Chapter 4

Insights from recent economic modeling on port adaptation to climate change effects

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1 Introduction

Scientific studies suggest that climate change may have led, and will likely lead, to an increase in both the occurrence and the strength of weather-related natural disasters (e.g., Keohane and Victor, 2010; Min et al., 2011; IPCC, 2013). Seaports are, especially, highly vulnerable to disasters, such as hurricanes, strong wind, and heavy rainfall (Wang and Zhang, 2018). Just a very recent and prominent example is typhoon Mangkhut hitting South China in September 2018. It completely shut down the Port of Shenzhen and the Port of Hong Kong (the world's third and fifth largest container ports in 2018, respectively) for more than three days, and it took several more days for the terminal operators to resume normal operations. As a result, more than 200 containerships were considerably delayed for loading and unloading, and the economic losses were huge along the supply chain.[a]

As seaports are critical nodes in global supply chains, any major loss or degradation of port services would have significant "knock-on" effects on national/global supply chain performance and overall economy (OECD, 2016; Jiang et al., 2017). Understandably, seaports around the world are now increasingly aware of the climate change-related threats and seriously consider the associated adaptation investments (Becker et al., 2013; Ng et al., 2018a,b; Yang et al., 2018). For the last several years, port adaptation has also attracted increasing

a. Hong Kong, Shenzhen Port shut down for three days from September 14 to 16 when Mangkhut passed by (see the article in http://www.sofreight.com/news_27402.html). There are more than 200 containerships were adversely affected and delayed in loading and unloading (see the article in https://baijiahao.baidu.com/s?id=1611936695711743447&wfr=spider&for=pc).

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attention from the academic field. There have been empirical (and case-based) studies to evaluate a port's risk of the climate change-related disasters (e.g., Yang et al., 2018), existing and planned adaptation measures (e.g., Ng et al., 2018a; He et al., 2019), and the suggested coordination among stakeholders (e.g., Becker et al., 2013; Messner et al., 2015; Ng et al., 2018a,b). These empirical studies have contributed to a better understanding of the basic issues and challenges faced by ports in adapting to climate change-related disasters in practice.

Compared to the empirical studies, economic modeling of port adaptation is relatively rare but is fast developing. These theoretical studies are exemplified by the recent work of Xiao et al. (2015), Wang and Zhang (2018), Liu et al. (2018), Randrianarisoa and Zhang (2019), and Wang et al. (2019). They developed analytical frameworks by applying industrial organization and game theoretical models, which provide a good tool to analyze complicated strategic interactions among different stakeholders and factors present in port adaptation investment decisions. The factors considered include disaster's uncertainty, interport and intraport market structures, and shipping market demand characteristics.

This chapter provides a review of existing modeling work on port adaptation to climate change-related disasters. First, we summarize the major issues and factors considered in the existing economic models and describe the basic modeling approaches, accordingly. Second, we reconcile and discuss the findings of the current analytical work. On one hand, we attempt to sort out what the main results are, regardless of the different model assumptions and specifications. These consistent findings are meaningful for general managerial and policy implications. On the other hand, we examine the seemingly "inconsistent" findings among the studies, especially when models differ in setups or assumptions. This review aims to help the readers better understand the complicated nature of the port adaptation decision-making along with the potential drivers of the decisions. Finally, we propose some avenues for future theoretical research on port adaptation investment.

The rest of this chapter is organized as follows: Section 2 summarizes modeling frameworks of the existing theoretical work, and the factors considered. Section 3 discusses and compares the major analytical conclusions of these papers. Future research avenues are discussed in Section 4. Section 5 concludes this chapter.

2 Theoretical framework

As mentioned above, economic modeling of port adaptation is emerging. In this section we review several papers on port adaptation, namely, Xiao et al. (2015), Wang and Zhang (2018), Liu et al. (2018), Randrianarisoa and Zhang (2019), and Wang et al. (2019). In Section 2.1, we highlight the basic elements and issues incorporated in each of their economic models, since these studies focus on several different aspects of port adaptation investment decisions. This part is summarized in Table 1. In Section 2.2, we focus on the recent and representative analytical models of Wang and Zhang (2018) and Randrianarisoa and Zhang (2019).

TABLE 1 Summary of the main issues and factors considered in existing economic models

(a) The climate change-related disaster uncertainty

Paper	Disaster occurrence uncertainty	Investment efficiency	Investment period
Xiao et al. (2015)	Uniform distribution	Deterministic	Two-period (information accumulation)
Wang and Zhang (2018)	Knightian uncertainty	Deterministic	Single period
Liu et al. (2018)	Exponential function	Deterministic	Single period
Randrianarisoa and Zhang (2019)	Bernoulli trial/Knightian uncertainty	Stochastic	Two-period (information accumulation)
Wang et al. (2019)	Knightian uncertainty	Deterministic	Single period

(b) The port structure and decision dimensions

Paper	Port system	PA, TOC adaptation	PA, TOC pricing	PA interport cooperation	PA intraport cooperation	TOC market structure	PA ownership
Xiao et al. (2015)	Single port	Yes, yes	No, No	NA	Yes	No	Private and public
Wang and Zhang (2018)	Two-port	Yes, yes	Yes, Yes	Yes	Yes	No	Private and public
Liu et al. (2018)	Two-port	Yes, NA	No, NA	Yes	NA	NA	Private
Randrianarisoa and Zhang (2019)	Two-port	Yes, no	Yes, Yes	Yes	No	No	Private and public
Wang et al. (2019)	Two-port	Yes, no	Yes, Yes	Yes	No	Yes	Private

Note: PA stands for "port authority" and TOC stands for "terminal operator company."

2.1 Basic economic issues in existing modeling work

Port adaptation investments are affected by two broad set of factors, namely (i) the nature of the uncertainties regarding the climate change-related disaster per se, which includes, among others, storm surge, hurricane, flooding, increased precipitations, high wind, tidal surge, typhoon surge, cyclone, and earthquake, and (ii) the port market structure. Table 1(a) and (b) summarize the existing theoretical studies focusing on various specific factors regarding the disaster uncertainties and port market structure. First, disaster uncertainties may evolve dynamically such that ports have to decide when to invest, i.e., now or later. While early investment is beneficial for shippers and presents several economic advantages for the ports, there is an option value to wait for later adaptation investment, especially if better information can be accumulated. Second, as shown in Table 1(b), the existing theoretical models have been conducted for a single port or two-port system. Most of them have examined the pricing and adaptation investment decisions of landlord ports, the specific type consisting of a private or public port authority (PA), and private terminal operator companies (TOCs). Existing research has also analyzed cooperation between PA and TOCs within a single port, and cooperation across two ports, when making adaptation investment. Some frameworks have incorporated the TOC's intraport competition and interport relations. Next, in Sections 2.1.1 and 2.1.2, we review detailed modeling elements.

2.1.1 Uncertainties affecting port adaptation

Although the potential damage is severe, the uncertainties associated with the climate change-related disasters are still very high. Xiao et al. (2015), as the first analytical work on this topic, modeled disaster uncertainty in a two-period dynamic setting, assuming the disaster to be a Bernoulli trial. By definition, a Bernoulli trial is a random experiment with two possible outcomes: success and failure. In our context, success represents the occurrence of a disaster and failure indicates that the disaster does not happen. The disaster occurrence probability is uniformly distributed at both periods, but the probability in the second period is more accurate (i.e., more narrowly bounded uniform distribution) due to information learning. It implies that there is an option value in investing later with better information accumulation on the disaster occurrence probability.

