Les Cahiers du GERAD ISSN: 0711–2440

Strategic adaptation and capacity investments for seaports under competition and climate-change uncertainty

J. Mishra, W. Xia, Y. Adulyasak

G–2023–11

April 2023

Citation suggérée : J. Mishra, W. Xia, Y. Adulyasak (Avril 2023). Strategic adaptation and capacity investments for seaports under competition and climate-change uncertainty, Rapport technique, Les Cahiers du GERAD G– 2023–11, GERAD, HEC Montréal, Canada.

Avant de citer ce rapport technique, veuillez visiter notre site Web (https://www.gerad.ca/fr/papers/G-2023-11) afin de mettre à jour vos données de référence, s'il a été publié dans une revue scientifique.

Suggested citation: J. Mishra, W. Xia, Y. Adulyasak (April 2023). Strategic adaptation and capacity investments for seaports under competition and climate-change uncertainty, Technical report, Les Cahiers du GERAD G–2023–11, GERAD, HEC Montréal, Canada.

Before citing this technical report, please visit our website (https://www.gerad.ca/en/papers/G-2023-11) to update your reference data, if it has been published in a scientific journal.

La publication de ces rapports de recherche est rendue possible grâce au soutien de HEC Montréal, Polytechnique Montréal, Université McGill, Université du Québec à Montréal, ainsi que du Fonds de recherche du Québec – Nature et technologies.

The publication of these research reports is made possible thanks to the support of HEC Montréal, Polytechnique Montréal, McGill University, Université du Québec à Montréal, as well as the Fonds de recherche du Québec – Nature et technologies.

Dépôt légal – Bibliothèque et Archives nationales du Québec, 2023
– Bibliothèque et Archives Canada, 2023

Legal deposit – Bibliothèque et Archives nationales du Québec, 2023
– Library and Archives Canada, 2023

GERAD HEC Montréal
3000, chemin de la Côte-Sainte-Catherine
Montréal (Québec) Canada H3T 2A7

Tél. : 514 340-6053
Téléc. : 514 340-5665
info@gerad.ca
www.gerad.ca

Strategic adaptation and capacity investments for seaports under competition and climate-change uncertainty

Jayanti Mishra [a]

Wenyi Xia [a, b]

Yossiri Adulyasak [a, b]

[a] *Department of Logistics and Operations Management, HEC Montréal, Montréal (Qc), Canada, H3T 2A7*

[b] *GERAD, Montréal (Qc), Canada, H3T 1J4*

wenyi.xia@hec.ca
yossiri.adulyasak@hec.ca

April 2023
Les Cahiers du GERAD
G–2023–11

Abstract : Seaports are highly vulnerable to climate-change induced events, which makes it necessary for them to invest in climate change adaptation measures to ensure operational continuity, as well as capacity expansion to accommodate the increasing demand for maritime transport. Meanwhile, investment and pricing decisions by ports can be largely influenced by inter-port competition. Against this background, we develop a game theoretic model to determine a port's strategic decisions on capacity and adaptation investments in conjunction with service charge, considering inter-port competition and climate-change uncertainty. We characterize the equilibrium decisions of three competition cases based on port ownership structures: profit-maximizing ports, welfare-maximizing ports, and first-best outcome. Through our numerical validation, we find that when faced with higher climate risk, a port would invest less in capacity to expose fewer assets at risk, but would not always invest more in protection, as less capacity may warrant less protection investment. Its competing port, however, would increase both capacity and protection investments. Welfare-maximizing and first-best ports invest more in both protection and capacity but charge less service fees than profit-maximizing ports. When the climate risk at one port is low, the first-best case would result in a considerably higher investment level at the low-risk port and lower investment level at the high-risk port, compared to the welfare-maximizing case. High climate risk would result in underinvestment in both port capacity and protection due to inter-port competition.

