018). Nonlinear adaptation costs will thus be examined in Appendix 1 to test the robustness of our analytical findings. With the above specifications, port i's expected profit is as follows:

$$E(\pi_i) = Pq_i - I_i - \rho(D_H q_i - \gamma I_i - \varphi\gamma \textstyle\sum_{j\neq i}^{N} I_j)^+ - (1-\rho)(D_L q_i - \gamma I_i - \varphi\gamma \textstyle\sum_{j\neq i}^{N} I_j)^+ \qquad (2)$$

Moreover, we define the social welfare as the sum of the port users' surplus and the port's profits as follows:[11]

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of port terminals, construction of seawalls, and widening of the drainage pipe to defend the heavy rains and hurricanes. The heights of the terminal elevation or seawalls, the diameters of the drainage pipe are all continuous measurements and reduce the flood damage on port facilities and cargos. In theory, when these adaptation measurements are sufficiently installed, they are able to totally block the flood or drain water quickly before causing any damage (i.e., full coverage against possible damage). Otherwise, the adaptation measurements can only reduce damage partially (i.e., partial coverage) depending on the level of adaptation investment. Here, we implicitly assume that a severe disaster would not destroy installed adaptation or totally disable the adaptation investment's effectiveness, for example, a collapse of seawalls. We thank the Editor for the suggestion to clarify this point.

[10] In order to keep the analysis tractable for clearer insights, we model the disaster loss using a binary random variable. However, it is worth noting that this approach can also express the stochastic characteristics of disaster occurrence (with $D_L = 0$ indicating the case where no disaster happens), as well as the disaster level (with the different ρ, the expected disaster loss E_D can also vary). Similar modelling assumption (using a binary variable to express the disaster occurrence or level) can be found in other related studies (e.g., Wang and Zhang, 2018; Gong et al., 2020).

[11] Whereas this is a textbook specification of social welfare, it is less straightforward for the port industry as it is for leading shipping companies that are international firms, since in many cases, ports are owned by local governments. It is not clear to what extent regulators or the government would consider the well-being of foreign companies. However, port adaptation is designed to protect both ports and their users, and there are many port users, in addition to shipping lines (i.e., port "tenants" providing services such as navigation, warehousing, logistics services, etc.). For similar specification and discussions on this issue, see, for example, Homsombat et al. (2013), Wang et al. (2012), Wang and Zhang (2018).

$$E(SW)=a\sum_{i}^{N}q_i-b\sum_{i}^{N}q_i^2/2-b\sum_{j\neq i}^{N}q_iq_j-\sum_{i}^{N}I_i-$$
$$\sum_{i}^{N}[\rho(D_Hq_i-\gamma I_i-\varphi\gamma\sum_{j\neq i}^{N}I_j)^{+}+(1-\rho)(D_Lq_i-\gamma I_i-\varphi\gamma\sum_{j\neq i}^{N}I_j)^{+}] \quad (3)$$

To regulate the port's adaptation investment behaviour, the government can choose between two regulation tools: the minimum requirement L_U, which is the upper limit of the expected disaster loss for each port, or the subsidy $\theta \in (0,1)$ for every unit of the adaptation investment. We model the regulator and the port's behaviour with the following multistage game:[12]

Stage One: The regulator chooses between subsidy and the minimum requirement policies. It then decides the optimal subsidy θ^* or the minimum requirement L_U^* to maximize the expected social welfare;

Stage Two: Ports simultaneously decide their adaptation investments under either the minimum requirement or subsidy policy. If the government decides to implement the subsidy policy in Stage One, the subsidy is actually paid to the ports in Stage Two, during or after the adaptation construction;

Stage Three: Ports simultaneously decide their outputs to maximize their expected profits.

2.2 Market equilibrium without regulation

Now, we investigate each port's output and adaptation investment in the market equilibrium without the government's regulation of port adaptation. The ports maximize their expected profits with respect to q_i and I_i, as shown in Eq. (2). We obtain the following proposition (where the superscript "*M*" indicates the market equilibrium without regulation). All proofs hereinafter can be found in Appendix 2.

Proposition 1. In the market equilibrium without regulation on port adaptation, each port's optimal output and adaptation investment depend on the adaptation effectiveness γ. *Specifically,*

(i) If $\gamma \in [0,1)$, *then* $I_i^M=0$, $q_i^M=\frac{a-E_D}{(N+1)b}$, *where* $E_D=\rho D_H+(1-\rho)D_L$;

(ii) If $\gamma \in [1,1/\rho)$, *then* $I_i^M=\frac{D_Lq_i^M}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^M=\frac{a-\rho(D_H-D_L)-D_L/\gamma}{(N+1)b}$;

(iii) If $\gamma \in [1/\rho,\infty)$, *then* $I_i^M=\frac{D_Hq_i}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^M=\frac{a-D_H/\gamma}{(N+1)b}$.

Proposition 1 shows that the port's output and adaptation investment illustrate a

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[12] In this paper, we use a static model rather than a dynamic model to investigate the ports' adaptation investment. Static models are often used in economics, transportation engineering and other fields to study inherently dynamic phenomena and optimization problems. It could be proved that our static model is compatible with the dynamic model under some mild conditions. Therefore, our static can be treated as the reduced form of the dynamic model.

stepwise structure depending on the adaptation effectiveness. When $\gamma < 1$, the marginal contribution of the investment to the port's profit (by reducing the disaster loss) is less than its marginal cost, and the port makes no adaptation investment. When $\gamma > 1$, the marginal contribution of the investment is larger than its cost, and the port is willing to make adaptation investments. Specifically, when $\gamma \in [1, 1/\rho)$, the marginal cost of the investment is larger than its expected marginal contribution to cover the high disaster loss but less than the marginal contribution to cover the low disaster loss. Thus, port i has full insurance for the damage experienced in a low-level disaster occurrence (i.e., $\gamma I_i^M + \varphi\gamma \sum_{j\neq i}^{N} I_j^M = D_L q_i^M$) but is only partly covered for the damage experienced in a high-level disaster occurrence. As ports target fully covering low-level disaster losses, an improving adaptation effectiveness would lower the adaptation investment (i.e., $\partial I_i^M / \partial\gamma < 0$).

When $\gamma > 1/\rho$, the marginal cost of the investment is less than its expected marginal contribution to cover the high-level disaster loss. Port i thus makes the investment to cover the possible high-level disaster loss as well. This leads to full coverage under both high-level and low-level disaster occurrences (i.e., $\gamma I_i^M + \varphi\gamma \sum_{j\neq i}^{N} I_j^M = D_H q_i^M$). As a result, the port would increase its level of adaptation investment, leading to a jump of port adaptation level at $\gamma = 1/\rho$ (see Figure 1a). Port adaptation also decreases as adaptation effectiveness increases (i.e., $\partial I_i^M / \partial\gamma < 0$). Overall, the relation between adaptation I_i^M and adaptation effectiveness γ is not monotone. Moreover, $\partial q_i^M / \partial\gamma > 0$ and $\partial^2 q_i^M / \partial\gamma^2 < 0$ suggest a positive marginal effect of adaptation effectiveness on port output, and such a relationship is continuous over $\gamma \in [\frac{1}{\rho}, \infty)$, as shown in Figure 1b.

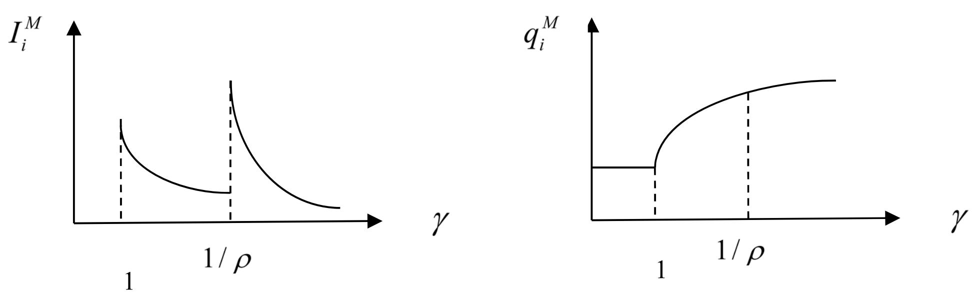

Figure 1a. The port's optimal adaptation investment

Figure 1b. The port's optimal output

In addition, $\partial q_i^M / \partial N < 0$ and $\partial I_i^M / \partial N < 0$. A less concentrated market with more competing ports can lead to less output and adaptation investment for individual ports. However, $\partial \sum_{i=1}^{N} q_i^M / \partial N > 0$ and $\partial \sum_{i=1}^{N} I_i^M / \partial N > 0$, which means that a less concentrated market results in higher total outputs and total adaptation investment in the region. These outcomes are consistent with the Cournot model that suggests that the presence of more competing firms hinders each player's output but promotes the total market output. On the other hand, $\partial I_i^M/\partial\varphi < 0$, which means that a larger positive externality exaggerates the free-riding behaviour of each port, thereby leading to lower levels of adaptation investment (for each port and the total investment). This point is crucial in our discussion on port adaptation regulations found in Section 3. Moreover, we have $\partial q_i^M/\partial a > 0$ and $\partial I_i^M/\partial a \geq 0$, which indicate that the market size increases each port's output and adaptation investment.

2.3 Regulation on port adaptation investment without ambiguity

The socially optimal port adaptation and port output are summarized by Proposition 2, where the superscript "S" indicates the social optimum. They can be solved to serve as benchmark for the analysis of alternative regulations, namely, the minimum requirement regulation vs. the subsidy policy. It is easy to find that both the port output and adaptation investment in the market equilibrium are lower than the social optimum, which makes the regulation necessary. The explanations are as follows. From the Industrial Economics literature, we know the socially optimal outputs are higher than the firms' total outputs when the firms engage in a Cournot competition (e.g., Jehle and Reny, 2001). In our paper, ports compete on their outputs and thereby their total outputs in the market equilibrium are lower than the social optimum. From Proposition 1 and 2, it is known that the adaptation investment is proportional to the output, when the port adaptation investment is necessary. As the socially optimal outputs are higher than the market equilibrium outputs, the socially optimal adaptation investment is higher than the market equilibrium adaptation investment.

Proposition 2. The socially optimal port's output and adaptation investment depend on the adaptation effectiveness γ. *Specifically,*

(i) If $\gamma \in [0,1)$, *then* $I_i^S = 0$, $q_i^S = \frac{a-E_D}{Nb}$;

(ii) If $\gamma \in [1, 1/\rho)$, *then* $I_i^S = \frac{D_L q_i^S}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^S = \frac{a-\rho(D_H-D_L)-D_L/\gamma}{Nb}$;

(iii) If $\gamma \in [1/\rho, \infty)$, *then* $I_i^S = \frac{D_H q_i^S}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^S = \frac{a-D_H/\gamma}{Nb}$.

2.3.1 Minimum requirement regulation

To derive the optimal minimum requirement regulation, backward induction is adopted, i.e., the port's optimal adaptation investment and output in Stage Two are first solved given the minimum requirement. Then, the government's optimal minimum requirement regulation in Stage One is solved.

Specifically, with the minimum requirement, the government regulates that the expected disaster loss of each port must be less than a target L_U. Ports maximize their individual expected profit by choosing their adaptation investments and outputs. The objective function of port *i* can be specified as follows:

$$\max_{q_i, I_i} \ \mathrm{E}(\pi_i)$$

s.t. $\rho(D_H q_i - \gamma I_i - \varphi\gamma \sum_{j\neq i}^{N} I_j)^+ + (1-\rho)(D_L q_i - \gamma I_i - \varphi\gamma \sum_{j\neq i}^{N} I_j)^+ \leq L_U$ (4)

Solving this problem, we obtain the following lemma. Here, the superscript "*R*" indicates the minimum requirement.

Lemma 1. Under the minimum requirement regulation, each port's adaptation investment and output depend on the adaptation effectiveness γ and the minimum requirement L_U.

As the impacts of γ and L_U on port adaptation and port output are somewhat complicated, we present the details of Lemma 1 in Appendix 2. To respond to the government's minimum requirement, the port has two options, namely, to increase the adaptation investment (to cover the disaster loss) or to decrease the port output (thus reduces the disaster loss). Lemma 1 illustrates the port's responses under different L_U. When the adaptation effectiveness is high, i.e., $\gamma \in [1/\rho, \infty)$, the minimum requirement regulation has no impact on the port output or adaptation investment compared to the market equilibrium without regulation. This is because the high adaptation effectiveness gives the port enough of an incentive to achieve full insurance under both low-level and high-level disaster loss occurrences (recall our statements in Section 2.2 that $\gamma I_i^M + \varphi\gamma \sum_{j\neq i}^{N} I_j^M = D_H q_i^M$ and that the disaster loss is 0 if $\gamma > 1/\rho$). When the adaptation effectiveness is intermediate but still larger than its cost (i.e., $\gamma \in [1, 1/\rho)$) in the market equilibrium without regulation, the port has the incentive to make an adaptation investment, albeit not always one high enough to reach the minimum requirement. If the minimum requirement is not very restrictive ($L_U \geq \frac{\rho(D_H-D_L)[a-\rho(D_H-D_L)-D_L/\gamma]}{(N+1)b}$), then it can be satisfied by the port voluntarily,[13] i.e., $I_i^R = I_i^M$. If the minimum requirement is restrictive ($L_U < \frac{\rho(D_H-D_L)[a-\rho(D_H-D_L)-D_L/\gamma]}{(N+1)b}$), then it forces the port to make more adaptation investments and to reduce its output simultaneously compared to the case without regulation (i.e., $I_i^R > I_i^M$ and $q_i^R < q_i^M$).[14] When the adaptation effectiveness is low (e.g., lower than its cost), then the port is not willing to make any adaptation investment absent regulation (i.e., market failure). If the minimum requirement is not very restrictive, i.e., $L_U \in (\frac{\rho(D_H-D_L)(a-E_D/\gamma)}{(N+1)b}, \frac{E_D(a-E_D)}{(N+1)b}]$, then the port uses the two options simultaneously, i.e., it decreases its output and increases its adaptation investment at the same time, to reach the target.[15]

After solving the ports' optimal problem, we turn to the government's choice of

[13] Note that L_U is the maximum expected loss allowed by the government. A larger L_U indicates less restrictive requirement.