Similar to Xiao et al. (2015), Randrianarisoa and Zhang (2019) adopted a two-period dynamic model, allowing port to invest in adaptation earlier or later. However, the uncertainty is assumed to be on the efficiency of port adaptation, instead of the disaster occurrence probability. It is noted that efficiency of port adaptation measures the return on investment in disaster prevention infrastructures—in terms of damage reduction—relative to the investment

b. The unit of measure can be percentage (%) or ratio. For instance, ports facing frequent inundation have three options in terms of adaptation: update storm defenses, elevate to compensate for projected sea levels, or relocate entirely. If the ports decide to invest in the second option, the efficiency of adaptation would be the return on the investment in elevation of some parts or the entire port facilities.

costs.[b] Over time, thanks to improved technology and better knowledge and planning of the adaptation projects, port adaptation is likely to be more efficient. Specifically, Randrianarisoa and Zhang (2019) assumed that the adaptation efficiency at later period stochastically dominates that in the earlier period. There is, thus, an option value to postpone port adaptation with higher expected efficiency of port adaptation investment. However, like Xiao et al. (2015), waiting may not always be optimal, especially when the disaster occurrence probability is high, exposing the port to no protection in early period.

Unlike Xiao et al. (2015), the work of Wang and Zhang (2018) and Wang et al. (2019) excluded dynamic choice of the ports in the timing to invest in adaptation. Instead, they focused on the degree of disaster uncertainty and its effect on the port adaptation. Specifically, Wang and Zhang (2018) first introduced the Knightian uncertainty (Knight, 1921) into the port adaptation modeling. This Knightian uncertainty assumes that the probability of a Bernoulli trial (disaster occurrence) is a random variable, with an expectation and variance. Knightian uncertainty has been well applied in economic decision and investment literature (Camerer and Weber, 1992; Nishimura and Ozaki, 2007; Gao and Driouchi, 2013), but it is the first time to be introduced to model climate change-related disaster uncertainty faced by ports. This concept is ideal for the port adaptation case, as it captures the existing great ambiguity on climate change-related disaster occurrence. Though scientists and port stakeholders try very hard to estimate the disaster occurrence probability, the prediction is always inaccurate and falls within a wide confidence interval, mainly due to our limited scientific knowledge. The Knightian uncertainty also captures the information accumulation on disaster occurrence probability by assuming the variance decreases over time. In Wang and Zhang (2018), to simplify the analysis, such variance totally disappears in later period, which is an extreme case of the information updating on disaster occurrence probability. But unlike Xiao et al. (2015) and Randrianarisoa and Zhang (2019), the port adaptation can only be made before information gaining. This is the major variation among these studies, causing seemingly contradictory conclusions (we will discuss in later section in detail).

Randrianarisoa and Zhang (2019) also considered Knightian uncertainty for the disaster occurrence probability and investigated how it would affect the model setup. Though they could not derive any explicit analytical results due to analytical tractability, they provided a framework for implementing simulation exercises and empirical analyses. Last, Liu et al. (2018) have considered neither dynamic period nor information gaining. They assumed a given disaster occurrence probability, with ports making adaptation investment in a single period.

To summarize, existing modeling has accounted for the major elements of the uncertainties on port adaptation decisions, such as option value in timing choice decision due to information accumulation, uncertainty of disaster occurrence probability and of efficiency of adaptation investment.

2.1.2 Port market structure

The port market structure could be complex depending on the port type, PA ownership, downstream TOC market, and interport and intraport competing or cooperative relationship. This leads to significant complexity when trying to capture the impact of port market structure on port adaptation investment decisions. Since it is extremely difficult to incorporate all these port market structural elements within one single model, existing studies chose to focus on the subset of these specific characteristics, as exhibited in Table 1(b). We discuss these major elements as follows:

- *Single or two-port system*

The first economic modeling work on port adaptation by Xiao et al. (2015) considered a single port. As their study is focused on the optimal timing of adaptation and intraport structure, the interport competition and cooperation are excluded. However, in real world, it is common to observe cluster of ports in one region competing or cooperating with each other. For example, in Pearl River Delta, Port of Hong Kong competes with Port of Shenzhen to be the gateway of South China; Hamburg-Le Havre (HLH) port ranges have several competing ports to be the gateways to West and North Europe; Port Authority of New York and New Jersey controls Port of Newark, Port of Perth Amboy and Port of New York, Georgia Port Authority controls Port of Savannah and Port of Brunswick on the East coast of the United States. These ports are likely to be exposed to a common disaster threat, leading to strategic interactions in port adaptation decisions.

Later theoretical studies extended to a two-port system, enabling to analyze interport competition and cooperation on the regional port adaptation investments. For example, Wang and Zhang (2018) explored the optimal adaptation levels when two ports cooperate and compete with each other. Wang et al. (2019) further recognized the joint venture (JV) of TOCs across two ports. With a dynamic investment setting, Randrianarisoa and Zhang (2019) modeled the asymmetric timing of port adaptation between two ports, i.e., one port invests early while the other late. Such equilibrium is compared to the cases of both investing in early or late period. While these studies assume that two ports' services are substitutable, Liu et al. (2018) considered the case of two ports with complementary services.

- *Intraport vertical structure*

Ports can be categorized into four types (Liu, 1992): service port, tool port, landlord port, and private port. A service port is characterized by a PA that is responsible for the provision of all port facilities. A tool port consists of a public PA that provides infrastructures and superstructures, while the provision of services is licensed to private operators. For a landlord port, the domain of the PA (public or private) is restricted to the provision of infrastructures, while investment in superstructures and port operations is the responsibility of licensed private companies. Finally, the provision of all the facilities and services of a private port is left to one single private entity. Xiao et al. (2015) and Wang and Zhang (2018) considered that the adaptation investments are made by the port authorities and port tenants, while Randrianarisoa and Zhang (2019) and Wang et al. (2019) focused on the case where the port authorities decide on the adaptation investments. In practice, the decisions on adaptation vary across ports. In some cases, the PAs fully support the costs of adaptation investments. This has been the case of Port of Boston's "Infrastructure Disaster Resiliency" project for 2016–20, which is entirely financed by Massport. In some other cases, collaboration between a wide range of public and private stakeholders is required. Becker et al. (2012) list the potential actors that can be involved in decision-making at different stages of adaptation planning. These actors, among others, are regulators, terminal operator companies, shippers, insurers, scientists, engineers, planners, and financers. The private/public stakeholders can also represent the federal, regional, and local government, city, port authorities, and nonprofit environmental and local organizations. For example, the adaptation project "Pier S Shoreline Protection: Seawall Retrofit" for Port of Long Beach to begin in 2020 is funded by the Port of Long Beach, Vopak (a private company that operates the chemical off load and storage facilities at the site), Nielson Beaumont Marine (the owner of the small boat marina), and the barge operators. Equivalently, the "Upgrade of Pavement Subgrade at Howland Hood Marine Terminal (part of the 2017 Sandy Program)" project at Port of New York New Jersey (NYNJ) was funded by insurance, federal public assistance, and PA of NYNJ.

With the exception of Liu et al. (2018) to study private ports, most theoretical papers have addressed the case of landlord ports, as the majority of ports around the world belong to this type (Cheon et al., 2010). A typical landlord port consists of an upstream PA (public or private) and downstream private TOCs. For example, PSA International, Hutchison Port Holding, APM terminals, DP World, and China Merchant Holding are the major TOC corporations operating worldwide. First, PA and TOCs have a vertical relationship in which the TOCs sign concession contracts with the PA to get access to the port basic infrastructures. TOCs, as tenants, own the superstructures of the port to handle the daily port operations and charge service fees to shipping companies/shippers (Trujillo and Nombela, 2000; De Monie, 2005; Notteboom, 2006). Second, PA is primarily responsible in investing in port adaptation, as it owns the basic port infrastructures and lands. Several adaptation measurements such as building breakwaters, storm barriers, and flood-control gates are not specific to particular terminal or berth (Becker et al., 2012); therefore adaptation investment has to been done by PA. TOCs might also be able to make adaptation investment specifically on their owned berth, terminals, and facilities, such as elevating terminal, upgrading the drainage system, and redesigning and retrofitting of the terminal facilities (Becker et al., 2012).