Keywords : Adaptation investment, capacity investment, port competition, climate change uncertainty

---

Acknowledgements: We would like to thank Jean-François Cordeau and Raf Jans for helpful comments. We acknowledge the financial support from the Fonds de recherche du Québec — Société et culture (FRQSC), funding reference number 2022–NP–297108, and Natural Sciences and Engineering Research Council of Canada (NSERC), funding reference number R1977.

1 Introduction

Seaports (henceforth ports) are integral hubs of global maritime supply chains and have served as critical gateways of international trade (Jiang et al. 2020; Hossain et al. 2021). Global maritime trade has grown enormously in the last 25 years, and now accounts for over 80 per cent of the total annual volume of global trade (UNCTAD 2021a). However, ports worldwide have been plagued with persistent challenges of climate change and capacity constraint, making it extremely crucial for them to develop and implement effective capacity enhancement and climate-change adaptation strategies (Nursey-Bray et al. 2013). Due to their location in low-lying coastal and riverine areas, ports are highly vulnerable to risks induced by climate change in terms of both their facilities and operations (Becker et al. 2012). The past decade has witnessed substantial costs to global economy and welfare due to the occurrence of climate-change induced events. These losses are expected to intensify in the coming years with worsening climate situation (Izaguirre et al. 2021; Ng et al. 2018). Despite rising climate-change related threats, global maritime trade has been rapidly increasing worldwide and is projected to grow 2.4 per cent annually over the next five years (UNCTAD 2021b). The demand has been robust even during the Covid-19 pandemic, with approximately 75 per cent of ports witnessing the number of vessel calls to be similar or even higher in 2020 as compared to the same period in 2019 (Notteboom 2021; ILO 2021). As the maritime trade continues to grow, the infrastructure can no longer accommodate the increasing vessel traffic and port operations (Peters et al. 2001, Kauppila et al. 2016). The problem further aggravates in times of global emergencies such as natural disaster, financial crisis and epidemics (De Monie et al. 2011; Notteboom & Siu Lee Lam 2014).

Climate change has pushed to the forefront the importance of climate change adaptation vis-à-vis port management, due to the catastrophic consequences that can potentially propagate through supply chains (Burkett & Davidson 2012; UNCTAD 2017). The past decade has witnessed increased frequency and intensity of climate-change induced events (Becker et al. 2018). For instance, damage to port infrastructure from previous hurricanes in USA ranged from USD 2.2 billion for Hurricane Katrina in 2005 to USD 46 million for Hurricane Florence in 2018 (Van Houtven et al. 2022). Economic losses from storm-related disruptions to port operations range from USD 65 million at Port of Dalian, caused by a 5-day disruption due to Typhoon Lekima in 2019 to USD 10 million at the Port of Shanghai, caused by a 2-day disruption due to Typhoon Haikui in 2012 (Lin 2020; Patel 2021). An evaluation of 141 incidences of storm-related disruptions across 74 ports in 12 countries and 27 disasters found median disruption duration of 6 days (Verschuur et al. 2020). Verschuur et al. (2020) also find that an increment of a 1-meter storm surge or 10 meters per second in wind speed is associated with a 2-day average increase in disruption duration. Volatile inland precipitation patterns further make ports prone to inland flooding and droughts. Flooding in Mississippi River in 2019 disrupted shipment of agricultural goods in USA, causing losses valued at almost USD 1 billion. In the same year, severe drought in the Panama Canal region caused global shipping industry between USD 230 million and USD 370 million. Higher global temperature and more extreme heat events induced by climate change cause substantial damage to shipping vessels and port infrastructure, in addition to disruption in port operations. Heatwaves in Australia in 2009 shut down sections of the Port of Melbourne for three days, causing work stoppages and resultant losses to productivity. These climate-related impacts are expected to intensify in coming years and are expected to cost the shipping industry USD 25 billion every year by 2100, attributable to annual damages to port infrastructure and operational disruptions (Van Houtven et al. 2022). Port adaptation investment to climate change (henceforth "protection investment") is thereby necessary to enhance port resilience against such climate risks. Ports have increasingly been undertaking investments in surge barriers, revetments, infrastructure elevation, bulkheads, seawalls, dikes, etc. to enhance resilience (Randrianarisoa et al. 2020; Zheng et al. 2021). For instance, the Port of Long Beach is planning to reconstruct revetment and more than 400 feet of its dilapidated seawall in 2023. With an estimated cost of USD 2.6 million, this protection project will be funded by the Federal Emergency Management Agency and Rockport Public Works (Cronin 2021). The Port of Baltimore has been undertaking numerous adaptation measures to enhance its resilience to sea-level rise and flooding. Using the proceeds of a Transportation Investment