[14] Because $\gamma \in [1, 1/\rho)$, we know that $q_i^R = \frac{a-D_H/\gamma}{(N+1)b} < q_i^M = \frac{a-\rho(D_H-D_L)-D_L/\gamma}{(N+1)b}$. Because $L_U < \frac{\rho(D_H-D_L)[a-\rho(D_H-D_L)-D_L/\gamma]}{(N+1)b}$, it can be proved that $I_i^R > I_i^M$.

[15] When $L_U \in (\frac{\rho(D_H-D_L)(a-E_D/\gamma)}{(N+1)b}, \frac{E_D(a-E_D)}{(N+1)b}]$, *then* $q_i^R = \frac{a-E_D/\gamma}{(N+1)b} < q_i^M = \frac{a-E_D}{(N+1)b}$ because $\gamma \in (0,1)$. Because $L_U < \frac{E_D(a-E_D)}{(N+1)b}$, we know that $E_D q_i^R - L_U > 0$, which leads to $I_i^R > I_i^M = 0$. When $L_U \in [0, \frac{\rho(D_H-D_L)(a-E_D/\gamma)}{(N+1)b}]$, $q_i^R = \frac{a-D_H/\gamma}{(N+1)b} < \frac{a-E_D/\gamma}{(N+1)b} < q_i^M = \frac{a-E_D}{(N+1)b}$ because $D_H > E_D$. Because $L_U < \frac{\rho(D_H-D_L)(a-E_D)}{(N+1)b}$, we know that $D_H q_i^R - L_U/\rho > 0$, which leads to $I_i^R > I_i^M = 0$,

the optimal L_U^* to maximize the expected social welfare. The following Lemma 2 can be obtained accordingly.

Lemma 2. Let $\gamma_1 = \frac{1}{\rho[1+\varphi(N-1)]}$. *The government's optimal minimum requirement regulation is described as follows:*
(i) If $\gamma \in [0, \gamma_1)$, *then no minimum requirement regulation is necessary*;
(ii) If $\gamma \in [\gamma_1, 1/\rho)$, *then* $L_U^* = 0$; *and*
(iii) If $\gamma \in [1/\rho, \infty)$, *then no minimum requirement regulation is necessary.*

To interpret Lemma 2, we first demonstrate the meaning of $\gamma[1+\varphi(N-1)]$, which is the expected effectiveness of the total adaptation investment in the equilibrium. When $\gamma \in [0, \frac{1}{\rho[1+\varphi(N-1)]})$, we know that $\gamma[1+\varphi(N-1)] < \frac{1}{\rho}$. It is not worthwhile to force the ports to increase their adaptation investment by placing restrictive minimum requirements because the adaptation effectiveness is low. When $\gamma \in [\frac{1}{\rho[1+\varphi(N-1)]}, \frac{1}{\rho})$, from the proof of Lemma 2, we know that the expected social welfare always increases with a more restrictive minimum requirement (i.e., a lower L_U^*), such that the most restrictive requirement $L_U^* = 0$ (i.e., full insurance) is the optimal regulation choice. This means that full insurance coverage becomes optimal, while the port will only partially cover the high-level disaster loss when the adaptation effectiveness is intermediate. As a result, the government has to set the most restrictive minimum requirement to prevent any *ex-post* disaster damage. When $\gamma \in [1/\rho, \infty)$, the port already has an incentive to make sufficient adaptation investment to reduce the expected disaster loss to 0. Therefore, minimum regulation is unnecessary.

2.3.2 Subsidy policy

Under the subsidy policy, the port's marginal adaptation investment cost is reduced from 1 to $1-\theta$ $(0 < \theta < 1)$. Analogous to Section 2.3.1, we have the following lemma to describe the ports' responses. Here, the superscript "*B*" indicates the subsidy policy.

Lemma 3. Under the subsidy policy, each port's adaptation investment and output depend on the adaptation effectiveness γ *and the subsidy* θ. *Specifically:*
(i) If $\gamma \in [0, 1-\theta)$, *then each port's adaptation investment and output are the same as those in the case without regulation;*
(ii) If $\gamma \in [1-\theta, (1-\theta)/\rho)$, *then* $I_i^B = \frac{D_L q_i^B}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^B = \frac{a-\rho(D_H-D_L)-(1-\theta)D_L/\gamma}{(N+1)b}$; *and*
(iii) If $\gamma \in [(1-\theta)/\rho, \infty)$, *then* $I_i^B = \frac{D_H q_i^B}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^B = \frac{a-(1-\theta)D_H/\gamma}{(N+1)b}$.

Lemma 3 indicates that the subsidy affects the ranges of parameter γ for the different corner solutions. It can be proven that $I_i^B > I_i^M$ and $q_i^B > q_i^M$, except when $\gamma < 1-\theta$. Unlike the minimum requirement regulation, the subsidy policy increases both the port's output and adaptation investment compared to the market equilibrium without regulation, so long as the adaptation effectiveness is not too small. Figure 2 illustrates the outcomes under the subsidy policy.

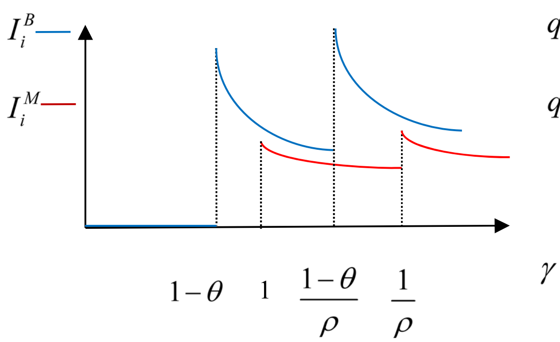

Figure 2a Port *i*'s adaptation investment under the subsidy and without regulation

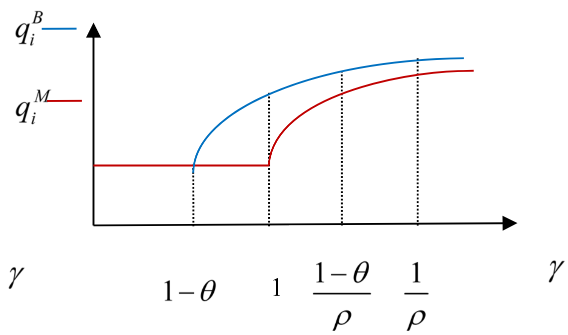

Figure 2b Port *i*'s output under the subsidy and without regulation

The next lemma describes the government's optimal subsidy policy, with the expressions of γ_2, γ_3, γ_4 available in Appendix 2.

Lemma 4. the government's optimal subsidy policy is described as follows:
(i) If $\gamma \in [0, \gamma_2)$, then no subsidy policy is necessary;
(ii) If $\gamma \in [\gamma_2, \gamma_3)$, then $\theta^* = \theta_1$;
(iii) If $\gamma \in [\gamma_3, \gamma_4)$, then θ^* can be either θ_1 or θ_2, whichever makes the social welfare larger; and
(iv) If $\gamma \in [\gamma_4, \infty)$, then $\theta^* = \theta_2$.

Comparing the two regulation policies (from Lemmas 2 and 4), it is found that the subsidy policy can stimulate port adaptation investment within a wider range of adaptation effectiveness γ than that of minimum requirement regulation. This can be seen as $\gamma_1 > \gamma_2$, and the subsidy policy still works when $\gamma > 1/\rho$. Moreover, the subsidy encourages adaptation investment without sacrificing the output at the same time, while the minimum requirement regulation limits the disaster loss by reducing the output (and promotes less investment increment compared to the subsidy policy). Therefore, the subsidy policy is a more active approach to encourage adaptation and output together, whereas the minimum requirement tends to be a more passive approach to control disaster damage by reducing output as well[16].

[16] From Eq. (3) we know that there are three parts that contribute to the social welfare function, namely, the port users' surplus (which increases with the output), the adaptation investment costs and the expected disaster loss (which are related to both the adaptation investment and the output).

2.3.3 Optimal regulation policies

Comparing the expected social welfare under three scenarios, namely, (a) no regulation, (b) the minimum requirement regulation, and (c) the subsidy policy, the government's optimal regulation policies are as follows.

Proposition 3. The optimal port adaptation investment regulation depends on the adaptation effectiveness γ*. Specifically, the optimal regulation policies are as follows:*
(i) If $\gamma \in [0, \gamma_2)$*, then no regulation is necessary;*
(ii) If $\gamma \in [\gamma_2, \gamma_1)$*, then the subsidy leads to the highest social welfare;*
(iii) If $\gamma \in [\gamma_1, \gamma_3)$*, then the optimal regulation policy can be a minimum requirement or subsidy. When* φ *is small enough, then the subsidy is better than the minimum requirement; and*
(iv) If $\gamma \in [\gamma_3, \infty)$*, then the subsidy policy leads to the highest social welfare.*

The explanations of Proposition 3 are as follows. In the market equilibrium without regulation, the port adaptation investment is equal to or lower than the social optimum. Therefore, the purpose of the regulation should be to promote the ports' adaptation investment when necessary. If the investment effectiveness is very low, i.e., $\gamma \in [0, \gamma_2)$, then it is unnecessary to promote the adaptation investment because of its low contribution to the remedy of the disaster loss. Comparing the two regulation policies, the subsidy policy is more proactive than the minimum requirement regulation in terms of promoting adaptation investment and outputs at the same time. To fulfil the minimum requirement, a port might not make enough adaptation investment and thus would resort to decreasing its output to avoid disaster loss. Such output reduction is detrimental to social welfare. Therefore, the subsidy policy dominates the minimum requirement regulation in most cases in terms of social welfare. For example, when $\gamma \in [\gamma_2, \gamma_1)$, the overall adaptation effectiveness is lower than its marginal cost, and the subsidy policy is more effective in encouraging adaptation while not reducing the output level so that ports are prepared for the low-level loss scenario. When $\gamma \in [\gamma_3, \infty)$, the adaptation effectiveness is higher than its marginal cost, and the port would pursue full insurance for both high-level and low-level disaster losses. Thus, the subsidy policy is still welfare-improving in that it would increase both port adaptation investment and output. However, when $\gamma \in [\gamma_1, \gamma_3)$, the adaptation effectiveness is less than its marginal cost but still at an intermediate level (note that $\gamma_3 < 1$). The minimum requirement regulation may be better than the subsidy policy (although this outcome is not for sure). This is because the large adaptation investment under the subsidy policy may be excessive and costly when the adaptation effectiveness is not high enough. As the adaptation effectiveness is not too low, ports would not aggressively cut output under the minimum requirement regulation. Thus, the minimum requirement regulation could outperform the subsidy policy. Moreover, we find that $\partial\gamma_2/\partial N < 0$, which means that the regulation is more necessary as port competition increases. This is because more port competition reduces the incentive of each port's adaptation investment, and thereby makes the government regulation more necessary. On the other side, we find that $\partial\gamma_2/\partial a < 0$, which means that the regulation is more necessary as the market size increases. This is because a larger market leads to higher ports' outputs and the related expected disaster loss. Therefore, it makes the government regulation more necessary to promote each port to invest more in its adaptation to cope with the possible higher disaster loss.

To summarize the above discussions, the subsidy policy is more social-welfare conducive either when adaptation effectiveness is low (i.e., $\gamma \in [\gamma_2, \gamma_1)$) or when adaptation effectiveness is high (i.e., $\gamma \in [\gamma_3, \infty)$). In both cases, the minimum requirement regulation discourages too much port output, although it increases the adaptation investment as well. When adaptation effectiveness is intermediate, the minimum requirement regulation could be better because it avoids excessive adaptation with subsidy policy while not significantly reducing the port output.

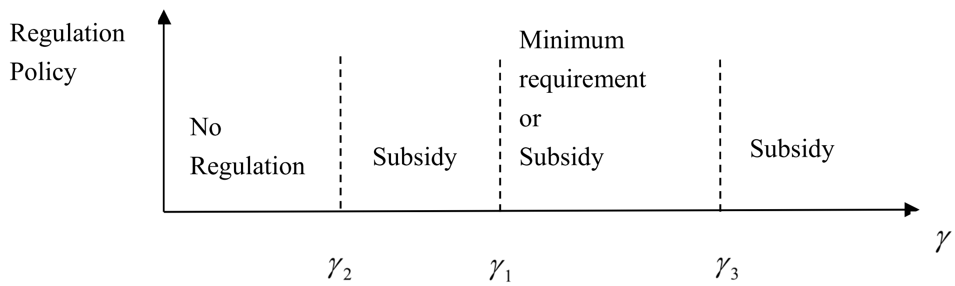

Figure 3 The optimal port adaptation investment regulation policies

The externality of port adaptation investment φ also affects the optimal choice of regulations. This is summarized as Corollary 1 with both the discussions and proofs in Appendix 2.