Thus, in principle, for a landlord port in the market, both PA and TOCs have two decision variables: pricing and adaptation investment. Since adaptation investment normally takes long time to plan and complete, while the port price is easy to adjust in a short term, the port pricing decisions could be conditional on port adaptation investment. This seems intuitive because a well-adapted port is able to charge a premium as their users are better protected against climate change-related disasters threat. In this way, the port pricing decisions are endogenized and linked with the port adaptation decisions.

Xiao et al. (2015) concentrated on the adaptation investment made by PA and TOCs by assuming exogenous port prices. Thus, the port strategic pricing behaviors and its impact on ex ante port adaptation investment cannot be analyzed. Recognizing this limitation, Wang and Zhang (2018) incorporated the pricing decisions of both PA and TOCs conditional on port adaptation investment in their setting. A vertical structure is imposed to model that the PA first decides on the concession fee to be charged to the downstream TOCs, and TOCs in turn decide the service charge to shipping companies/shippers. Wang and Zhang (2018) also allowed TOCs to invest in adaptation. Randrianarisoa and Zhang (2019) and Wang et al. (2019) are basically in the spirit of Wang and Zhang (2018) to endogenize port pricing decisions conditional on the port adaptation. However, these two models rule out the adaptation decisions by TOCs in order to guarantee model tractability.

- *Public or private port authorities*

For landlord port, one essential issue in existing theoretical model is PA's ownership. Public PA is assumed to maximize social welfare, and the private PA for its own profit. Normally, social welfare includes the profits of PA and TOCs, along with the shipper's surplus (Xiao et al., 2015; Wang and Zhang, 2018). As the adaptation investment decisions have to be made ex ante, the social welfare, profits, and shippers' surplus all refer to their expected values. As an important extension, Randrianarisoa and Zhang (2019) further considered the positive spill-over effect of port adaptation on the nearby communities and regional economy. Thus, the social welfare is extended to a larger social scope.

Section 2.1 summarizes the major issues and factors included in the existing economic models on port adaptation. In the next subsection, we review the representative modeling framework in detail. It helps explain more clearly how the economic issues are actually modeled. Moreover, with a basic economic model framework, we discuss possible feasible extensions to accommodate different economic issues as future research avenues.

2.2 Economic modeling

In this section, we introduce and discuss the economic model developed by Wang and Zhang (2018) upon which the models of Randrianarisoa and Zhang (2019) and Wang et al. (2019) are based on. While Xiao et al. (2015) is the first economic modeling work on port adaptation, Wang and Zhang (2018), Randrianarisoa and Zhang (2019), and Wang et al. (2019) have more rich factors being modeled. The model of Liu et al. (2018) is less sophisticated, without considering port pricing, intraport vertical structure, and investment timing issues. Thus, the extensions of the framework in Liu et al. (2018) are quite limited.

Wang and Zhang's (2018) model is divided into two parts, namely the operation stage with port pricing and the adaptation investment stage. Randrianarisoa and Zhang (2019) basically followed Wang and Zhang (2018) in the port pricing stage set-up conditional on port adaptation, while they extended the port adaptation investment stage to a two-period dynamic setup. By contrast, Wang et al. (2019) made extension only on the operation stage by considering more complicated structure in TOC market structure. Table 2 summarizes the notations and parameter definitions in the model of Wang and Zhang (2018).

Wang and Zhang (2018) considered a two-port region subject to a common disaster threat, as shown in Fig. 1. They examine the impacts of interport competition and cooperation between PAs and intraport cooperation between the PAs and TOCs on port adaptation. A multistage game is used to model both the adaptation investment stage and the operation stage conditional on the adaptation investments. The timeline of the model is given in Fig. 2. Wang and Zhang (2018) assumed the disaster to be a Bernoulli trial at the operation stage with occurrence probability x. The probability of disaster occurrence x is assumed to be ambiguous at the adaptation investment stage, which is a Knightian uncertainty.

TABLE 2 Notational glossary of the model parameters in Wang and Zhang (2018)

Parameter	Definition
V	Utility to shipper of using the port service
D	Disaster damage level to the shipper, and we assume $D<V$
η	Adaptation efficiency to reduce damage
t	Unit distance transport cost for the shipper to move cargo to the port
I_i^a	Adaptation investment made by port authority at port i
I_i^t	Adaptation investment made by TOC at port i
x	Random variable denoting probability of the disaster occurrence
Ω	Expectation of x at the adaptation investment stage
Σ	Variance of x at the adaptation investment stage
Ψ	Second moment of x, which is equal to $\Omega^2+\Sigma$
p_i	Service fee charged by TOC to shippers at port i
ϕ_i	Concession fee charged by port authority to TOC port i
Q_i	Demand for service at port i at the operation stage
Π_i	Profit of TOC at port i at operation stage
π_i	Profit of port authority at port i at operation stage

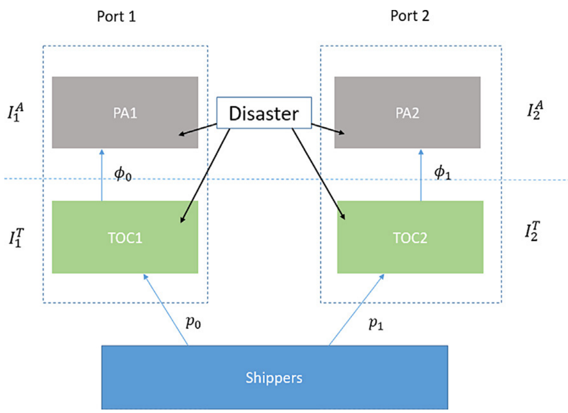

FIG. 1 The market structure of the two-port system in Wang and Zhang (2018).

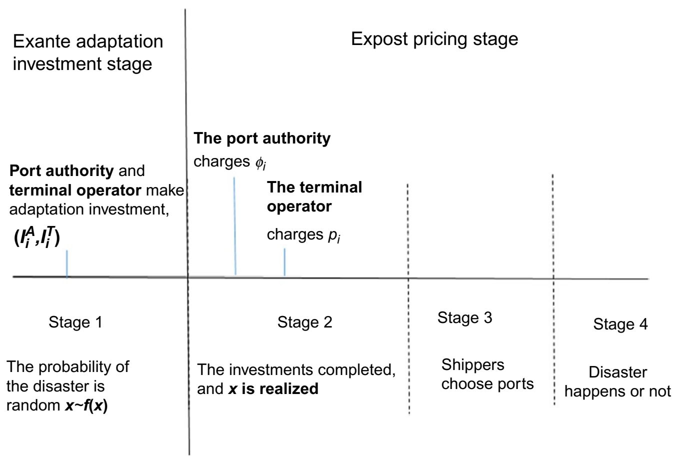

FIG. 2 The timeline of the decisions of different parties in Wang and Zhang (2018).

Knightian uncertainty implies that the disaster occurrence probability x can be a random variable at the adaptation investment stage, with a probability density function (pdf) $f(x)$, expectation Ω, and variance Σ. But this probability only becomes realized later at the operation stage when the ports decide the price and the shippers choose a port. This improvement in information reflects a relevant setting in which a better knowledge of climate change and related disasters is accumulated during the lengthy period of adaptation investment.

2.2.1 *Port demand and pricing decisions conditional on port adaptation*

At the operation stage, Wang and Zhang (2018) adopted an infinite linear city model to derive shippers' demand conditional on port service charges p_i and port adaptation investments $\{I_i^a, I_i^t\}$ in response to disaster occurrence probabil-

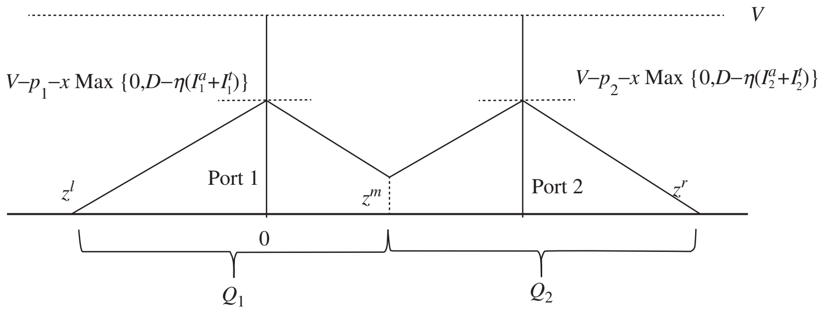

FIG. 3 Shipper's utility at each port after completion of adaptation investments in Wang and Zhang (2018).

ity x, where I_i^a is the adaptation by PA and I_i^t by TOC. This demand function has also been inherited by Randrianarisoa and Zhang (2019) and Wang et al. (2019). The infinite linear city model is demonstrated in Fig. 3.