Generating Economic Recovery (TIGER) grant received by the US government, the port set up a wet basin stormwater management system in its Fairfield Marine Terminal and enabled elevation of some of its important assets. The port also constructed stormwater vault at the Dundalk Marine Terminal (EESI 2020). However, choosing the right scale of protection investment is challenging due to uncertainty about frequency and intensity of disasters, rate of climate change, and irreversibility of investment in physical infrastructure (Wang et al. 2022; Xia and Lindsey 2021).

Despite rising intensity and frequency of climate-change induced events, global seaborne trade has been increasing rapidly, driven by factors such as globalization, population growth, and rising demand for commodities. ITF (2019) projects maritime freight demand to witness annual growth of 3.6 per cent through 2050, which is expected to triple maritime trade volume over the period. Over this period, containers moved are forecasted to increase by 73 percent globally to at least 2.2 billion per year by 2050 (ITF 2017; Housni et al. 2022). Based on such demand and trade estimates, port capacity is inadequate to meet demand as early as 2030 and capacity investment is pertinent to handle larger vessels and increased volume of cargo traffic (OECD 2012; UNCTAD 2021b; Luo et al. 2012; Kauppila et al. 2016). Ports with reliable and sufficient capacity will benefit by eliminating cargo handling delays due to port congestion and high traffic densities (Zhen et al. 2019; Cong et al. 2020). We see an increasing number of ports investing in capacity enhancements. For instance, Port of Montreal is planning construction of a new container terminal in Contrecœur with an estimated investment outlay of $850 million. With the capacity to handle 1.15 million TEUs per year, this container terminal is expected to be fully operational by 2026 (Port of Montreal 2022). In 2011, Port of Long Beach planned "Middle Harbor Terminal Redevelopment Project" costing USD 1.49 billion to combine its two aging shipping terminals into a mega-terminal. The terminal completed in August 2021 has an annual capacity of 3.3 million TEUs, which is more than double the capacity of the two terminals it is replacing (Port of Long Beach 2021). In 2017, Royal Vopak and AltaGas started constructing Canada's first propane export facility, Ridley Island Propane Export Terminal, on a property leased from the Prince Rupert Port Authority. With an investment outlay of over USD 450 million, the terminal has the capacity to move approximately 40,000 barrels of propane per day (AltaGas 2016).

Driven by globalization, trade liberalization, technological advancement and changes in inter-port relations and port-hinterland relationships, port competition has intensified in the past decade inducing ports to become more responsive to the needs of shippers and other stakeholders. As a result, the scale of protection and capacity investment undertaken by the port is largely influenced by inter-port competition. For instance, Port of Gulfport, Mississippi suffered severe damage because of hurricane Katrina in 2005. Soon afterwards, USD 570 million was allocated from the Federal Community Development and Block Grant to rebuild and restore the damage to Gulfport's facilities. As part of the restoration, the port announced that it would raise its West Pier by 25 feet to ensure better protection from storm surge. Ironically, the port nixed its proposed plan one day after hurricane Sandy hit the Port of New York and New Jersey. The reason stated behind the decision of reducing pier elevation was mainly based on business and competition considerations of attracting new port tenants and better serving existing ones. (Xiao et al. 2015; Thomas 2012).