3. Adaptation Investment and Regulation with Ambiguity

In this section, the model in Section 2 is extended to incorporate the ambiguity related to the disaster occurrence probability. The market equilibrium and the government's optimal regulation under ambiguity are examined. Specifically, we investigate the impacts of ambiguity on port adaptation investment and output, social welfare and regulation outcomes. The results are benchmarked with Section 2 to better identify the impacts of ambiguity.

3.1 Market equilibrium under ambiguity

Ambiguity means that the probability distribution of an event is unknown or uncertain. Many factors, including information accessibility and quality, the different perceptions among decision makers, and their confidence in the perceived probability, can cause uncertainty in the probability distribution (Knight, 1921; Camerer and Weber, 1992; Nishimura and Ozaki, 2007; Gao and Driouchi, 2013). A disaster is not an event that occurs frequently. The decision makers inside an organization (e.g., a government or a port) may have different opinions towards the prospect of a disaster due to the lack of historical data and samples. Therefore, it is difficult for a government or a port to precisely know the disaster occurrence probability ρ. In this paper, we consider that the government and the port only know that ρ varies on $[\underline{\rho}, \bar{\rho}]$. Note that we do not stipulate any specific distribution forms of ρ. Let $\Delta\rho = \bar{\rho} - \underline{\rho}$, with a larger $\Delta\rho$ indicating more ambiguity *ceteris paribus*. To simplify the problem, we assume that the ports and the government have the same belief regarding ρ.[17] Next, we need to define the utility functions of the ports and the government under ambiguity. The $\alpha-$MEU model is used (Ghirardato et al., 2004), which expresses the decision maker's utility as a convex combination of two extreme preferences (i.e., the worst and the best case). The $\alpha-$MEU model also has the benefit of separating the decision maker's ambiguity degree from the ambiguity attitude. The port's and government's objective functions under ambiguity can be expressed as follows:

$$E(\pi_i) = \alpha \inf_{\rho} E(\pi_i) + (1-\alpha) \sup_{\rho} E(\pi_i) \tag{5}$$

$$E(SW) = \alpha \inf_{\rho} E(SW) + (1-\alpha) \sup_{\rho} E(SW) \tag{6}$$

where α indicates the degree of pessimism of the ports and the government, with a larger α indicating higher levels of pessimism. To obtain more concise expressions, we further define the following symbols: $\Phi_D = \Omega D_H + (1-\Omega)D_L$ and $\Omega = \alpha\bar{\rho} + (1-\alpha)\underline{\rho}$. Maximizing Eq. (5) with respect to q_i and I_i, we obtain the following proposition. The added superscript "*A*" hereinafter indicates the results obtained under ambiguity.

Proposition 4. In the market equilibrium under ambiguity, each port's optimal adaptation investment and output depend on the adaptation effectiveness γ. *Specifically:*

(i) If $\gamma \in [0,1)$, *then* $I_i^{MA} = 0$ *and* $q_i^{MA} = \frac{a-\Phi_D}{(N+1)b}$;

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[17] For ρ, if its bounds (i.e., $\underline{\rho}$ and $\bar{\rho}$) are the same to the ports and the government, the different belief on ρ between the ports and the government has no impacts on the results, because only these two extreme cases are considered in the $\alpha-$MEU model. For α, the situation becomes more complicated. Qualitatively, if the government has bigger (or smaller) pessimism degree than the ports', it may restrict (or loosen) the minimum requirement, or provide more (or less) subsidy to the ports, which may promote (or inhibit) the regulation, and thus amplifies the regulation impact on port adaptation, port output and social welfare. As our purpose is to propose one of the first analytical studies to examine and compare the two regulatory policies on port adaptation with and without ambiguity, the symmetry assumption is adopted. The detailed quantitative analysis with asymmetry ambiguity and pessimism degree can be a natural extension for future research.

(ii) If $\gamma \in [1,1/\Omega)$*, then* $I_i^{MA} = \frac{D_L q_i^{MA}}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^{MA} = \frac{a-\Omega(D_H-D_L)-D_L/\gamma}{(N+1)b}$*; and*

(iii) If $\gamma \in [1/\Omega,\infty)$*, then* $I_i^{MA} = \frac{D_H q_i^{MA}}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^{MA} = \frac{a-D_H/\gamma}{(N+1)b}$.

Comparing Propositions 1 and 4, we know that the stepwise structures of the port's decisions still hold under ambiguity. Our calculation shows that $\partial\Omega/\partial\alpha \geq 0$. Moreover, $\partial\Omega/\partial\Delta\rho \leq 0$ given $\overline{\rho}$, and $\partial\Omega/\partial\Delta\rho \geq 0$ given $\underline{\rho}$. Therefore, $\frac{\partial q_i^{MA}}{\partial\Delta\rho} \leq 0$ and $\frac{\partial I_i^{MA}}{\partial\Delta\rho} \leq 0$ (or $\frac{\partial q_i^{MA}}{\partial\Delta\rho} \geq 0$ and $\frac{\partial I_i^{MA}}{\partial\Delta\rho} \geq 0$, respectively) given $\underline{\rho}$ (or $\overline{\rho}$, respectively), which indicates that the impacts of ambiguity on port operation are uncertain.[18] Given the lower bound of disaster occurrence probability (i.e., $\underline{\rho}$), higher ambiguity degree means higher chance of larger upper bound of disaster occurrence probability (i.e., $\overline{\rho}$). The $\alpha-$MEU model indicates that the port makes the decisions according to a weighted average criterion of the "worst" and the "best" outcomes. As the best outcome is given (a fixed value of $\underline{\rho}$), the worst outcome (i.e., larger $\overline{\rho}$) leads to the port's more conservative decisions where lower outputs and corresponding lower adaptation investments are made.

An increasing degree of pessimism will decrease a port's output (i.e., $\partial q_i^{MA}/\partial\alpha \leq 0$), as ports are more conservative. However, its impact on port adaptation is uncertain. There exists a threshold value of α', which leads to a corresponding threshold value Ω', such that $\partial I_i^{MA}/\partial\alpha \begin{cases} = 0 & if \quad \gamma < 1 \\ \leq 0 & if \quad 1 \leq \gamma < 1/\Omega' \\ \geq 0 & if \quad 1/\Omega' \leq \gamma < 1/\Omega \\ 0 & if \quad \gamma \geq 1/\Omega \end{cases}$. As shown in Figure 4, when the adaptation effectiveness is not very high (i.e., $1 \leq \gamma < 1/\Omega'$), then ports only have partial insurance coverage for high-level damage loss. Port output decreases when a port is more conservative/risk averse, such that port adaptation investment decreases accordingly. However, when the adaptation effectiveness is reasonably high

[18] As Nishimura and Ozaki (2007) point out, "an increase in risk is characterized by a mean-preserving spread", while "Knightian uncertainty is increased in the sense that the degree of confidence contamination is increased" (Nishimura and Ozaki, 2007, pp.673). The degree of confidence contamination is represented by the deviation of the probability to its assumed value, i.e., ε, and "an increase in ε can be considered as an increase in Knightian uncertainty" (Nishimura and Ozaki, 2007, pp.673). An increase in ε leads to an increase in spread between the highest and the lowest probability of the state. It is very similar to our case where an increase in $\Delta\rho = \bar{\rho} - \underline{\rho}$ indicates more ambiguity degree. In the $\alpha-$MEU model, similar approach of the ambiguity degree can also be found, for example, in Schröder (2011). It is also noted that the $\alpha-$MEU model only considers the "worst" and "best" scenarios of the probability, while the probability itself is unknown (i.e., it does not have a "mean value", and is also not captured by the $\alpha-$MEU model.

(i.e., $1/\Omega' < \gamma < 1/\Omega$), then the port would make more adaptation investment even when its output is reduced. This approach would be more effective in reducing the expected disaster damage when the port is more conservative/risk averse. Last, when $\gamma \geq 1/\Omega$, the port is willing to invest enough in adaptations to achieve full insurance coverage under both low-level and high-level disaster occurrences. Thus, the degree of pessimism would have no impact on port output or adaptation investment. As $\partial\Omega/\partial\alpha \geq 0$ (i.e., $\frac{\partial(\frac{1}{\Omega})}{\partial\alpha} \leq 0$), the port is more likely to achieve full insurance coverage with an increasing degree of pessimism. The above findings can be summarized as the following proposition 5.

Proposition 5. Without regulation, a port's increasing degree of pessimism induces it to take full insurance coverage for both low-level and high-level damage losses. When full insurance coverage is achieved, then degree of pessimism has no impact on port adaptation investment. However, when partial insurance is made for high-level damage loss, we have the following:

(i) If $\gamma \in [0,1)$*, then a port's higher degree of pessimism has no impact on its output and adaptation investment;*

(ii) If $\gamma \in [1, 1/\Omega')$*, then a port's higher degree of pessimism decreases both output and adaptation investment; and*

(iii) If $\gamma \in [1/\Omega', 1/\Omega)$*, then a port's higher degree of pessimism decreases output while increasing port adaptation investment.*

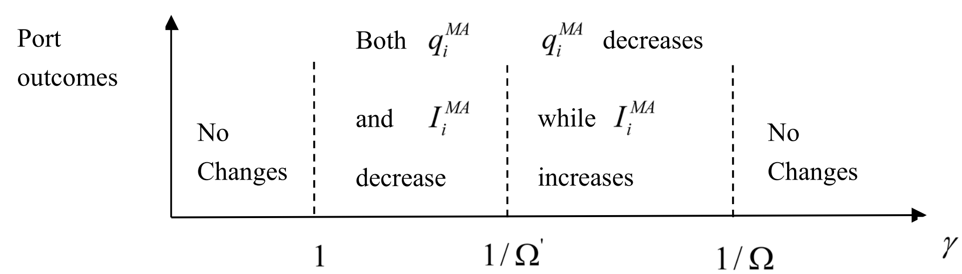

Figure 4 The impacts of a larger α on the regulation outcomes

3.2 Regulation on port adaptation investment under ambiguity

Analogous to Section 2.3, it is straightforward to show that $I_i^{SA} = 0$ and $q_i^{SA} = \frac{a-\Phi_D}{Nb}$ when $\gamma \in [0,1)$, $I_i^{SA} = \frac{D_L q_i^{SA}}{\gamma[1+\varphi(N-1)]}$ and $q_i^{SA} = \frac{a-\Omega(D_H-D_L)-D_L/\gamma}{Nb}$ when $\gamma \in [1, 1/\Omega)$, and $I_i^{SA} = \frac{D_H q_i^{SA}}{\gamma[1+\varphi(N-1)]}$ and $q_i^{SA} = \frac{a-D_H/\gamma}{Nb}$ when $\gamma \in [1/\Omega, \infty)$. We thus have consistent conclusions that both the port's output and adaptation investment in the market equilibrium are lower than the social optimum under ambiguity. We have similar conclusions about the impacts of the pessimism degree and the ambiguity level on social welfare.

Corollary 2. Increases in the degree of pessimism always reduce port profits and social welfare. However, the effects of the ambiguity level on the port's profit and social welfare are uncertain.

3.2.1 Minimum requirement regulation

Similar to Section 2.2.1, this subsection discusses the optimal minimum requirement regulation and its impact on port outcomes but does so under the ambiguity of the disaster occurrence probability. Now, port *i* maximizes the following objective function subject to the government's minimum requirement L_{UA}:

$$\max_{q_i, I_i} \ E(\pi_i) = \alpha \inf_{\rho} E(\pi_i) + (1-\alpha) \sup_{\rho} E(\pi_i)$$

$$\text{s.t.} \quad \begin{aligned} &\alpha[\bar{\rho}(D_H q_i - \gamma I_i - \varphi\gamma \textstyle\sum_{j\neq i}^{N} I_j)^+ + (1-\bar{\rho})(D_L q_i - \gamma I_i - \varphi\gamma \textstyle\sum_{j\neq i}^{N} I_j)^+] \\ &+(1-\alpha)[\underline{\rho}(D_H q_i - \gamma I_i - \varphi\gamma \textstyle\sum_{j\neq i}^{N} I_j)^+ + (1-\underline{\rho})(D_L q_i - \gamma I_i - \varphi\gamma \textstyle\sum_{j\neq i}^{N} I_j)^+] \leq L_{UA} \end{aligned} \tag{7}$$

The port's responses under the different L_{UA} can be summarized in the following lemma.

Lemma 5. Under the minimum requirement regulation and ambiguity, each port's adaptation investment and output depend on adaptation effectiveness γ *and the minimum requirement* L_{UA}.

As the impacts of γ and L_U on port adaptation and port output are somewhat complicated, we present the details of Lemma 5 in Appendix 2. Similar to Section 2.3.1, we obtain the optimal minimum requirement regulation under ambiguity as follows.

Lemma 6. Let $\gamma_{1A} = \frac{1}{\Omega[[1+\varphi(N-1)]}$. *The government's optimal minimum requirement regulation under ambiguity is described as follows:*
(i) If $\gamma \in [0, \gamma_{1A})$, *then no minimum requirement regulation is necessary*;
(ii) If $\gamma \in [\gamma_{1A}, 1/\Omega)$, *then* $L_{UA}^* = 0$; and
(iii) If $\gamma \in [1/\Omega, \infty)$, *then no minimum requirement regulation is necessary.*

3.2.2 Subsidy policy

Similar to Section 2.2.2, we can derive a port's optimal adaptation investment and output with ambiguity for the disaster occurrence probability. This leads to the following lemma.