The value to a shipper of using the port service, denoted by V, is exogenously given. Shippers who are the owners of cargo to be shipped to the destination choose which port to use before observing if the disaster occurs or not. If the disaster occurs, shippers will incur damage $D-\eta(I_i^a+I_i^t)$, where D is the damage level without any port adaptation, and $\eta(I_i^a+I_i^t)$ is the reduction of damage owing to port adaptation investments. η measures the adaptation efficiency to mitigate damage when the disaster occurs. The disaster damage to shippers can include the cargo damage and inventory delay cost. If the disaster does not occur, the shippers do not incur any cargo damage. With disaster occurrence probability x, the expected damage incurred by the shippers is $x\text{Max}\,\{0,D-\eta(I_i^a+I_i^t)\}$.

Shippers are assumed to be uniformly distributed along the linear city with density 1. Each shipper incurs a cost per unit distance, denoted by t, to transport cargo from its location to the port. This transport cost can also capture any horizontal differentiation (service homogeneity) of two ports' services perceived by the shippers. Shippers choose which port to use, and directly pay the service price to TOC. TOC, in turn, pays a concession fee to PA in exchange for the use of the port lands and basic infrastructures. The port charging thus takes place in a vertical structure: PA chooses its concession fee, ϕ_i, on TOC first, and then TOC chooses service charge, p_i, on shippers.

For a shipper located at point z in the two ports' common hinterland, the utility of using port 1 is $V-p_1-zt-x\text{Max}\,\{0,D-\eta(I_1^a+I_1^t)\}$, and the utility of using port 2 is $V-p_2-(1-zt)-x\text{Max}\,\{0,D-\eta(I_2^a+I_2^t)\}$. For a shipper located at point z in port 1's captive hinterland, the utility is $V-p_1-|z|t-x\text{Max}\,\{0, D-\eta(I_1^a+I_1^t)\}$, and for a shipper located at point z in port 2's own hinterland, the utility is $V-p_2-(z-1)t-x\text{Max}\,\{0,D-\eta(I_2^a+I_2^t)\}$. We can therefore derive the locations of the marginal shipper (i) who is indifferent between using port 1's service and not using the port service at all, denoted by z^l; (ii) the one who is indifferent between using port 2's service and not using the port services, denoted by z^r; and (iii) the one who is indifferent between using port 1 and port 2's service, denoted by z^m. The locations are given by

$$|z^l| = \frac{V - p_1 - x\,\mathrm{Max}\left\{0, D - \eta\left(I_1^a + I_1^t\right)\right\}}{t}; \tag{1a}$$

$$z^r = 1 + \frac{V - p_2 - x\,\mathrm{Max}\left\{0, D - \eta\left(I_2^a + I_2^t\right)\right\}}{t}; \tag{1b}$$

$$z^m = \frac{1}{2} + \frac{p_2 - p_1 - x\,\mathrm{Max}\left\{0, D - \eta\left(I_1^a + I_1^t\right)\right\} + x\,\mathrm{Max}\left\{0, D - \eta\left(I_2^a + I_2^t\right)\right\}}{2t}. \tag{1c}$$

The demand at the operation stage is $Q_1(p) = |z^l| + z^m$ for port 1 and $Q_2(p) = (1 - z^m) + (z^r - 1)$ for port 2. That is

$$Q_i(p) = \frac{1}{2} + \frac{2V + p_j - 3p_i + x\,\mathrm{Max}\left\{0, D - \eta\left(I_j^a + I_j^t\right)\right\} - 3x\,\mathrm{Max}\left\{0, D - \eta\left(I_i^a + I_i^t\right)\right\}}{2t}, \tag{2}$$

where $i = 1, 2$. With the above shipper demand function, private TOCs maximize profits Π_i conditional on the port adaptation and the concession fee charged by PA. That is

$$\mathrm{Max}\,\Pi_{i\,p_i} = \left(p_i - \phi_i\right) Q_i \tag{3}$$

where

$$\begin{aligned} p_i\left(\phi_i, \phi_j\right) = {} & 0.2[(2V + t) + 2.57\phi_i + 0.42\phi_j - 2.43x\,\mathrm{Max}\{0, D - \eta(I_i^a + I_i^t)\} \\ & + 0.42\,\mathrm{Max}\{0, D - \eta(I_j^a + I_j^t)\}]. \end{aligned} \tag{4}$$

The port authorities in turn maximize their profits, π_i, if they are privately owned, and regional social welfare if they are public. The social welfare is the sum of consumer surplus, *CS*, which represents the shippers' benefits arising from the utilization of the port facilities, TOC profits, π_i, and PA profits, Π_i. It is noted that this social welfare does not account for any positive externality of shipping activities on general economy, while considering it will not change all the analytical conclusions qualitatively. The PA profits and regional social welfare are specified as follows:

$$\pi_i = \phi_i Q_i\left(p_i\left(\phi_i, \phi_j\right), p_j\left(\phi_i, \phi_j\right)\right) \tag{5}$$

$$\begin{aligned} CS = {} & \int_0^{|z^l|} [V - p_1 - x\,\mathrm{Max}\{0, D - \eta(I_1^a + I_1^t)\} - z\,t]\,dz \\ & + \int_0^{z^m} [V - p_1 - x\,\mathrm{Max}\{0, D - \eta(I_1^a + I_1^t)\} - z\,t]\,dz \\ & + \int_{z^m}^{1} [V - p_2 - x\,\mathrm{Max}\{0, D - \eta(I_2^a + I_2^t)\} - (1 - z)\,t]\,dz \\ & + \int_1^{z^r} [V - p_2 - x\,\mathrm{Max}\{0, D - \eta(I_2^a + I_2^t)\} - (z - 1)\,t]\,dz. \end{aligned} \tag{6}$$

One notable feature of this infinite linear city shipper demand is the parameter t, capturing the intensity of interport competition (or service heterogeneity). As can be seen later, we are able to shed light on its impact on port adaptation investment.

Based on the above setup, Randrianarisoa and Zhang (2019), and Wang et al. (2019) made some changes to incorporate new elements.