Our contributions can be stated as follows. We present a framework to analyze port's strategic decisions on capacity and protection in conjunction with port charges, considering competition with other ports and uncertainty about climate-change induced events. To this end, we develop a game theoretic model featuring two ports and a continuum of shippers. We characterize the equilibrium decisions of the three cases of competition based on port ownership structure: profit-maximizing ports, welfare-maximizing ports, and first-best outcome where a central government makes decisions on behalf of the ports with the objective of maximizing overall welfare. We propose a numerical approach to solve the model under symmetric and asymmetric scenarios. In symmetric scenario, parameter values for both ports are assumed to be identical, corresponding to the situation where two ports are subject to the same climate-change risk. Conversely, in asymmetric scenario, parameter values for both ports are assumed to be different, addressing the situation where two ports are subject to the different climate-change risk and preference from shippers. Using operating cost and investment data from Canadian ports, we conduct comparative statics under symmetric scenario and asymmetric scenario and discuss managerial insights with respect to the implications of capacity and protection investment decisions of ports under competition. To the best of our knowledge, this is the first work that links port competition, capacity, and adaptation in a holistic fashion. The outcomes of this work can benefit the port operators and policy makers, and the framework can be adopted to guide their strategic investment decisions

We demonstrate the following findings. First, when a port faces higher climate risk, this port would invest less in capacity to expose fewer assets at risk, but would not always increase its protection investment, as less capacity may warrant less protection investment. Its competing port, however, would increase capacity to take up the demand shifting from its competitor that entails higher climate risk. Consequently, protection investment at the competing port also increases to ensure the increased capacity infrastructure is protected. Second, welfare-maximizing ports and ports under first-best outcome invest more in both protection and capacity but charge less service fees than profit-maximizing ports. Welfare-maximizing ports are more inclined to increase port charge than profit-maximizing ports when congestion occurs. When the climate risk at one port is low, the central government would prioritize investments of one port over the other, resulting in a considerably higher investment level at the low-risk port and lower investment level at the high-risk port, compared to the welfare-maximizing case. Third, under both welfare-maximizing and first-best cases, corner solutions can happen where port charges are set to zero, indicating the ports try to satisfy all market demand at the expense of their profits. Corner solutions are more likely to happen when the climate risk is low, when utility of using the port is high, when congestion cost to shippers is low, when unit operating or investment cost is low, or when the randomness in shippers' behavior is small. Fourth, the effect of shippers' congestion cost on port capacity and protection investments is non-monotone. Last, the pricing behavior of ports under the three ownership structures is different depending on the focus of the ports, which could be exercising market power, limiting congestion, attracting shippers, or satisfying market demand.

The structure of the paper is as follows. In the next section, an overview of the literature on port adaptation investment to climate change and port capacity investment is presented. Section 3 describes the model that incorporates varied port objectives based on three types of port ownership structure. Section 4 presents numerical analyses under two scenarios. Section 5 concludes the paper and points out limitations for future study.

2 Literature review

This study involves two research streams, namely, port congestion and capacity investment and port adaptation investment to climate-change.

2.1 Port congestion and capacity investment

There have been studies on optimal port capacity investment decisions for a single port. For instance, Jansson and Shneerson (1982) and Noritake and Kimura (1983) use queuing theory to determine the optimal number and capacity of berths in a port reflecting the variation of cargo demands; Devanney and Tan (1975) propose dynamic programming to analyze optimal timing of capacity expansion for a port facing a volatile, price-dependent cargo demand, and Allahviranloo and Afandizadeh (2008) develop an integer-programming model to examine the optimum port investment in a country.