Lemma 7. Under the subsidy policy and ambiguity, each port's adaptation investment

and output depend on the adaptation effectiveness investment γ *and the subsidy* θ*. Specifically:*
(i) If $\gamma \in [0,1-\theta)$, then *each port's output and adaptation investment are the same as those in the case without regulation*;
(ii) If $\gamma \in [1-\theta,(1-\theta)/\Omega)$ *, then* $I_i^{BA} = \frac{D_L q_i^{BA}}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^{BA} = \frac{a-\Omega(D_H-D_L)-(1-\theta)D_L/\gamma}{(N+1)b}$*; and*
(iii) If $\gamma \in [(1-\theta)/\Omega,\infty)$*, then* $I_i^{BA} = \frac{D_H q_i^{BA}}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^{BA} = \frac{a-(1-\theta)D_H/\gamma}{(N+1)b}$.

We further obtain the optimal subsidy policy under ambiguity as follows (with the expressions of $\gamma_{2A}, \gamma_{3A}, \gamma_{4A}, \theta_{1A}, \theta_{2A}$ available in Appendix 2).

Lemma 8.
The government's optimal subsidy policy under ambiguity is described as follows:
(i) If $\gamma \in [0,\gamma_{2A})$*, then no subsidy policy is necessary*;
(ii) If $\gamma \in [\gamma_{2A},\gamma_{3A})$*, then* $\theta_A^* = \theta_{1A}$*;*
(iii) If $\gamma \in [\gamma_{3A},\gamma_{4A})$*, then* θ_A^* *can be either* θ_{1A} *or* θ_{2A}*, whichever makes social welfare larger; and*
(iv) If $\gamma \in [\gamma_{4A},\infty)$*, then* $\theta_A^* = \theta_{2A}$.

3.2.3 Optimal regulation policies
Comparing the minimum requirement regulation and subsidy policy under ambiguity, we have the following Proposition 6.

Proposition 6. The optimal government regulation under ambiguity depends on adaptation effectiveness γ *. Specifically, the optimal regulation policies under ambiguity are as follows:*
(i) If $\gamma \in [0,\gamma_{2A})$*, then no regulation is necessary;*
(ii) If $\gamma \in [\gamma_{2A},\gamma_{1A})$*, then the subsidy leads to the highest social welfare;*
(iii) If $\gamma \in [\gamma_{1A},\gamma_{3A})$*, then the optimal regulation policy can be a minimum requirement or subsidy. When* φ *is small enough, then the subsidy is better than the minimum requirement; and*
(v) If $\gamma \in [\gamma_{3A},\infty)$*, then the subsidy leads to the highest social welfare.*

It can be seen that the optimal regulation policies under ambiguity are qualitatively consistent with those under no ambiguity, except for different threshold values of γ. These threshold values are affected by the degree of pessimism α. We would like to examine how pessimism affects regulation policies and social welfare. The results are summarized in the following propositions.

Proposition 7. The increasing degree of pessimism makes (i) the regulation less necessary; (ii) the minimum requirement more likely to be used when $\gamma \in [\gamma_{1A},\gamma_{3A})$*;*

and (iii) the needed subsidy of each adaptation investment decreases if the subsidy policy is used.

The increasing degree of pessimism makes the government more conservative and favours port output reduction in regard to lowering the expected disaster loss. Because port adaptation is used to protect port output, the increasing degree of pessimism thus makes the government more reluctant to intervene in raising the level of port adaptation investment.

Previous discussions show that the subsidy policy is more proactive than the minimum requirement regulation because the former increases the port output and adaptation investment, whereas the latter reduces the port output. More pessimistic governments are inclined to use more conservative policies by reducing the port output to avoid disaster loss, which makes minimum requirement regulations more likely to be used. When the subsidy policy is preferred, the government's increased conservativeness is reflected by its reduced willingness to provide subsidies. Meanwhile, the ambiguity indicated by $\Delta\rho$ has an uncertain impact on the choice of optimal regulation, depending on whether $\Delta\rho$ is enlarged from the upper or lower limits.

3.3 Numerical analysis

This subsection conducts a numerical simulation to verify our theoretical results under ambiguity. More essentially, it is also aimed to examine the impact of regulation with ambiguity on the expected social welfare, which is hard to show analytically. This is to answer the questions whether the ambiguity would always harm the expected social welfare and whether the regulation would always benefit the expected social welfare in the presence of ambiguity.

To conduct the numerical simulation, the following set of parameter values are chosen as an example and guarantee the non-negativity of port output and price: $a = 10$, $b = 0.5$, $N = 2$, $D_H = 2$, $D_L = 1$, $\gamma \in (0,4]$, $\alpha \in [0,1]$, $\overline{\rho} = 0.7$, $\underline{\rho} = 0.3$, $\varphi = 0.8$. The port adaptation investment and output in the market equilibrium under ambiguity are illustrated in Figures 5 and 6, respectively. These numerical results are consistent with earlier theoretical analyses. As shown in Figure 5, a more pessimistic port is more likely to have full coverage such that they are more likely to increase their adaptation investment at a relatively lower level of adaptation effectiveness. The pessimism degree has no impact on adaptation investment when the port is fully covered. Moreover, when the adaptation effectiveness is low and ports are partially covered for large disaster losses, then an increase in the degree of pessimism can reduce the level of port adaptation because of the significant reduction in port output, as shown in Figure 6.

The optimal unit subsidy θ under ambiguity is illustrated in Figure 7. The subsidy amount first increases with adaptation effectiveness when it is relatively low. This is because ports have a lower incentive to self-protect, and the government needs to encourage ports to make adaptation investments and increase their output accordingly.

However, when the adaptation effectiveness is sufficiently high, the government reduces the subsidy because the ports have more incentives to self-invest in adaptation. Moreover, the subsidy is shown to decrease with a higher degree of pessimism (i.e., larger α) or more ambiguity of higher values of ρ (i.e., increasing the upper limit $\overline{\rho}$).[19]

Next, numerical simulations can be used to compute the "true" expected social welfare under ambiguity (without and with regulation). Such "true" expected social welfare under the ambiguity is calculated based on the optimal port output and adaptation decisions under ambiguity, while using the true disaster occurrence probability ρ (i.e. objective probability determined by nature, not a subjectively perceived value. This value is usually unknown to the researcher, but can be simulated in numeric analysis). That is, a higher "true" expected social welfare should benefit the society more, regardless the presence of ambiguity or not. Let $E(SW^{BA}|\rho)$ and $E(SW^{MA}|\rho)$ be the "true" expected social welfare with and without regulation, respectively, under ambiguity. They are calculated by incorporating the optimal port adaptation and output under ambiguity (i.e., I_i^{BA} and q_i^{BA}; I_i^{MA} and q_i^{MA}) into Eq. (3). The expected social welfares without ambiguity are $E(SW^B)$ and $E(SW^M)$, respectively, and have been calculated in Section 2.2 and 2.3. Two ratios are defined as follows:

$$\widetilde{\Lambda} = E(SW^{MA}|\rho)/\ E(SW^M)$$

and

$$\overline{\Lambda} = E(SW^{MA}|\rho)/E(SW^{BA}|\rho)$$

The ratio $\widetilde{\Lambda}$ demonstrates the impact of ambiguity on the "true" expected social welfare, when government does not intervene in port adaptation decisions. If $\widetilde{\Lambda} < 1$ (>1), the ambiguity would lead to worse (better) "true" expected social welfare. Figure 8 shows the numerical values of $\widetilde{\Lambda}$ with changing ρ by assuming different levels of pessimism degree α and adaptation effectiveness γ. It is clear that it is possible for $\widetilde{\Lambda} > 1$, such that the ambiguity actually helps improve social welfare. Whether ambiguity harms the "true" social welfare depends on "true" probability of disaster occurrence probability ρ. When ρ is small (or large, respectively), ambiguity leads to worse (or better, respectively) "true" expected social welfare. This is because, we have $\partial q_i^M/\partial\rho \le 0$ and $\partial I_i^M/\partial\rho \le 0$, $\partial q_i^{MA}/\partial\Omega \le 0$, $\partial I_i^{MA}/\partial\Omega \le 0$. As proved in Section 2, the socially optimal adaptation and output are larger than the market equilibrium without ambiguity. Under ambiguity, the ports make decisions based on a "mean" level of ρ, i.e., $\Omega = \alpha\overline{\rho} + (1-\alpha)\underline{\rho}$. When ρ is small (or large, respectively), the ambiguity exaggerates (or deflates) the "perceived" ρ (i.e., Ω) and thereby reduces (or increases) the port output and adaptation investment. This causes them to further deviate from (or converge to) the social optimum, such that the "true" social

[19] The numerical simulations in Figure 5, 6 and 7 mainly aim to better illustrate the theoretical results of Proposition 3 and Lemma 8. The patterns of the numerical results are determined by underlying modelling results, and do not change qualitatively if the chosen parameter values vary.

welfare under ambiguity is worse (or better) than without ambiguity. Therefore, the ambiguity is not necessarily harmful to the social welfare. When ρ is high, the ambiguity indeed makes the ports underestimate the disaster occurrence probability, thus preventing them to aggressively reduce port output and the corresponding adaptation. This would improve the "true" social welfare as a result. As shown in Figure 8, the value of $\widetilde{\Lambda}$ is also affected by α and γ, but they play a much minor role compared to ρ.[20]

In addition, the ratio $\overline{\Lambda}$ helps answer whether or not the regulation indeed improves the "true" expected social welfare under ambiguity. If $\overline{\Lambda} < 1$ (>1), the regulation would lead to better (worse) "true" expected social welfare. Figure 10 shows the numerical values of $\widetilde{\Lambda}$ with changing ρ by assuming different levels of pessimism degree α and adaptation effectiveness γ. It is clear that, the adaptation effectiveness γ plays a dominant role in determining the relative performance of regulation under ambiguity. Specifically, when γ is large (i.e., $\gamma = 1.5$), $\overline{\Lambda} < 1$ such that the regulation under ambiguity improves the "true" expected social welfare. However, when γ is small (i.e., $\gamma = 0.15$), $\overline{\Lambda} > 1$ such that the regulation under ambiguity harms the "true" expected social welfare relative to doing nothing. Sensitivity tests have also been conducted with more values of γ (not shown in Figure 9). It is found, when γ is smaller, the regulation under ambiguity is more likely to worsen, instead of improving the "true" expected social welfare than doing nothing. This is because, with small γ, the regulation under ambiguity would lead to a larger amount of subsidy, much more excessive than the "true" socially optimal adaptation. This costly adaptation investment would lower the "true" expected social welfare. This finding has important policy implications. The government should withhold any regulatory intervention in port adaptation investment, when the adaptation effectiveness is low and there is significant ambiguity in disaster's occurrence probability. Moreover, as shown in Figure 9, when γ is small (i.e., $\gamma = 0.15$), the regulation under ambiguity brings even worse "true" expected social welfare with an increasing ρ. This is because, under ambiguity, the government and ports make decisions based on a "mean" level of ρ, i.e., $\Omega = \alpha\bar{\rho} + (1-\alpha)\underline{\rho}$. When $\rho$is large, the ambiguity deflates the "perceived" ρ (i.e., Ω). Both the government and ports have incentive to increase port output and the corresponding adaptation, leading to more excessive adaptation compared to "true" socially optimal level.

Figure 10 is drawn to better summarize the observed impacts of ambiguity and regulation on the "true" expected social welfare. Specifically, without ambiguity, the regulation always improves the "true" expected social welfare. However, under ambiguity, the regulation could bring worse "true" expected social welfare than doing nothing. This happens when the adaptation effectiveness γ is small, such that regulation under ambiguity leads to more excessive adaptation investment than the "true" socially optimal level. Moreover, the ambiguity does not necessary result in poorer "true" expected social welfare, in absence of government regulation. When the

[20] Extensive sensitivity tests have been conducted with different parameter values. The findings suggested by Figure 8 are not qualitatively changed.

true disaster occurrence probability ρ is large, the ambiguity would make ports underestimate the disaster occurrence probability, thus increasing port output (and corresponding port adaptation). This would actually lead to higher "true" expected social welfare.