- *Random adaptation efficiency by* Randrianarisoa and Zhang (2019)

Unlike Wang and Zhang (2018), who modeled disaster occurrence probability as a random variable (Knightian uncertainty), Randrianarisoa and Zhang (2019) considered a random adaptation efficiency parameter η in the shipper demand function. Specifically, they modeled η as a random variable that is distributed over the positive support $[0, \eta_{max}]$, with probability density function, $g(\eta)$ and cumulative density function $G(\eta)$. Furthermore, they built up a two-period dynamic model which assumes information updating on adaptation efficiency over time. This can be achieved with the technology and knowledge development, along with better planning and cooperation among different stakeholders of the port over time. To capture this efficiency improvement mathematically, the distribution of η in the later period is assumed to first-degree stochastically dominate that in the earlier period. In other words, the investment efficiency remains a random variable with same distribution functions over the two periods, but its observed values in the second period are higher. It implies that on average, efficiency of investment in the second period is higher than that in the first period.[c]

- *Terminal operator market structure by* Wang et al. (2019)

Most of the modeling work assumed a single TOC within one port. This greatly simplifies the model setup and derivation (Xiao et al., 2015; Wang and Zhang, 2018; Randrianarisoa and Zhang, 2019). However, one prominent feature of port market structure is that multiple TOCs may be present at one port. These TOCs may be operated by several independent companies. For example, PSA International, Hutchison Port Holding (HIT), APM terminals, DP World, and China Merchants Holding are the major TOC companies in the world. Not only do they actively compete with each other at many container ports (i.e., intraport competition of TOCs) but also they may compete across nearby ports for shippers in the common hinterland (interport competition of TOCs). In addition, the same TOC may be present at two nearby ports at the same time, thus forming an interport JV. Such market structure of intra- and interport TOC competition and JV can be well exemplified by Hong Kong Port and Shenzhen Port. Hong Kong Port has nine major container terminals, where Modern Terminal Limited (MTL) operates in four of them, HIT in four, HIT and COSCO jointly in one, DP World in one, and ACT in one. These TOCs compete with each other within Hong Kong Port. Meanwhile, MTL also invests in Shekou and

c. In their simulation exercise, Randrianarisoa and Zhang (2019) assumed that in the first period, investment efficiency follows log normal distribution with a mean of 0.2% and standard deviation of 0.1%. In the second period, efficiency follows the same distribution but with a higher mean of 1.2%.

Dachaiwan terminals, the major terminals of Shenzhen Port, and HIT operates another major terminal, Yantian terminal, in Shenzhen Port. Thus, these TOCs can coordinate their operations in Hong Kong Port and Shenzhen Port through the common ownership (joint venture).

Wang et al. (2019) extended the existing economic models, especially Wang and Zhang (2018), to formally examine the impact of the TOC market structure on port adaptation. The two-port structure is now revised compared to that of Wang and Zhang (2018) in Fig. 1, as shown in Fig. 4. Their study assumed a number N of TOCs at each port.

The profit of one TOC, denoted by $\pi_{r,i}$, where subscript $i \in \{1,2\}$ stands for the port, and $r \in \{1,2,\ldots,N\}$ stands for the TOCs at one port, is given by

$$\pi_{r,i} = \left(p_i(Q_1,Q_2|I_1,I_2) - \phi_i\right)q_{r,i}, \text{where } i = 1,2. \quad (7)$$

Wang et al. (2019) assumed quantity competition among TOCs (i.e., Cournot competition). Under a Cournot competition, the TOCs simultaneously decide on the amount of output they produce in a specific period so as to maximize their own profits. Then, given the amount of output, they set the service prices to be charged to the shippers. As observed in real business world, TOCs across the ports could be independent and compete with each other, or the same TOC may operate in two ports at the same time. If TOCs across ports compete independently, the first-order condition (FOC) for the TOC by choosing optimal quantity $q_{r,i}$ is

$$V - \phi_i - x\max\{0, D - I_i\} - \frac{t}{4}\left(3Q_i + Q_j - 2\right) - \frac{3t}{4}q_{r,i} = 0. \quad (8)$$

If the TOCs have joint venture across the ports, they maximize a joint profit, $\pi_{r,i} + \pi_{r,j}$, given by

$$\pi_{r,i} + \pi_{r,j} = (p_i(Q_1,Q_2|I_1,I_2) - \phi)q_{r,i} + (p_j(Q_1,Q_2|I_1,I_2) - \phi_j)q_{r,j} \quad (9)$$

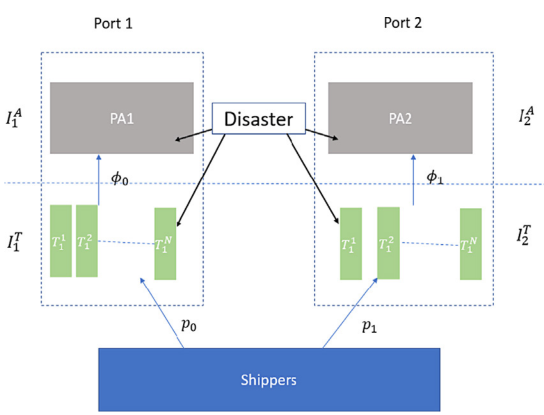

FIG. 4 Market structure of the two-port and multiple-operator system in Wang et al. (2019).

The FOCs for the TOC by simultaneously choosing optimal $q_{r,i}$ and $q_{r,j}$ are

$$V-\phi_i - x\max\{0, D-I_i\} - \frac{t}{4}(3Q_i + Q_j - 2) - \frac{3t}{4}q_{r,i} - \frac{t}{4}q_{r,j} = 0, \quad (10)$$

$$V-\phi_j - x\max\{0, D-I_j\} - \frac{t}{4}(3Q_j + Q_i - 2) - \frac{3t}{4}q_{r,j} - \frac{t}{4}q_{r,i} = 0. \quad (11)$$

Since the rest of the model derivations are analogous to Wang and Zhang (2018), we only present the crucial equations in this section. Moreover, with the current setting, we are able to generate new insights on how the TOC market structure affects port adaptation investment decisions.

2.2.2 Port adaptation investment

Existing economic models vary significantly in their treatment of disaster uncertainties and timing of adaptation investment. We have summarized this in Section 2.1. Wang and Zhang (2018) and Wang et al. (2019) assumed Knightian uncertainty of disaster occurrence probability, and this probability can be updated over time. But the adaptation investment is made at one single period. Randrianarisoa and Zhang's (2019) analysis, however, is based on a two-period dynamic setup and is focused on the timing of adaptation (earlier vs later period), with an information accumulation on the adaptation efficiency. They also considered how the assumed Knightian uncertainty for the disaster occurrence probability affects the modeling framework, thereby the main insights from the model. As these two frameworks [Wang and Zhang (2018) vs Randrianarisoa and Zhang (2019)] represent two different aspects of disaster or adaptation uncertainties, in this subsection, we review the detailed modeling approaches for port adaptation investment in both studies.

- *Knightian uncertainty in port disaster occurrence probability*

Wang and Zhang (2018) modeled a Knightian uncertain disaster occurrence probability such that PA and TOC of the two ports have to decide adaptation ex ante without any information updating on the disaster occurrence probability. Thus, the PAs maximize the expected profits or expected social welfare, depending on their ownership, and the TOCs, as private entity, maximize expected profits. The expected profits for private PAs at the investment stage are $E[\pi_i] = [\int \pi_i f(x)dx] - 0.5\omega I_i^{a2}$, and the expected profits for the terminal operators are $E[\Pi_i] = [\int \Pi_i f(x)dx] - 0.50\omega I_i^{t2}$. The expected social welfare for public PAs is $E[SW_i] = [\int SW_i f(x)dx] - 0.5\omega I_i^{a2}$. Constraint $\eta(I_i^a + I_i^t) \le D$ must be imposed since ports cannot adapt beyond the maximum disaster damage level D. Therefore, we have: $\text{Max}_{I_i^a}\ E[\pi_i], \text{st.}\ \eta(I_i^a + I_i^t) \le D$ and $\text{Max}_{I_i^t}\ E[\Pi_i], \text{st.}\ \eta(I_i^a + I_i^t) \le D$. Here, we assume an increasing marginal adaptation investment cost with a quadratic function, $0.5\omega I_i^{a2}$ and $0.50\omega I_i^{t2}$, where superscripts a and t stand for PA and TOC, respectively (see Table 2 for reference on the parameter definition).