Capacity investment decisions undertaken by competing ports have been studied in various contexts. Most studies address capacity investment decisions by competing ports under certainty, albeit under different settings including regional development, hinterland accessibility, and port specialization. De Borger and Van Dender (2006) examine pricing and capacity investment decisions of congestible ports in a duopoly with each port having a congestible transport network to a common hinterland. Anderson et al. (2008) propose a game-theoretic best response framework to examine two competing ports' capacity investments and conclude that the investments depend on their costs. They apply their model to investment and competition prevailing between Ports of Busan and Shanghai. De Borger et al. (2008) investigate optimal pricing of two duopolistic ports that have the same overseas customers, downstream congested transport networks to a common hinterland and optimal investments of corresponding governments in ports' facilities. Their analysis, based on numerical illustrations, reveals that the ports internalize the hinterland congestion costs and charge their customers accordingly. They also conclude ports' capacity levels to be negatively correlated with the charges. Following De Borger et al. (2008), Zhang (2009) examine how hinterland access conditions influence uncongested ports' competition in both quantity and price. Xiao et al. (2012) study the impact of port ownership structure and governance mechanism on pricing and capacity investment decisions of ports. They also model the implications of changes in port ownership and governance on social welfare and port service level. Luo et al. (2012) analyze pricing and capacity expansion of ports using a two-stage duopoly game and derive the conditions for ports to profit from a rising capacity level.

Literature on capacity investment decisions undertaken by firms in an uncertain and competitive setting is well developed. Grenadier (2002) formulates a tractable real options framework to derive the equilibrium investment strategies in an uncertain dynamic and assesses the impact of competition on investment strategies using a continuous-time Cournot-Nash framework. Huisman and Kort (2015) derive a strategic real options model to determine the timing and quantum of capacity investments in a duopolistic framework given uncertainty and competition between firms. Nishimura and Ozaki (2007) and Niu et al. (2019) examine the effect of Knightian uncertainty on investment decisions. Nishimura and Ozaki (2007) investigate the impact of Knightian uncertainty on the value of irreversible investment opportunity undertaken by a risk-neutral and uncertainty averse firm. Niu et al. (2019) proposes a model that incorporates Knightian uncertainty into the standard model of capacity choice and examines its effect on the firm's expansion decision.

There is a growing literature on capacity investment decisions undertaken by congestible ports under uncertainty. Ishii et al. (2013) propose a multi-period non-cooperative theoretical model to examine inter-port competition under demand uncertainty where each port selects port charges strategically in the timing of port capacity investment. They apply the model to the case of port competition between Port of Busan and Port of Kobe. Chen et al. (2017) develop a three-period game to examine optimal capacity investment of risk-averse governments and optimal pricing of risk-neutral ports under demand uncertainty and service differentiation. Chen and Liu (2016) develop a similar model encompassing two stages by considering simultaneous investments of risk-averse ports under uncertain market demand and congestion. They examine the impact of operation costs, facility levels, and uncertain demand on ports' equilibrium prices. They analyze such impact by considering the behaviors of risk-averse ports vis-à-vis risk-neutral ports, and ports' behaviors under uncertainty and no-uncertainty. Balliauw et al. (2019) propose a real options model based on a geometric Brownian motion to determine optimal timing and scale of capacity investments in a service port given congestion and uncertainty. Balliauw et al. (2020a) extend this study to examine the impact of congestion and uncertainty in a landlord port with two actors where public ownership is possible. Balliauw et al. (2020b) propose a continuous-time real options model to examine the timing and scale of capacity investment undertaken by ports under quantity competition and uncertain demand. They analyze the influence of competition, congestion costs, expected growth, public money involvement, uncertainty, and cost advantage of one port on the capacity investment decision of ports. Studies have also been extended to other transportation settings such as airports and railways. For instance, Xiao et al. (2013) model the effects of demand uncertainty on airport capacity choice where uncertain demand follows a continuous probability distribution. They benchmark the behavior of a welfare-maximizing versus that of profit-maximizing airport. Gao and Driouchi (2013) propose a real options framework for investment in rail transit infrastructure under Knightian uncertainty. They focus on a rail transit project's congestion relief value under uncertain urban population growth. Smit (2003) proposes a discrete-time options-game model to investigate optimal infrastructure investment. The model focuses on the analysis of European airport expansion given uncertain airport growth opportunities and future cash-flows.