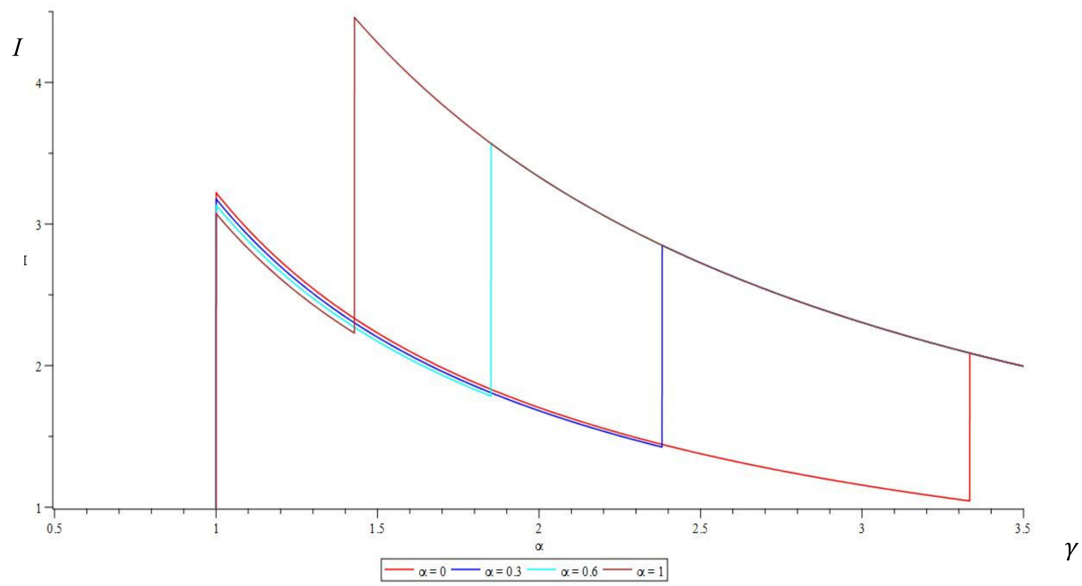

Figure 5 The adaptation investments in the market equilibrium under ambiguity

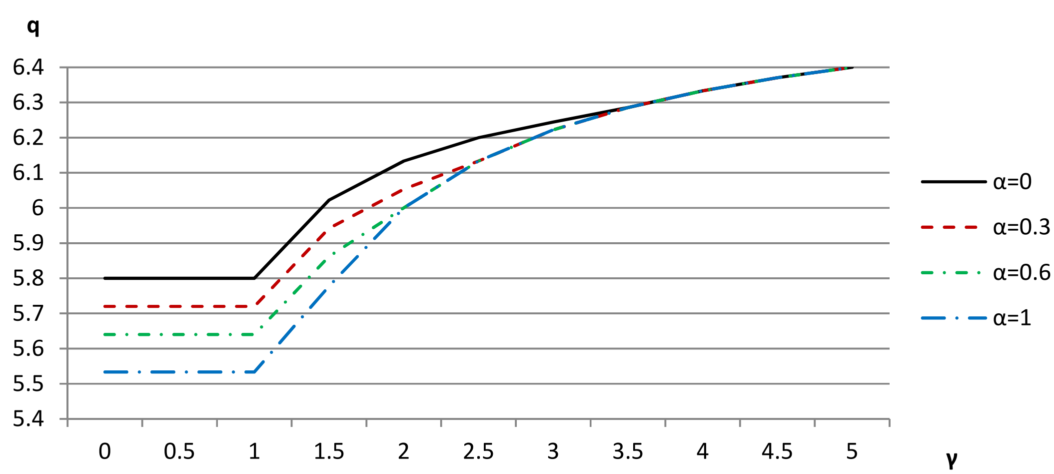

Figure 6 The outputs in the market equilibrium under ambiguity

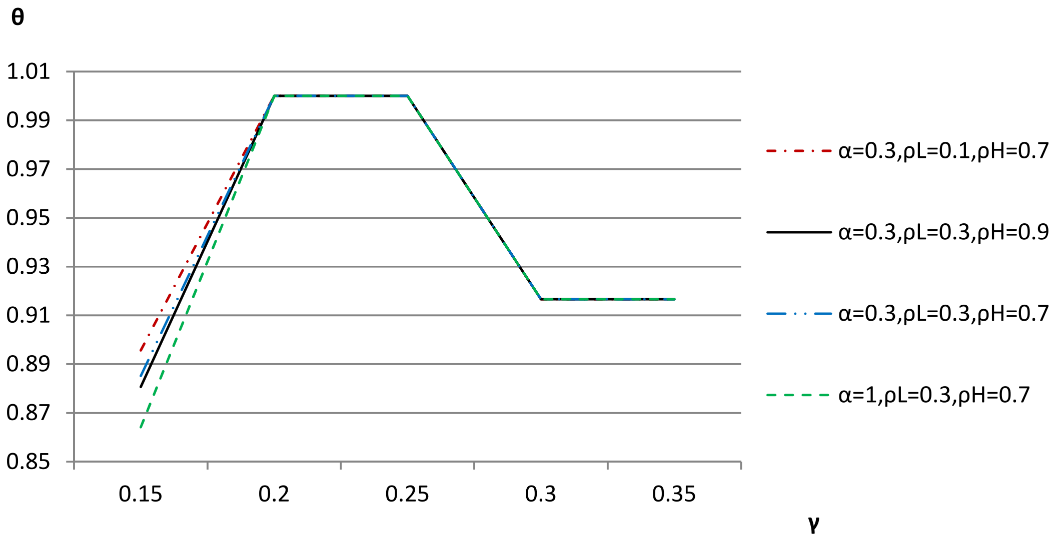

Figure 7 The adaptation investment subsidy under ambiguity

Note: When $0 \leq \gamma \leq 0.15$, then $\theta_A^* = 0$ for all cases. When $\gamma \geq 0.35$, then $\theta_A^* = 0.918$ for all cases. Therefore, we do not illustrate them.

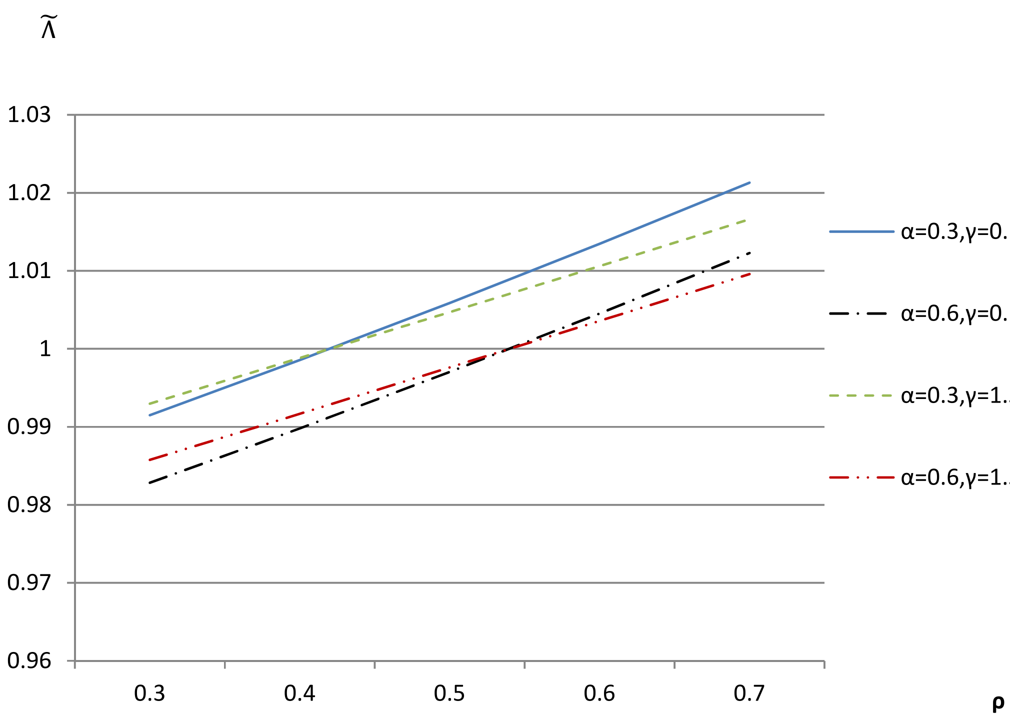

Figure 8 The "true" expected social welfare comparison under ambiguity and without ambiguity

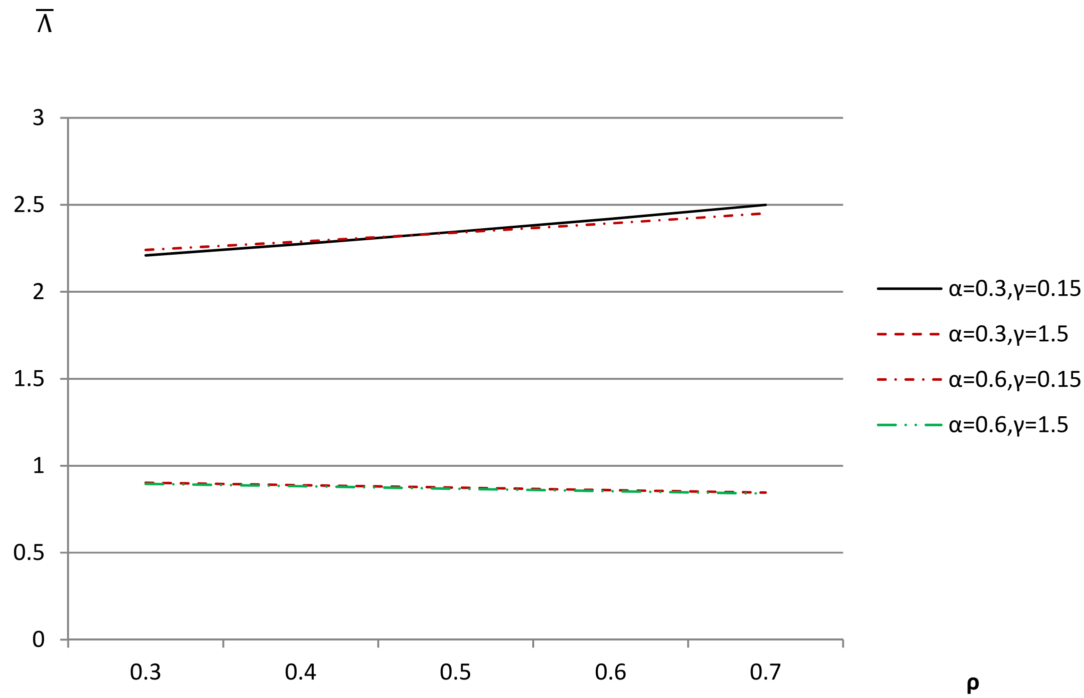

Figure 9 The "true" expected social welfare comparison with and without regulation under ambiguity

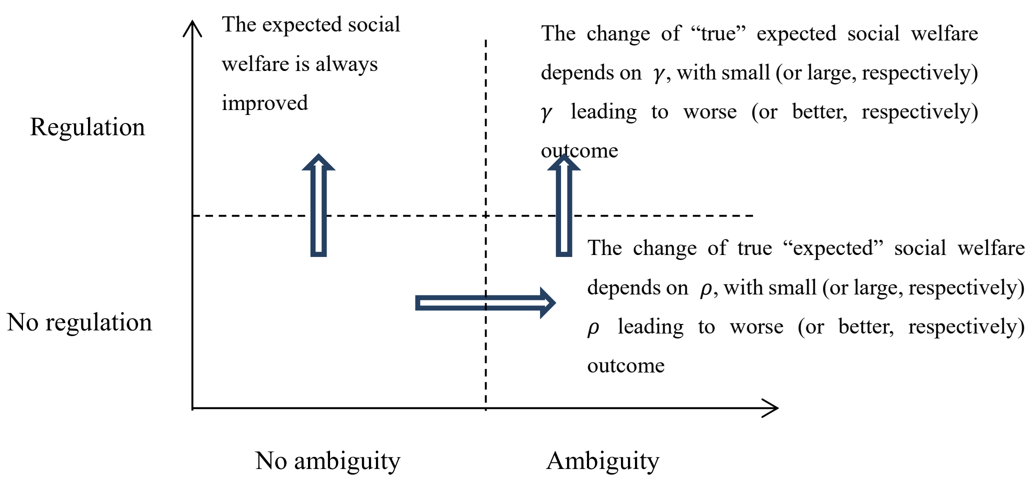

Figure 10 The impacts of ambiguity and regulation on the "true" expected social welfare

4. Conclusions

This paper develops an economic model to analytically examine the effects of regulation on ports' adaptation investment. Two commonly adopted policies, namely, a minimum requirement regulation and a subsidy policy, are examined and compared. To the best of our knowledge, this is the first study to formally benchmark the optimal conditions and performances between these two policies for port adaptation. The model also explicitly accounts for the ambiguity of the disaster occurrence probability and the spill-over externality of port adaptation across ports. The impacts of these policies on port output, adaptation investment and optimal policy options are discussed. All these features introduce new dimensions of port adaptation modelling and allow us to obtain fresh insights.

Specifically, the analytical results show that both a minimum requirement regulation and a subsidy policy promote port adaptation investment. However, under a minimum requirement regulation, ports balance the option of increasing their level of adaptation vs. reducing their economic activities. Such output reduction could harm social welfare, which makes subsidy policy more appealing. However, when adaptation effectiveness is intermediate (neither very low nor high) or when the spill-over externality on other ports is strong, then output reduction would be a less serious issue under the minimum requirement regulation, whereas a subsidy policy could be too proactive in the sense of excessive adaptation investment. These outcomes can make the minimum requirement regulation preferred. Without the ambiguity, the regulation helps improve the expected social welfare. The ambiguity of disaster will change the optimal designs of minimum requirement regulations and subsidy policies but will not change their relative rankings qualitatively. More risk-averse ports (i.e., those with a larger degree of pessimism) would reduce their outputs, although they are more likely to achieve full coverage. Thus, ports might increase their port adaptation despite their output reduction. A more risk-averse government is less likely to implement any regulatory policies. Our numerical simulations further demonstrate that the regulation under ambiguity could bring a lower "true" expected social welfare than doing nothing. On the other hand, when the "true" disaster occurrence is high, the ambiguity could lead to better "true" expected social welfare (i.e., calculated using the "true" disaster occurrence probability) than without ambiguity. Therefore, the effects of ambiguity could go either way. The government should withhold intervention when adaptation effectiveness is low in the presence of significant ambiguity.