Wang and Zhang (2018) also modeled different interport and intraport competition and cooperation cases for private and public PAs. Specifically, the two ports can compete with each other in port adaptation such that two PAs maximize their own expected profits or regional social welfare as follows: $\text{Max}_{I_i^a} E[\pi_i]$, st. $\eta(I_i^{\,a}+I_i^{\,t})\leq D$ or $\text{Max}_{I_i^a} E[SW]$, st. $\eta(I_i^{\,a}+I_i^{\,t})\leq D$. Alternatively, the two ports can cooperate (the monopoly) so as to maximize a joint expected profit or total social welfare. That is: $\text{Max}_{I_i^a,I_j^a} E[\pi_i+\pi_j]$, st. $\eta(I_i^{\,a}+I_i^{\,t})\leq D$ or $\text{Max}_{I_i^a,I_j^a} E[SW_i+SW_j]$, st. $\eta(I_i^{\,a}+I_i^{\,t})\leq D$. They also considered intraport coordination in port adaptation by PA and TOC within the same port. In this case, the maximization problem is: $\text{Max}_{I_i^a,I_i^t} E[\pi_i+\Pi_i]$, s. t. $\eta(I_i^{\,a}+I_i^{\,t})\leq D$ or $\text{Max}_{I_i^a,I_i^t} E[SW_i]$, s. t. $\eta(I_i^{\,a}+I_i^{\,t})\leq D$.

- *Option value of adaptation timing*

Randrianarisoa and Zhang (2019) adopted a two-period dynamic setting, incorporating the PA's decision on adaptation timing (i.e., earlier vs later). An option value exists such that investing later is associated with better adaptation efficiency thanks to information accumulation and better cooperation among stakeholders. But this delay in adaptation would leave the port exposed to no protection in the first period, bringing high disaster damage risk for shippers. PA's objective function is highlighted as $\text{Max}_{\boldsymbol{I},\boldsymbol{q}^i,\boldsymbol{q}^{ii}} W_j = W_j^i + kW_j^{ii}$, where $W_j^T=\pi_j^T+\alpha(\Pi_j^T+CS_j^T)$ denotes total welfare of port $j=1, 2$ at period T, π_j^T the PA profits, $\Pi_j^T$the TOC profits, and CS_j^Tconsumer surplus. The two periods are represented with the superscripts i and ii, respectively.

The weighted objective function W_j, introduced by the authors, combines PA's own profit with a share of TOC's profit and shipper's surplus. The share is captured by the parameter α. Therefore, when α is larger (smaller) and close to 1 (to zero), PA resembles more to a public entity (private entity) which maximizes social welfare (profits). It is noted that the two PAs must decide which period to install the adaptation facilities, at either period i or period ii, together with the specific investment levels, captured by the decision variable vector $\boldsymbol{I}$. The model also allows the two ports to choose the timing of adaptation in an asymmetric manner (one adapts early, and the other late). Unlike earlier studies that assume price competition between PAs, Randrianarisoa and Zhang (2019) considered Cournot competition such that the PAs decide on quantities in each period, which are captured by the decision variable vectors $\boldsymbol{q}^i$ and $\boldsymbol{q}^{ii}$.The decision variables and timings in their model are summarized in Table 3.

A more detailed expression of the objective function W_j is given by

$$W_j = \left(f_j^i q_j^i - C_j^i\right) + k\left(f_j^{ii} q_j^{ii} - C_j^{ii}\right) + \alpha\left[\left(p_j^i - f_j^i\right)q_j^i + k\left(p_j^{ii} - f_j^{ii}\right)q_j^{ii} + \left(CS_j^i + kCS_j^{ii}\right)\right] \quad (12)$$

where $f_j^T$is the concession fee charged by PA j to its TOC at period T, p_j^i is the price charged by TOC to shippers, and q_j^T is the quantity produced by port j at period T. The disaster damage cost for the port is C_j^i and C_j^{ii} in the first and second periods, respectively, and their values depend on the port adaptation

TABLE 3 The decision variables and adaptation timing in Randrianarisoa and Zhang (2019)

	First period ($T = i$)	Second period ($T = ii$)
A and B invest early	(I_A, I_B), (q_A^i, q_B^i)	(q_A^{ii}, q_B^{ii})
A and B invest late	(q_A^i, q_B^i)	(I_A, I_B), (q_A^{ii}, q_B^{ii})
A invests early and B waits j	(I_A, q_A^i, q_B^i)	$(I_B, q_A^{ii}, q_B^{ii})$
A waits and B invests early j	(I_B, q_A^i, q_B^i)	$(I_A, q_A^{ii}, q_B^{ii})$

investment level and random adaptation efficiency s η and its CDF $G(\eta)$. It is assumed that the distribution of η in the second period has a first-degree stochastic dominance over that in the first period, i.e., G_2 first-degree stochastically dominates G_1.

3 Discussions on existing theoretical findings

This section reconciles and compares the main analytical findings in our reviewed economic modeling work. On one hand, we show some robust conclusions less dependent on various model assumptions and specifications, thereby more general to be applied for business and policy implications. On the other hand, we highlight some seemingly contradictory findings, and scrutinize the underlying assumptions or mechanisms leading to such diversion.

Specifically, we can categorize the existing analytical findings into three major aspects: timing of port adaptation investment, effect of the disaster uncertainty, and effect of the port market structure. For the port market structure, we investigate several detailed elements, such as interport cooperation and competition on port adaptation, intraport vertical structure, PA ownership, and TOC market structure. We first summarize the major findings in Table 4 for easy reference.

3.1 Timing of port adaptation investment

The optimal timing of adaptation investment is modeled in Xiao et al. (2015) and Randrianarisoa and Zhang (2019) with a two-period real options model. While Randrianarisoa and Zhang (2019) assumed an information accumulation on the adaptation efficiency over periods, Xiao et al. (2015), instead, considered the information updating on the disaster occurrence probability. Both papers found that, when the average disaster occurrence probability is high, it is optimal to adapt in early period. This is because leaving the port exposed to high disaster risk without protection in the early period could be costly. However, when the disaster occurrence probability is low, waiting is a better option so as to take advantage of the information gain on disaster occurrence probability or adaptation efficiency. This is summarized in the following Proposition 1.

TABLE 4 The summary of major theoretical findings on port adaptation

	Port adaptation		Timing
Higher disaster occurrence probability	+		Early
	Xiao et al. (2015), Wang and Zhang (2018), Randrianarisoa and Zhang (2019), and Wang et al. (2019)		Xiao et al. (2015) and Randrianarisoa and Zhang (2019)
Higher disaster uncertainty	+	−	Late
	Xiao et al. (2015) and Randrianarisoa and Zhang (2019)	Wang and Zhang (2018) and Wang et al. (2019)	Xiao et al. (2015) and Randrianarisoa and Zhang (2019)
Interport competition	+		Early
	Wang and Zhang (2018), Randrianarisoa and Zhang (2019), and Wang et al. (2019)		Randrianarisoa and Zhang (2019)
Intraport coordination (between PA and TOC)	+		NA
	Xiao et al. (2015) and Wang and Zhang (2018)		
Public port ownership	+		Early
	Xiao et al. (2015), Wang and Zhang (2018), and Randrianarisoa and Zhang (2019)		Xiao et al. (2015) and Randrianarisoa and Zhang (2019)
TOCs competition	+		NA
	Wang et al. (2019)		

Note: the "+" sign indicates increase in port adaptation, and "−" sign indicates decrease.

Proposition 1 *When the disaster occurrence probability is high, it is optimal for decision makers to invest in early period, despite the option value associated with the information accumulation on the disaster occurrence probability or adaptation efficiency. On the contrast, when the disaster occurrence probability is low or intermediate, it is optimal to wait to achieve the option value by utilizing the information updating on the disaster uncertainty.*

Randrianarisoa and Zhang (2019) further incorporated two-port competition into their analysis, and found that interport competition encourages ports to adapt early not late. This is stated as Proposition 2. The rationale is that when port has competitive pressure, they are more willing to make the adaptation earlier to gain competitive advantage. Randrianarisoa and Zhang (2019) also showed that the impacts of disaster risk and adaptation on investment timing are as important as that of competition and information accumulation. For instance, when the risk of being hit by a disaster is very high, the port that invests early would attract more shippers than the one investing late. This is because shippers value resilient infrastructures, and by using the most resilient port, they would reduce their expected disaster-related damage costs. They also showed that greater disaster occurrence probability requires large adaptation investment. The same reasoning applies when the shippers change ports. Specifically, the most resilient port will always receive higher demand, given all other variables. For instance, if port A is highly vulnerable to hurricane but its rival, say port B, is at a lower risk, without adaptation by port A, the shippers will choose port B, *ceteris paribus*.