This study is subject to some limitations while opening new avenues for future study. First, by adopting a subsidy policy, a government can face implicit costs (i.e., shadow price) by using public money, as the fund can be allocated to other sectors, such as education and health care, to improve wellbeing elsewhere. This implicit cost of a subsidy is not explicitly incorporated in the model. Intuitively, the inclusion of this cost would make the subsidy policy unfavourable *ceteris paribus* when compared with the minimum requirement regulation. However, the main conclusions should remain qualitatively unchanged. In addition, when disaster occurrence probability is ambiguous, we assume the port and the government have the same information (i.e., information symmetry) regarding such ambiguity and have similar risk attitudes. However, it is possible for one side to have better information, such that additional instruments/contracts can be designed to overcome such information asymmetry. These are additional issues that are meaningful for future investigations but are out of scope of the current paper.

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Appendix 1. Extension with Increasing Marginal Adaptation Investment Cost

In previous sections, to simplify the model derivations and draw clearer economic insights, we adopted constant marginal adaptation investment cost. However, many studies suggest that the ports can have increasing marginal adaptation investment cost (e.g., Wang and Zhang, 2018; Randrianarisoa and Zhang, 2019; Wang et al., 2020). Thus, in this appendix, we extend our model by relaxing the assumption of constant adaptation investment cost. This would help check the robustness of the above analytical results. Specifically, we follow the quadratic form to model adaptation investment cost same as Wang and Zhang (2018), $\omega I_i^2/2$. By replicating our analysis in Section 2, we have the following propositions.

Proposition 8. Let $H_1 = \sqrt{\dfrac{\omega D_L(a-E_D)}{b(N+1)[1+\varphi(N-1)]}}$, $H_2 = \sqrt{\dfrac{\omega D_L(a-\rho D_H)}{\rho b(N+1)[1+\varphi(N-1)]}}$, $H_3 = \sqrt{\dfrac{\omega D_H(a-\rho D_H)}{\rho b(N+1)[1+\varphi(N-1)]}}$. *Under the quadratic adaptation cost and the market equilibrium without regulation, each port's optimal adaptation investment and output are as follows:*

(i) If $\gamma \in [0, H_1)$, *then* $I_i^{MN} = \dfrac{\gamma}{\omega}$, $q_i^{MN} = \dfrac{a-E_D}{(N+1)b}$;

(ii) If $\gamma \in [H_1, H_2)$, *then* $I_i^{MN} = \dfrac{D_L q_i^{MN}}{\gamma[1+\varphi(N-1)]}$, $q_i^{MN} = \dfrac{\gamma^2[1+\varphi(N-1)][a-\rho(D_H-D_L)]}{b\gamma^2(N+1)[1+\varphi(N-1)]+\omega D_L^2}$;

(iii) If $\gamma \in [H_2, H_3)$, *then* $I_i^{MN} = \dfrac{\rho\gamma}{\omega}$, $q_i^{MN} = \dfrac{a-\rho D_H}{(N+1)b}$;

(vi) If $\gamma \in [H_3, \infty)$, *then* $I_i^{MN} = \dfrac{D_H q_i^{MN}}{\gamma[1+\varphi(N-1)]}$, $q_i^{MN} = \dfrac{a\gamma^2[1+\varphi(N-1)]}{b\gamma^2(N+1)[1+\varphi(N-1)]+\omega D_H^2}$.

The optimal adaptation investment and output under the quadratic investment cost are presented in Figure 11. Comparing Proposition 1 and 8, we find that the stepwise structures of the ports' outputs and adaptation investment still hold under increasing marginal adaptation investment cost. However, contrast to the corner solutions in the constant marginal cost case, there are both the interior solutions and the corner solutions under the quadratic adaptation cost. When $\gamma \in [0, H_1)$ and $\gamma \in [H_2, H_3)$, the interior solutions exist. The port will invest in port adaptation but the increasing level of adaptation investment (caused by the increasing investment effectiveness) is not enough to fully insure the low-level disaster and high-level disaster loss, respectively. Thus, the increasing port adaptation cannot promote the port outputs. When $\gamma \in [H_1, H_2)$ and $\gamma \in [H_3, \infty)$, the corner solutions exist and each port's adaptation investment can cover (at least the low-level) disaster loss, and can thus promote the port output.

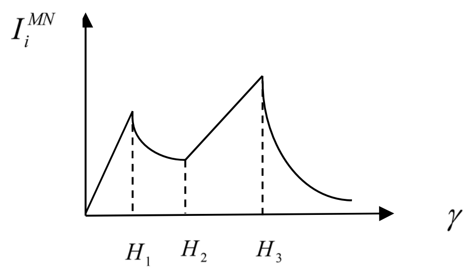

Figure 11a. The port's optimal adaptation investment under nonlinear investment cost

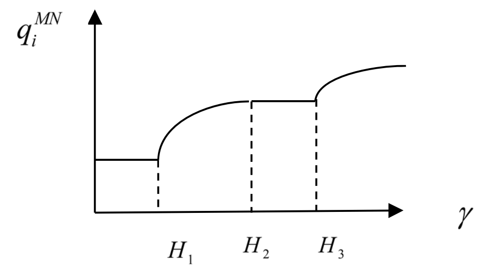

Figure 11b. The port's optimal output under nonlinear investment cost

Next we explore the socially optimal minimum requirement regulation and obtain the following lemma.

Lemma 9. The government's optimal minimum requirement regulation under the quadratic adaptation investment cost is described as follows:

(i) If $\gamma \in [0, H_3)$, *then* $L_{UN}^* = \dfrac{a\rho D_H[D_H^2 N\omega + b\gamma^2(2N^2 - N + 2 + \varphi(N^2 - 3N + 2))]}{b[bN\gamma^2(1+N)^2 + D_H^2\omega(3N-2)]}$;

(ii) If $\gamma \in [H_3, \infty)$, *then no minimum requirement regulation is necessary.*

Compared to the constant marginal adaptation cost case, two differences prevail. Under the quadratic cost assumption, the adaptation investment is always needed under both the market equilibrium and the social optimum. Therefore, unlike the case of the constant marginal adaptation cost, the minimum requirement regulation is always necessary although the investment effectiveness is small. Moreover, the most restrictive requirement may not be the optimal regulation choice because of the existence of the interior solutions. In the social optimum under the quadratic adaptation cost, the existence of interior solutions makes the social disaster loss larger than zero when no adaptation is installed. Thereby a positive minimum requirement regulation is still needed given very low adaptation investment effectiveness. Consistent with the constant marginal adaptation cost case, when adaptation effectiveness is sufficiently high, the port would have strong incentive to have full insurance coverage under both low-level and high-level disaster loss cases, making the minimum requirement regulation unnecessary. For the subsidy policy under the quadratic adaptation cost case, we have the following lemma.

Lemma 10. Let
$\theta_{1N} = (N-1)\varphi\gamma$,

$$\theta_{2N} = \frac{\gamma[a-\rho(D_H - D_L)][b(N^2-2N+2)(1+\varphi(N-1))^2\gamma^2 + D_L^2\omega\varphi N(N-1)]}{D_L[b(3N-2)(1+\varphi(N-1))^2\gamma^2 + D_L^2 N\omega]},$$

$$\theta_{3N} = [1-\rho+(N-1)\varphi]\gamma,$$

$$\theta_{4N} = \frac{a\gamma[b(N^2-2N+2)(1+\varphi(N-1))^2\gamma^2 + D_H^2\omega\varphi N(N-1)]}{D_H[b(3N-2)(1+\varphi(N-1))^2\gamma^2 + D_H^2 N\omega]},$$

$$\mathrm{K}_1 = \{\gamma \mid 0 \le \frac{\gamma(\theta_{1N}+\gamma)[1+\varphi(N-1)]}{\omega} \le \frac{D_L(a-E_D)}{b(N+1)}\},$$

$$\mathrm{K}_2 = \{\gamma \mid \frac{D_L(a-E_D)}{b(N+1)} \le \frac{\gamma(\theta_{2N}+\gamma)[1+\varphi(N-1)]}{\omega} \le \frac{D_L(a-\rho D_H)}{\rho b(N+1)}\},$$

$$\mathrm{K}_3 = \{\gamma \mid \frac{D_L(a-\rho D_H)}{\rho b(N+1)} \le \frac{\gamma(\theta_{3N}+\rho\gamma)[1+\varphi(N-1)]}{\omega} \le \frac{D_H(a-\rho D_H)}{\rho b(N+1)}\},$$

$$\mathrm{K}_4 = \{\gamma \mid \frac{D_H(a-\rho D_H)}{\rho b(N+1)} \le \frac{\gamma(\theta_{4N}+\rho\gamma)[1+\varphi(N-1)]}{\omega}\}.$$

The government's optimal subsidy under the quadratic adaptation investment cost is described as follows:
(i) If $\gamma \in K_i$*,then* $\theta_N^* = \theta_{iN}$, $\forall i = 1,2,3,4$*;*
(ii) If γ *belongs to the interval of the two adjacent areas, the optimal subsidy per adaptation investment can be one of the two adjacent* θ_N^**, whichever makes the social welfare larger.*

Comparison between this Lemma 10 and Lemma 4 in Section 2 indicates that the subsidy is always needed under the quadratic adaptation cost case. The reason is similar to the discussion of the minimum requirement regulation. In order to obtain the optimal regulation policy, we have to compare the social welfare under the optimal minimum requirement regulation and the subsidy policy. However, due to derivation complexity, it is difficult to summarize the comparison results straightforwardly. The results resemble Proposition 3 in Section 2, while the threshold values of adaptation effectiveness γ are very complicated expressions.

The analysis under the ambiguity also produces qualitatively similar conclusions as in Section 3, except that the optimal subsidy and minimum requirement regulation can be non-zero despite very low adaptation effectiveness. Thus, our main conclusions and insights have been proven to be robust with increasing marginal adaptation investment cost. The different adaptation investment cost structures only change the magnitude of the optimal adaptation investment, minimum requirement regulation and subsidy policy, but not the fundamental insights.

Appendix 2. Proposition Proofs

A.1 Proof of Proposition 1

When $\gamma \in [0,1)$, the sign of I_i in Eq.(2) is always negative. To maximize the objective function Eq.(2), I_i should reach its minimum, i.e., $I_i = 0$. Substituting this into Eq.(2) and maximizing it with respect to q_i, we impose the symmetry on $q_i, \forall i$, and obtain Part (i) of Proposition 1.

When $\gamma > 1$, the sign of I_i in Eq.(2) is always positive. To maximize the objective function Eq.(2), I_i should reach its maximum. When

$$\gamma I_i + \varphi\gamma \sum_{j \neq i}^{N} I_j = D_L q_i \quad (8),$$

we know that $D_H q_i > \gamma I_i + \varphi\gamma \sum_{j \neq i}^{N} I_j$ now. Then Eq.(2) becomes:

$$E(\pi_i) = (a - b\sum_{i=1}^{N} q_i)q_i - I_i - \rho(D_H q_i - \gamma I_i - \varphi\gamma \sum_{j \neq i}^{N} I_j)^+ \quad (9)$$

Substituting Eq.(8) into Eq.(9) and maximizing Eq.(9) with respect to q_i, we obtain $q_i^M = \frac{a-\rho(D_H-D_L)-D_L/\gamma}{(N+1)b}$. Then substituting this into Eq.(8) and imposing the symmetry on $I_i, \forall i$, we can prove Part (ii) of Proposition 1.

When $\gamma I_i + \varphi\gamma \sum_{j \neq i}^{N} I_j = D_H q_i$ (10),

we know that $D_L q_i < \gamma I_i + \varphi\gamma \sum_{j \neq i}^{N} I_j$ now. Then Eq.(2) becomes

$$E(\pi_i) = (a - b\sum_{i=1}^{N} q_i)q_i - I_i \quad (11)$$

Substituting Eq.(10) into Eq.(11) and maximizing Eq.(11) with respect to q_i, we still obtain $q_i^M = \frac{a-D_H/\gamma}{(N+1)b}$. Substituting this into Eq.(10) and imposing the symmetry on $I_i, \forall i$, we can prove Part (iii) of Proposition 1. □

A.2 Proof of Proposition 2

Maximizing the expected social welfare of Eq. (3) with respect to q_i and I_i, we obtain the socially optimal adaptation investment and port output under different γ, based on the similar logic as in the proof of Proposition 1. □

A.3 Lemma 1 (proof and discussions)

The impacts of γ and L_U on port adaptation and port output are as follows:

(i) If $\gamma \in [0,1)$,

when $L_U \in [\frac{E_D(a-E_D)}{(N+1)b}, \infty)$, *then each port's adaptation investment and output are the same as those in the case without regulation;*

when $L_U \in (\frac{\rho(D_H - D_L)(a - E_D/\gamma)}{(N+1)b}, \frac{E_D(a-E_D)}{(N+1)b}]$, *then* $I_i^R = \frac{E_D q_i^R - L_U}{\gamma[1+\varphi(N-1)]}$ *and*

$q_i^R = \frac{a - E_D/\gamma}{(N+1)b}$;

when $L_U \in [0, \frac{\rho(D_H - D_L)(a - E_D/\gamma)}{(N+1)b}]$ *, then* $I_i^R = \max\{\frac{D_H q_i^R - L_U/\rho}{\gamma[1+\varphi(N-1)]}, 0\}$ *and*

$q_i^R = \frac{a - D_H/\gamma}{(N+1)b}$.

(ii) If $\gamma \in [1, 1/\rho)$*,*

when $L_U \in [\frac{\rho(D_H - D_L)[a - \rho(D_H - D_L) - D_L/\gamma]}{(N+1)b}, \infty)$*, then each port's output and adaptation investment are the same as those in the case without regulation;*

when $L_U \in [0, \frac{\rho(D_H - D_L)[a - \rho(D_H - D_L) - D_L/\gamma]}{(N+1)b}]$*, then* $I_i^R = \max\{\frac{D_H q_i^R - L_U/\rho}{\gamma[1+\varphi(N-1)]}, 0\}$

and $q_i^R = \frac{a - D_H/\gamma}{(N+1)b}$.

(iii) If $\gamma \in [1/\rho, \infty)$*, then each port's output and adaptation investment are the same as those in the case without regulation.*

The proof is organized based on the different γ.

(i) When $\gamma \in [0,1)$, substituting q_i^M and I_i^M into the LHS of Eq.(4), we find that Eq.(4) can be satisfied if $L_U \geq \frac{E_D(a - E_D)}{(N+1)b}$. If $L_U < \frac{E_D(a - E_D)}{(N+1)b}$, Eq.(4) becomes constrained in the optimum. Substituting the constrained Eq.(4) into the objective function Eq.(2), we change the objective function as:

$$E(\pi_i) = (a - b\sum_{i=1}^{N} q_i) q_i - I_i - L_U \quad (12)$$

If $D_L q_i \geq \gamma I_i + \varphi\gamma \sum_{j \neq i}^{N} I_j$ (13),

the constrained Eq.(4) becomes:

$$E_D q_i - \gamma I_i - \varphi\gamma \sum_{j \neq i}^{N} I_j = L_U \quad (14)$$

Substituting Eq.(14) into Eq.(12) and maximizing it with respect to q_i, we obtain

$$q_i^R = \frac{a - E_D/\gamma}{(N+1)b} \quad (15)$$

Substituting Eq.(15) into Eq.(14) and imposing the symmetry, we obtain

$$I_i^R = \frac{E_D q_i^R - L_U}{\gamma[1+\varphi(N-1)]} \tag{16}$$

Substituting Eq.(15) and Eq.(16) into Eq.(13) to check it, we find the next inequality $L_U \geq \frac{\rho(D_H - D_L)(a - E_D / \gamma)}{(N+1)b}$ needs to be hold.

If $D_H q_i \geq \gamma I_i + \varphi\gamma \sum_{j \neq i}^{N} I_j > D_L q_i$ (17),

the constrained (4) becomes:

$$\rho(D_H q_i - \gamma I_i - \varphi\gamma \sum_{j \neq i}^{N} I_j) = L_U \tag{18}$$

Substituting (18) into (12) and maximizing it with respect to q_i, we obtain

$$q_i^R = \frac{a - D_H / \gamma}{(N+1)b} \tag{19}$$

Substituting Eq.(19) into Eq.(18) and imposing the symmetry, we obtain

$$I_i^R = \frac{D_H q_i^R - L_U / \rho}{\gamma[1+\varphi(N-1)]} \tag{20}$$

Substituting Eq.(19) and Eq.(20) into Eq.(17) to check it, we find the next inequality $L_U \leq \frac{\rho(D_H - D_L)(a - D_H/\gamma)}{(N+1)b}$ needs to hold. When $\frac{\rho(D_H - D_L)(a - D_H/\gamma)}{(N+1)b} < L_U \leq \frac{\rho(D_H - D_L)(a - E_D/\gamma)}{(N+1)b}$, $I_i^R = 0$.

(ii) When $\gamma \in [1, 1/\rho)$, substituting q_i^M and I_i^M into the LHS of (4), we find that (4) can be satisfied if $L_U \geq \frac{\rho(D_H - D_L)[a - \rho(D_H - D_L) - D_L/\gamma]}{(N+1)b}$. If $L_U < \frac{\rho(D_H - D_L)[a - \rho(D_H - D_L) - D_L/\gamma]}{(N+1)b}$, because $\gamma \geq 1$, I_i should reach its maximum to maximize the objective function Eq.(2), which makes the constrained Eq.(4) becoming Eq.(18). Substituting Eq.(18) into Eq.(12) and maximizing it with respect to q_i, we obtain Eq.(19) as well. Substituting Eq.(19) into Eq.(18) and imposing the symmetry, we obtain Eq.(20) too.

(iii) When $\gamma \in [1/\rho, \infty)$, the expected disaster loss in the market equilibrium is 0. Therefore, any minimum requirements can be satisfied. □

A.4 Proof of Lemma 2

(i) if $\gamma \in [0,1)$,

When $L_U \in (\frac{\rho(D_H - D_L)(a - E_D/\gamma)}{(N+1)b}, \frac{E_D(a-E_D)}{(N+1)b}]$, substituting Eq.(15) and Eq.(16) into the social welfare function Eq.(3), we have:

$$E(SW) = \frac{(a\gamma - E_D)[(a\gamma(1+(N-1)\varphi) - E_D)(2N^2 - N + 2) - \varphi E_D(3N-2)(N-1)]}{2b\gamma^2(1+N)^2(1+(N-1)\varphi)} + L_U N[\frac{1}{\gamma(1+(N-1)\varphi)} - 1] \quad (21)$$

It is known that if $\gamma > \frac{1}{1+(N-1)\varphi}$, maximizing Eq.(21) leads to $L_U^* = \frac{\rho(D_H - D_L)(a - E_D/\gamma)}{(N+1)b}$. Otherwise, $L_U^* = \frac{E_D(a-E_D)}{(N+1)b}$, which leads to the same outcomes as the market equilibrium, and thus no minimum requirement regulation is necessary.

When $L_U \in [0, \frac{\rho(D_H - D_L)(a - E_D/\gamma)}{(N+1)b}]$, substituting Eq.(19) and Eq.(20) into the social welfare function Eq.(3), we have:

$$E(SW) = \frac{(a\gamma - D_H)[(a\gamma(1+(N-1)\varphi) - D_H)(2N^2 - N + 2) - \varphi E_D(3N-2)(N-1)]}{2b\gamma^2(1+N)^2(1+(N-1)\varphi)} + L_U N[\frac{1}{\rho\gamma(1+(N-1)\varphi)} - 1] \quad (22)$$

It is known that if $\gamma > \frac{1}{\rho[1+(N-1)\varphi]}$, maximizing Eq.(22) leads to $L_U^* = 0$. Otherwise, $L_U^* = \frac{\rho(D_H - D_L)(a - E_D/\gamma)}{(N+1)b}$. Substituting $L_U^* = \frac{E_D(a-E_D)}{(N+1)b}$ into Eq.(21) and $L_U^* = 0$ into Eq.(22), and comparing them, we know that if $\gamma > \frac{1}{\rho[1+(N-1)\varphi]}$, $L_U^* = 0$ leads to the maximum $E(SW)$. Otherwise, no minimum requirement regulation is necessary.

(ii) When $\gamma \in [1, 1/\rho)$, substituting Eq.(19) and Eq.(20) into the social welfare function Eq.(3), we obtain the same form of $E(SW)$ as Eq.(22). Therefore, $L_U^* = 0$.

(iii) When $\gamma \in [1/\rho, \infty)$, from lemma 1 we know that no minimum requirement is necessary. □

A.5 Proof of Lemma 3

The proofs are based on the similar logic as in Lemma 1. □

A.6 Proof of Lemma 4

$$\gamma_2 = \frac{D_L N(N+1)}{\{(N^2 - 2N + 2)[a - \rho(D_H - D_L)] + D_L(3N-2)\}[1 + \varphi(N-1)]},$$

$$\gamma_3 = \frac{D_L N(N+1)}{[(N^2 - 2N + 2)(a - \rho D_H) + \rho D_L N(N+1)][1 + \varphi(N-1)]},$$

$$\gamma_4 = \frac{D_H N(N+1)}{[a(N^2-2N+2)+\rho D_H(3N-2)][1+\varphi(N-1)]},$$

$$\theta_1 = \min[\frac{[a-\rho(D_H-D_L)](N^2-2N+2)\gamma}{D_L(3N-2)} - \frac{N^2-2N+2-(3N^2-5N+2)\varphi}{(3N-2)[1+\varphi(N-1)]},1], \textit{ and}$$

$$\theta_2 = \min[\frac{a\gamma(N^2-2N+2)}{D_H(3N-2)} - \frac{N^2-2N+2-(3N^2-5N+2)\varphi}{(3N-2)[1+\varphi(N-1)]},1].$$

If $\gamma \in [1-\theta,(1-\theta)/\rho)$, Substituting I_i^B and q_i^B into the social welfare function Eq.(3), we have:

$$E(SW) = \frac{\begin{array}{c}[(a-\rho D_H)\gamma - D_L(1-\theta-\rho\gamma)][(a-\rho(D_H-D_L))(1+(N-1)\varphi)(2N^2-N+2)\gamma \\ -D_L(2N^2+\theta(3N-2)+2-N-(1-\theta)(3N-2)(N-1)\varphi)]\end{array}}{2b\gamma^2(1+N)^2(1+(N-1)\varphi)} \tag{23}$$

Maximizing Eq.(23) with respect to θ, we have:

$$\theta^* = \frac{[a-\rho(D_H-D_L)](N^2-2N+2)\gamma}{D_L(3N-2)} - \frac{N^2-2N+2-(3N^2-5N+2)\varphi}{(3N-2)[1+\varphi(N-1)]}$$

It can be proven that $\theta^* > 0$. Because $\theta \le 1$, we obtain θ_1. Because $1-\theta_1 \le \gamma < (1-\theta_1)/\rho$, solving this inequality we obtain $\gamma_1 \le \gamma < \gamma_2$.
If $\gamma \in [(1-\theta)/\rho),\infty)$, Substituting I_i^B and q_i^B into the social welfare function Eq.(3), we have:

$$E(SW) = \frac{\begin{array}{c}[a\gamma - D_H(1-\theta)][a\gamma(1+(N-1)\varphi)(2N^2-N+2) \\ -D_H(2N^2+\theta(3N-2)+2-N-(1-\theta)(3N-2)(N-1)\varphi)]\end{array}}{2b\gamma^2(1+N)^2(1+(N-1)\varphi)} \tag{24}$$

Maximizing Eq.(24) with respect to θ, we have:

$$\theta^* = \frac{a\gamma(N^2-2N+2)}{D_H(3N-2)} - \frac{N^2-2N+2-(3N^2-5N+2)\varphi}{(3N-2)[1+\varphi(N-1)]}.$$

It can be shown that $\theta^* > 0$. Because $\theta \le 1$, we obtain θ_2. Because $\gamma > (1-\theta_2)/\rho$, solving this inequality we obtain $\gamma \ge \gamma_3$. When $\gamma \in [\gamma_2,\gamma_3)$, θ^* can take the value of θ_1 or θ_2, depending on which one is larger between the following two: Eq.(23) with $\theta = \theta_1$ and Eq.(24) with $\theta = \theta_2$. □

A.7 Proof of Proposition 3

By calculation we find that $\gamma_1 > \gamma_2$, and combining Lemma 2 and 4 lead to the proof of (i) and (ii).

When $\gamma \in [\gamma_1,\gamma_3)$, $E[SW^B(\theta_1)] - E[SW^R(L_U^*)] = \frac{\Gamma}{2b\gamma^2(1+(N-1)\varphi)}$, where

$$\Gamma = \frac{N^2[(a-\rho(D_H - D_L))(1+(N-1)\varphi) - D_L]}{(3N-2)(1+(N-1)\varphi)} - \frac{(a\gamma - D_H)[a\gamma(1+(N-1)\varphi)(2N^2-N+2) - D_H(2N^2-N+2-(3N-2)(N-1)\varphi)]}{(1+N)^2}$$

. We know that $\frac{\partial^2 \Gamma}{\partial \varphi^2} = \frac{2(D_L N)^2 (N-1)^2}{(3N-2)(1+(N-1)\varphi)^3} > 0$. When $\varphi = 0$, $\Gamma > 0$. Therefore, there exits $\varphi' > 0$, and $\Gamma > 0$ when $\varphi < \varphi'$. This proves (ii).

When $\gamma \in [\gamma_3, \infty)$,

$$E[SW^B(\theta_2)] - E[SW^R(L_U^*)] = \frac{[a\gamma(1+(N-1)\varphi)(2N^2-N+2) - D_H(2(1-\varphi) + N^2(1-3\varphi) + N(5\varphi-2))]^2}{2b\gamma^2(3N-2)(1+N+(N^2-1)\varphi)^2} > 0$$

, which proves (iv).

□

A.8 Corollary 1 (proof and discussions)

Corollary 1. The effects of the externality of the port adaptation investment, as measured by φ*, on the regulation outcomes are summarized as follows:*

(i) A larger externality makes the regulation (i.e., subsidy) more necessary, i.e., $\partial\gamma_2/\partial\varphi < 0$.

(ii) A larger externality makes the minimum requirement more likely to be used when $\gamma \in [\gamma_1, \gamma_3)$. *Moreover, when the minimum requirement is used, a larger externality leads to a lower level of adaptation investment, while it has no impact on the port's outputs or the required minimum loss standard, i.e.,* $\partial I_i^R/\partial\varphi < 0$, $\partial q_i^R/\partial\varphi = 0$ *and* $\partial L_U^*/\partial\varphi = 0$.