Proposition 2 *When competition is intensified, it is optimal for ports to invest earlier than later. Immediate investments are less preferred when competition is weak, even lesser in the presence of information accumulation.*

3.2 Uncertainty of disaster and adaptation efficiency

Our reviewed analytical work diverts in the approaches to model uncertainties related to adaptation. For example, Xiao et al. (2015) assumed a uniformly distributed disaster occurrence probability in two periods, with the one in the second period having a narrowed range to reflect the information updating. Randrianarisoa and Zhang (2019) assumed a constant disaster occurrence probability, while the adaptation efficiency follows a more general distribution in both periods. For analytical tractability reasons, they proceeded with simulations to derive the main insights from the model, and assumed log normal distributions for the investment efficiency. The efficiency in the later period is updated based on the early one, implying that the distribution in the second period has a first-degree stochastic dominance over that in the first period. Both studies concluded that the ports would adapt less in the presence of information accumulation either on the disaster occurrence probability or on adaptation efficiency.

Wang and Zhang (2018) modeled the disaster occurrence probability with the Knightian uncertainty, and it does not restrict to any specific form of distribution. That said, the disaster occurrence probability is a general random variable. Then, the authors investigated how port adaptation changes with such Knightian uncertainty (i.e., expectation and variance of disaster occurrence probability). They found that the port adaptation is increased with a higher expectation but a lower variance of the disaster occurrence probability.

It is noted that, under Wang and Zhang (2018), port adapts more when disaster occurrence probability has low variance (less Knightian uncertainty). But Xiao et al. (2015) and Randrianarisoa and Zhang (2019) concluded that the information accumulation (less uncertainty at later period) could reduce port's incentive to adapt. The above results are not contradictory, in the sense that Wang and Zhang (2018) referred to ex ante adaptation decision before any information updating, while Xiao et al. (2015) and Randrianarisoa and Zhang (2019) are for the ex post adaptation decision made post the information accumulation. This seems intuitive as the lower ex ante ambiguity in disaster occurrence imposes lower risk to decision maker, thus increasing the expected investment return (Camerer and Weber, 1992; Nishimura and Ozaki, 2007; Gao and Driouchi, 2013), while a lower ex post uncertainty in disaster occurrence makes the port to have better information to make the optimal level adaptation, not necessarily to overinvest. These results are stated in Proposition 3.

Proposition 3 *When adaptation is invested ex ante (before information accumulation on disaster uncertainty), less uncertainty in disaster uncertainty encourages port adaptation investment. But when adaptation is made ex post, the presence of the information accumulation on the disaster uncertainty reduces port adaptation.*

3.3 Port market structure

Port's optimal adaptation investment is affected not only by the disaster uncertainty but also by the port market structure. In this subsection, we review the analytical results related to the port market structure and its impact on port's adaptation investment.

- *Interport cooperation and competition*

Wang and Zhang (2018), Randrianarisoa and Zhang (2019), and Wang et al. (2019) considered interport competition, and analyzed its effect on port adaptation investment. All studies found that interport competition would increase the port adaptation. Wang and Zhang (2018) defined it as the "competition effect" on port adaptation. Three studies also concluded that such competition effect can be strengthened with more intensity of the interport competition (service homogeneity). This intensity is captured by the road toll or transport cost parameter t in the infinite linear model of shipper demand. This finding is stated in Proposition 4.1.

Proposition 4.1 *Interport competition increases port adaptation (the "competition effect"). More intense interport competition (less service heterogeneity) strengthens such competition effect on adaptation.*

The intuition of this proposition is that adaptation investment can be regarded as a competitive tool for ports to attract shipper demand. Adaptation across ports is a strategic substitute such that ports have incentives to invest more in adaptation to compete with each other. In addition, as discussed earlier, in a dynamic setup (Randrianarisoa and Zhang, 2019), it is also found that the interport competition makes it more likely for two ports to adapt to early period than waiting. With Knightian uncertainty on the disaster occurrence probability (Wang and Zhang, 2018), the competition effect is further strengthened by a higher expected value and variance of the disaster occurrence probability.

- *Intraport vertical structure*

As discussed earlier, a landlord port consists of PA (upstream) and TOC (downstream). In Xiao et al. (2015) and Wang and Zhang (2018), both PA and TOC can make adaptation investment. The two papers found there is a free-riding in adaptation efforts between the PA and TOC at the same port. Specifically, the aggregate adaptation investment is higher if the two parties are able to coordinate. This free riding happens because the port adaptation at the same port benefits both PA and TOC (a positive externality to each other), but the investment cost is private. This thus discourages individual incentive to invest in adaptation, leading to a suboptimal adaptation level. Therefore, it is suggested that a vertical coordination among different shareholders within the same port should be promoted to overcome the free-riding problem. Besides, in practice, the decision-making on adaptation may involve multiple levels of governments as well as public and private stakeholders. For example, the U.S Army Corps of Engineers discussed sea-level rise (SLR) and storm surge impacts on the 2010 multimillion $ project: "Savannah Harbor Expansion Project" for the Port of Savannah. The participants include US Army Corps of Engineers (USACE), Environmental organizations (Georgia Conservancy), Georgia Port Authority, and State of Georgia. Proposition 4.2 summarizes this result.

Proposition 4.2 *PA and TOC within the same port free-ride each other in making port adaptation. Coordination between the two entities would then stimulate the aggregate adaptation investments.*

- *PA ownership (public vs private)*

Wang and Zhang (2018) directly benchmarked port adaptation levels between public and private PAs, and found that public PA invests more port adaptation. Randrianarisoa and Zhang (2019) further showed that public PA is also more likely to invest early. However, higher or early port adaptation by public port does not necessarily lead to a higher expected social welfare. Xiao et al. (2015) suggested that there are risks of overinvestment (i.e., the marginal benefits of investments are zero ex post if there is no disaster) such that a regulatory intervention is not always optimal when the regulator does not have a good understanding of disaster probability distribution. Similarly, Wang and Zhang (2018) found that, with intraport coordination between PA and TOC in adaptation efforts, the public PA could overinvest over socially optimal level when trying to correct the lower adaptation incentive of the private TOC.

However, the current modeling work has not well accounted for the external benefit of port adaptation for the neighboring regions. The local communities and regional economic activities near the port areas can also be protected by the port adaptation investment. Randrianarisoa and Zhang (2019) is the only work attempting to incorporate such external benefit by adding an extra positive term in the social welfare expression. Intuitively, the socially optimal port adaptation level should be higher and installed earlier when the social welfare is enlarged to a broader scope. Meanwhile, the concern of overinvestment by public port could be partially alleviated as well. We summarize the above discussions in Proposition 4.3.

Proposition 4.3 *Public PA invests more adaptation than the private. However, there may be overinvestment, thus not necessarily resulting in the socially optimal adaptation (the first best outcome). When accounting for the positive externality of port adaptation on neighboring communities or regional economy, the socially optimal port adaptation level is higher, and the overinvestment concern associated with the public PA is partly alleviated.*

- *TOC market structure*

Among our reviewed analytical modeling work, Wang et al. (2019) is the only paper to consider the specific market structure of TOCs. As shown in Fig. 4, they assumed that there are *N* TOCs at each of the two competing ports. TOCs conduct Cournot (quantity) competition within and across the ports. Across-port TOCs could also form JV due to the common ownership. Wang et al. (2019) showed that the TOC market structure considerably affects port adaptation investment. Specifically, they found that port adaptation increases with the number of TOCs present at each of the two ports. Interport competition among TOCs leads to higher port adaptation than that under cross-port JV (i.e., the competition effect of terminal operator). They also followed Wang and Zhang (2018) in adopting the Knightian uncertainty assumption on disaster occurrence probability, and showed that a more competitive TOC market would make PA more aggressive to invest in port adaptation. This strengthens the positive effect of the expected disaster occurrence probability on adaptation, while weakening the negative effect of its variance.