(iii) When the subsidy is used, a larger externality leads to higher levels of subsidies and port outputs but lower levels of adaptation investment, i.e., $\partial\theta_1/\partial\varphi > 0$, $\partial\theta_2/\partial\varphi > 0$, $\partial q_i^B/\partial\varphi > 0$ *and* $\partial I_i^B/\partial\varphi < 0$.

Proof: (i) Based on Lemma 4, we obtain $\partial\gamma_2/\partial\varphi < 0$ through direct calculations.

(ii) Based on Lemma 1 and Lemma 2, we obtain $\partial I_i^R/\partial\varphi < 0$, $\partial q_i^R/\partial\varphi = 0$ *and* $\partial L_U^*/\partial\varphi = 0$ through direct calculations.

(iii) Based on Lemma 3 and Lemma 4, we obtain $\partial\theta_1/\partial\varphi > 0$, $\partial\theta_2/\partial\varphi > 0$, $\partial q_i^B/\partial\varphi > 0$ *and* $\partial I_i^B/\partial\varphi < 0$ through direct calculations. □

The explanation of Corollary 1(i) is as follows: a larger positive externality exaggerates the free riding behaviour of each port and thereby leads to lower levels of adaptation investment. This, therefore, calls for government regulation to remedy the more severe shortage of the adaptation investment caused by the larger φ. Corollary 1(ii) is also intuitive in that when the adaptation effectiveness is intermediate, a larger positive externality φ helps ports benefit from each other's adaptation, thus reducing their motivation to reduce their output. The ports also satisfy the minimum requirement without investing excessive adaptation compared to that of a subsidy policy. This makes the minimum requirement superior. From Lemma 2, we know that the most restrictive requirement $L_U^* = 0$ is always the optimal regulation choice if the minimum requirement is used. A change in the adaptation investment externality has no impact on the minimum standard or the port outputs. Last, for Corollary 1(iii), the government has to provide more subsidies to correct the more serious free-riding problem caused by larger positive externalities φ. The port output is also boosted as a result. The subsidy policy does not fully eliminate the free-riding problem, as the equilibrium port adaptation investment still decreases with φ.

A.9 Proof of Proposition 4

From Proposition 1 we know that

(1) When $\gamma \in [0,1)$, $I_i^M = 0$, $q_i^M = \frac{a-E_D}{(N+1)b}$. Substituting I_i^M and q_i^M into Eq.(2) and Eq.(3), we obtain $E(\pi_i) = \frac{(a-E_D)^2}{(N+1)^2 b}$ and $E(SW) = \frac{(a-E_D)^2(2N^2-N+2)}{2b(N+1)^2}$, respectively. Because $\frac{\partial E(\pi_i)}{\partial \rho} \leq 0$, and $\frac{\partial E(SW)}{\partial \rho} \leq 0$, we have $E(\pi_i) \to sup$ and $E(SW) \to sup$ when $\rho = \underline{\rho}$, and $E(\pi_i) \to inf$ and $E(SW) \to inf$ when $\rho = \bar{\rho}$.

(2) When $\gamma \in [1,1/\rho)$, $I_i^M = \frac{D_L q_i^M}{\gamma[1+\varphi(N-1)]}$, $q_i^M = \frac{a-\rho(D_H-D_L)-D_L/\gamma}{(N+1)b}$. Substituting I_i^M and q_i^M into Eq.(2) and Eq.(3), we obtain $E(\pi_i) = \frac{[(a-\rho(D_H-D_L))\gamma-D_L][(a-\rho(D_H-D_L))(1+\varphi(N-1))\gamma-D_L(1-\varphi N(N-1))]}{b\gamma^2(N+1)^2[1+\varphi(N-1)]}$ and $E(SW) = \frac{[(a-\rho(D_H-D_L))\gamma-D_L][(a-\rho(D_H-D_L))(2N^2-N+2)(1+\varphi(N-1))\gamma-D_L(2N^2-N+2+(3N-2)(N-1)\varphi)]}{2b\gamma^2(N+1)^2[1+\varphi(N-1)]}$, respectively. Because $\frac{\partial E(\pi_i)}{\partial \rho} \leq 0$, and $\frac{\partial E(SW)}{\partial \rho} \leq 0$, we have $E(\pi_i) \to sup$ and $E(SW) \to sup$ when $\rho = \underline{\rho}$, and $E(\pi_i) \to inf$ and $E(SW) \to inf$ when $\rho = \bar{\rho}$.

(3) When $\gamma \in [1/\rho, \infty)$, $I_i^M = \frac{D_H q_i}{\gamma[1+\varphi(N-1)]}$, $q_i^M = \frac{a-D_H/\gamma}{(N+1)b}$. It is easy to find that $\frac{\partial E(\pi_i)}{\partial \rho} = 0$, and $\frac{\partial E(SW)}{\partial \rho} = 0$.

To summarize these outcomes, we know that when $\rho = \bar{\rho}$ (or $\rho = \underline{\rho}$, respectively), $E(\pi_i)$ reaches its infinum (or supernum, respectively). Then using the similar logic as in the proof of Propostition 1, we can prove Proposition 4. □

A.10 Proof of Proposition 5

Based on Proposition 4 we obtain the following results through direct calculations:

(1) When $\gamma \in [0,1]$, $\partial q_i^{MA}/\partial\alpha < 0$, $\partial I_i^{MA}/\partial\alpha = 0$.

(2) When $\gamma \in [1,1/\Omega')$, $\partial q_i^{MA}/\partial\alpha < 0$ and $\partial I_i^{MA}/\partial\alpha < 0$.

(3) When $\gamma \in [1/\Omega', 1/\Omega)$, $q_i^{MA} = \frac{a-\Omega(D_H-D_L)-D_L/\gamma}{(N+1)b}$ and $I_i^{MA} = \frac{D_L q_i^{MA}}{\gamma[1+\varphi(N-1)]}$ before α increases, and $q_i^{MA} = \frac{a-D_H/\gamma}{(N+1)b}$ and $I_i^{MA} = \frac{D_H q_i^{MA}}{\gamma[1+\varphi(N-1)]}$ after α increases. Therefore, increasing α decreases q_i^{MA} while increases I_i^{MA}. Meanwhile,

(4) When $\gamma \in [1/\Omega, \infty)$, $\partial q_i^{MA}/\partial\alpha = 0$, $\partial I_i^{MA}/\partial\alpha = 0$. □

A.11 Proof of Corollary 2

Substituting I_i^{MA}, q_i^{MA} into Eq.(5) and I_i^{SA}, q_i^{SA} into Eq.(6), we know that $\partial E(\pi_i^{MA})/\partial\alpha \le 0$ and $E(SW^{SA})/\partial\alpha \le 0$. However, the signs of $\partial E(\pi_i^{MA})/\partial\Delta\rho$ and $E(SW^{SA})/\partial\Delta\rho$ depend on $\underline{\rho}$ and $\bar{\rho}$. Therefore, they are uncertain. □

A.12 Lemma 5 (discussions)

The impacts of γ and L_U on port adaptation and port output under the minimum requirement regulation and ambiguity are as follows:

(i) If $\gamma \in [0,1)$*,*

when $L_{UA} \in [\frac{\Phi_D(a-\Phi_D)}{(N+1)b}, \infty)$*, then each port's output and adaptation investment are the same as those in the case without regulation;*

when $L_{UA} \in [\frac{\Omega(D_H-D_L)(a-\Phi_D/\gamma)}{(N+1)b}, \frac{\Phi_D(a-\Phi_D)}{(N+1)b})$*, then* $I_i^{RA} = \frac{\Phi_D q_i^{RA} - L_{UA}}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^{RA} = \frac{a-\Phi_D/\gamma}{(N+1)b}$*; and*

when $L_{UA} \in [0, \frac{\Omega(D_H-D_L)(a-\Phi_D/\gamma)}{(N+1)b})$*, then* $I_i^{RA} = \frac{D_H q_i^{RA} - L_{UA}/\Omega}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^{RA} = \frac{a-D_H/\gamma}{(N+1)b}$*.*

(ii) If $\gamma \in [1,1/\Omega)$*,*

when $L_{UA} \in [\frac{\Omega(D_H-D_L)[a-\Omega(D_H-D_L)-D_L/\gamma]}{(N+1)b}, \infty)$*, then each port's output and adaptation investment are the same as those in the case without regulation; and*

when $L_{UA} \in [0, \frac{\Omega(D_H-D_L)[a-\Omega(D_H-D_L)-D_L/\gamma]}{(N+1)b})$*, then* $I_i^{RA} = \frac{D_H q_i^{RA} - L_{UA}/\Omega}{\gamma[1+\varphi(N-1)]}$ *and* $q_i^{RA} = \frac{a-D_H/\gamma}{(N+1)b}$*.*

(ii) If $\gamma \in [1/\Omega, \infty)$*, then each port's output and adaptation investment are the same as those in the case without regulation.*

A.13 The expression of $\gamma_{2A}, \gamma_{3A}, \gamma_{4A}, \theta_{1A}, \theta_{2A}$ in Lemma 8

$$\gamma_{2A}=\frac{D_L N(N+1)}{[(N^2-2N+2)(a-\Omega(D_H-D_L))+D_L(3N-2)][1+\varphi(N-1)]},$$

$$\gamma_{3A}=\frac{D_L N(N+1)}{[(N^2-2N+2)(a-\Omega D_H)+\Omega D_L N(N+1)][1+\varphi(N-1)]},$$

$$\gamma_{4A}=\frac{D_H N(N+1)}{[a(N^2-2N+2)+\Omega D_H(3N-2)][1+\varphi(N-1)]},$$

$$\theta_{1A}=\min[\frac{[a-\Omega(D_H-D_L)](N^2-2N+2)\gamma}{D_L(3N-2)}-\frac{N^2-2N+2-(3N^2-5N+2)\varphi}{(3N-2)[1+\varphi(N-1)]},1],\ and$$

$$\theta_{2A}=\min[\frac{a\gamma(N^2-2N+2)}{D_H(3N-2)}-\frac{N^2-2N+2-(3N^2-5N+2)\varphi}{(3N-2)[1+\varphi(N-1)]},1].$$

A.14 Proof of Lemma 5, 6, 7 and 8

Use the similar logic as in the proof of Lemmas 1, 2, 3 and 4. □

A.15 Proof of Proposition 6

Use the similar logic as in the proof of Proposition 3. □

A.16 Proof of Proposition 7

Because $\partial\gamma_{2A}/\partial\alpha > 0$, an increase in α leads to the shrink of the regulation area, which proves (i). When $\gamma \in [\gamma_{1A}, \gamma_{3A})$, $\frac{\partial E[SW^{RA}(L_U^*)]}{\partial \alpha} = 0$, $\frac{\partial E[SW^{BA}(\theta_{1A})]}{\partial \alpha} < 0$ and $\frac{\partial E[SW^{BA}(\theta_{2A})]}{\partial \alpha} = 0$. Therefore, the difference between $E(SW^{RA})$ and $E(SW^{BA})$ decreases, which proves (ii). $\partial\theta_{1A}/\partial\alpha < 0$ and $\partial\theta_{2A}/\partial\alpha = 0$, which proves (iii). □

A.17 Proof of Proposition 8

Under the nonlinear adaptation cost, Port *i*'s expected profit function is:

$$E(\pi_i)=Pq_i-\omega I_i^2/2-\rho(D_H q_i-\gamma I_i-\varphi\gamma\sum_{j\neq i}^{N}I_j)^+-(1-\rho)(D_L q_i-\gamma I_i-\varphi\gamma\sum_{j\neq i}^{N}I_j)^+ \quad (25)$$

If $D_L q_i \geq \gamma I_i + \varphi\gamma\sum_{j\neq i}^{N} I_j$ (26)

Eq.(25) becomes:

$$E(\pi_i)=Pq_i-\omega I_i^2/2-E_D q_i+\gamma I_i+\varphi\gamma\sum_{j\neq i}^{N}I_j \quad (27)$$

Its interior solution is $I_i^{MN}=\frac{\gamma}{\omega}$ and $q_i^{MN}=\frac{a-E_D}{(N+1)b}$. Substituting them into Eq.(26), we obtain the condition of the existence of the interior solution as $\gamma \in [0, H_1)$, which proves Part (i). Otherwise, the corner solution exists and the constraint Eq.(26) is binding. Substituting the binding Eq.(26) into Eq.(27), we obtain the corner solution and its existence condition as Part (ii).

If $\quad D_H q_i \geq \gamma I_i + \varphi\gamma \sum_{j \neq i}^{N} I_j > D_L q_i$ (28)

Eq.(25) becomes:

$$E(\pi_i) = Pq_i - \omega I_i^2 / 2 - \rho(D_H q_i - \gamma I_i - \varphi\gamma \sum_{j \neq i}^{N} I_j) \quad (29)$$

Its interior solution is $I_i^{MN} = \frac{\rho\gamma}{\omega}$ and $q_i^{MN} = \frac{a - \rho D_H}{(N+1)b}$. Substituting them into Eq.(28), we obtain the condition of the existence of the interior solution as $\gamma \in [H_2, H_3)$, which proves Part (iii). Otherwise, the corner solution exists and the constraint Eq.(28) is binding. Substituting the binding Eq.(28) into Eq.(29), we obtain the corner solution and its existence condition as Part (iv). □

A.18 Proof of Lemma 9 and 10

Use the similar logic as in the proof of Lemmas 1, 2, 3 and 4.