Proposition 4.4 *PA increases adaptation investment with a larger number of TOCs at each port. Under the assumption of Knightian uncertainty for disaster occurrence probability, a larger number of TOCs at each port strengthens the effect of expected disaster occurrence probability on port adaptation investment at the port adaptation stage, while weakening the effect of its variance. Interport competition among the independent TOCs induces higher port adaptation than that of TOCs' joint venture (i.e., competition effect of TOCs).*

The intuition of Proposition 4.4 is as follows: When TOC market is more competitive, the port throughput would be enlarged due to lower port service charge, ceteris paribus. This then increases the marginal benefit of PA's adaptation investment, as the same level of adaptation can protect more cargos at the port. As a result, PA has stronger incentive to make the port adaptation investment.

4 Avenues for future research

The economic modeling of port adaptation investment is still at the developing stage. The existing analytical frameworks have already offered a couple of valuable insights into this topic, and laid solid foundation for future extension. This section thus discusses three main avenues with significant potential for future explorations.

4.1 Asymmetry in disaster uncertainty and other port features

Current analytical studies on the two-port region assume that the ports are subject to a common disaster threat, i.e., the same disaster occurrence probability, maximum damage level, and adaptation efficiency. Although this assumption greatly simplifies the model derivations and guarantees the existence of closed-form analytical solutions, it deviates from the reality. Two ports can be very close, such as Shenzhen and Hong Kong, yet their geographic conditions and landscape can be very different. As a result, the same disaster event can bring very asymmetric damages on two ports. When ports are further separated, they could be subject to quite different threats of climate change-related disasters.

Port asymmetries could also come from other sources, such as adaptation investment, PA ownership, and downstream TOC market structure. The equilibrium analyses under these asymmetries could resemble more the real-world cases. The existing models can be extended to accommodate several port asymmetries. For example, Wang and Zhang (2018) can be extended to account for different Knightian uncertainties in disaster occurrence probabilities for two ports, respectively. The maximum disaster damage parameter D can also be made specific to each port as D_i. Two ports can also have different adaptation investment cost parameter ω_i. In Wang et al. (2019), the two ports can have asymmetric number of TOCs, and different subset of across-port JVs.

However, these treatments could complicate the model derivation greatly, making it difficult to derive closed-form solutions for clear-cut economic insights. It is quite likely to rely on simulation to conduct such analyses.

4.2 Vertical concession contract between PA and TOCs

After reviewing existing economic modeling work, it is noted that the vertical strategic relationship between PA and TOCs has not been well explored, especially in the presence of multiple TOCs at one port. In addition to Wang et al. (2019), there should be more strategic interactions to be examined.

For example, it is possible for PA to form exclusive contract with a subset of TOCs to jointly finance the port adaptation. To reward TOCs' participation, PA can consider to offer favorable concession terms (i.e., lower concession fee or revenue sharing) to them. Such discussions have already been provided in several airport economics studies. For example, Fu and Zhang (2010) and Zhang et al. (2010) modeled the revenue sharing between airport and airlines. To maximize the profits or social welfare, airport can strategically determine a subset of airlines to form the revenue-sharing contract.

In addition to the noncooperative game theoretic approach widely used, future studies can also implement alternative approaches, such as Nash-bargaining (Yang et al., 2015) and cooperative game theory (Wan et al., 2016) which have been applied in transport economic analysis. These approaches could be more appropriate, as there is an increasing trend for PA to involve more stakeholders to cooperate in the adaptation planning and investment (Becker et al., 2013). More rich implications on the vertical relationship between PA and TOCs, and the effects on port adaptation can be generated.

4.3 Positive externality of port adaptation on regional economy

Existing economic modeling framework has not well captured the externality of port adaptation on local community and regional economy. Randrianarisoa and Zhang (2019) is the only one trying to account for this aspect. But their treatment is still preliminary, just adding a positive term (proportionally to the adaptation investment level) on the social welfare function. There should be more detailed issues to be examined. For example, to achieve higher positive externality of the port adaptation on the broader region, it may require more sophisticated type of adaptation with higher investment cost. Then, it also comes to a question on whether the port should finance the project or government subsidy is called for.

In addition, we question if the current economic models are enough to tackle this complex externality issue, as current studies are basically partial equilibrium models, focusing only on the shipping sector. Thus, a general equilibrium model that well incorporates the different economic sectors and stakeholders should be developed to provide a more comprehensive framework. Specifically, future research should be able to endogenize the positive externality of the port adaptation and analyze a system-wide economy equilibrium, while deriving the overall economic and social welfare effect of the port adaptation on the whole region.

5 Conclusion

In recent years, port adaptation has attracted increasing attention from the academic field. This chapter comprehensively reviews the existing economic modeling of port adaptation, represented by Xiao et al. (2015), Wang and Zhang (2018), Liu et al. (2018), Randrianarisoa and Zhang (2019), and Wang et al. (2019). We compare how the disaster uncertainty and the port market structure have been incorporated in these models in terms of the commonality and differences. The analytical findings of the studies are then reconciled and compared. Last, the future research avenues are identified.

We found that the existing theoretical studies have applied game theory and real options approach to model the timing of port adaptation, disaster uncertainties, port market structure, and their effects on port adaptation. Several robust findings have been reached despite some distinct modeling specifications and assumptions. Among others, port adapts earlier and at higher level when the port is highly vulnerable to climate-related disasters and in presence of interport competition. In general, the likelihood of occurrence for extreme events (within the lifetime of the infrastructure) can be classified into three categories, including low ($x \leq 1\%$), moderate ($1\% < x \leq 10\%$), high ($10\% < x \leq 20\%$), and virtually certain or already occurring (>20%). Some world ports fall into the "high risk" category while others are not, depending on the geographical location of the ports. For instance, Japanese ports are highly vulnerable to Earthquake, the Port of Vancouver in Canada is threatened by flood from both the ocean and the river (Fraser river) side, high tides, and storm surges, and the Port of Los Angeles in the United States has low risk impacts from sea-level rise and flooding. However, ports have more incentives to wait when they can accumulate better knowledge of the disaster occurrence probability and of adaptation efficiency in the next period. Moreover, there is an intraport free riding in port adaptation between PA and TOCs at the same port. Public ports are likely to overinvest in adaptation, not necessarily leading to socially optimal outcomes compared to private ports. Meanwhile, there are some seemingly inconsistent findings, mainly driven by variation in specification and modeling factors. For example, some studies suggest ports to adapt more with less ex ante disaster uncertainty but adapt less with less ex post disaster uncertainty (information accumulation).

Based on existing models, we proposed several avenues for the future studies. First, the asymmetry in the disaster risk, the port disaster uncertainty, the adaptation efficiency, and the investment cost may be further considered in order to better reflect real-world situations. Second, the vertical relationship between PA and TOCs at the same port can be better explored. More sophisticated concession contracts involving adaptation investment, joint financing, and revenue sharing can be examined. Meanwhile, other than the conventional noncooperative game theoretical approaches, Nash-bargaining and the cooperative game approach may also be introduced to analyze more complicated vertical interactions between PA and TOCs in adaptation investment. Third, the discretely made investment decisions may be extended to the decisions made in a continuous fashion (e.g., Balliauw et al., 2019). Fourth, it would also be interesting to test the validity of the assumptions of the current models with actual data on disasters, such as hurricane, earthquake, or the typhoons striking ports like Hong Kong. Finally, the economic modeling of the positive externality of port adaptation on regional economy can be improved. To achieve a more comprehensive and objective analysis, a general equilibrium model that incorporates different economic sectors and stakeholders can be established, enabling to derive the overall economic and social welfare effects on the whole region.

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