2.2 Port adaptation to climate change

Most of the earlier studies in this area are descriptive (Esteban et al. 2009, Nicholls et al. 2010, Becker et al. 2012, Becker et al., 2013, Ng et al., 2013, Ng et al., 2015, Becker et al., 2018, Yang et al., 2018). However, studies that examine port adaptation investment under uncertainty using theoretical economic models are emerging (e.g., Xiao et al. 2015, Wang and Zhang, 2018, Asadabadi and Miller-Hooks, 2018, Randrianarisoa and Zhang 2019, Wang et al., 2020).

Xiao et al. (2015) examine the optimal timing of port adaptation investment over a two-period horizon at a cost-minimizing landlord port given information accumulation and climate risk uncertainty. Their model also considers the investment benefit spillovers between the port authority and the terminal operator. They find that port has an incentive to postpone its adaptation investment when the disaster uncertainty is significant.

Wang and Zhang (2018) and Wang et al. (2020) extend Xiao et al. (2015) to consider inter and intra-port competition and cooperation in port adaptation investments. Wang and Zhang (2018) extend Xiao et al. (2015)'s analytical framework to examine the impact of intra-port and inter-port competition on adaptation investment undertaken by two-landlord ports considering that disaster occurrence probability follows Knightian uncertainty. They also conclude that a higher expectation of the disaster occurrence probability increases the scale of adaptation investment, and larger variance reduces such level of investment. Wang et al. (2020) examine the impact of the downstream terminal operator market structure on the inter-port competition/coordination on port adaptation. They conclude that co-opetition within and between seaports would reduce the impact of risk uncertainty on adaptive investment. Randrianarisoa and Zhang (2019) extend Wang and Zhang (2018) to a two time-period model. They also consider the uncertainty associated with the efficiency of adaptation investment. Like Xiao et al. (2015) and Wang and Zhang (2018), they assume that ports can only invest in protection in either period 1 or period 2, but not both. They solve the model numerically and conclude that the optimal timing of adaptation investment is influenced by the level of competition, disaster occurrence probability and potential information gain over time. Wang et al. (2020) propose a two-period game model to investigate the scale and timing of prevention and adaptation investments by port authorities with asymmetric risk probability ambiguity, risk-sensitive behavior of decision makers, and information accumulation in a competitive environment.

Port adaptation investment has also been studied in various contexts, such as maritime networks, climate change mitigation, and regulatory policies. Asadabadi and Miller-Hooks (2018) investigate port adaptation investment in a co-opetitive maritime network that serves a common liner shipping market. Jiang et al. (2020) incorporate mitigation and adaptation investment decisions of two ports and compare their relative impact on the market outcomes. Few studies have attempted to examine the effects of regulatory policies on port adaptation investments. For example, Zheng et al. (2021a) examine the effects of regulatory policies, namely subsidy and minimum requirement, on port adaptation investment considering the disaster occurrence uncertainty, investment spill-over externality and decision-maker's attitude towards risk. They demonstrate the varied impacts of these two policies on port adaptation investment and on other market outcomes and suggest the superiority of either policy under different conditions. Zheng et al. (2021b) incorporate asymmetric disaster damages and levels of adaptation resources to model inter-port competition in adaptation investments. They develop an economic model to examine the implications of adaptation sharing mechanisms.

The above studies consider only one type of investment - either port adaptation investment or port capacity investment. We, however, consider both adaptation and capacity investments. Very few studies explore port capacity and adaptation investment simultaneously. Gong et al. (2020) consider port investment in both capacity and adaptation under budget constraint in a one-period model. They investigate port investment resource allocation between capacity and adaptation. Another study is Xia and Lindsey (2021) who investigate how a port decides optimal timing and scale of port adaptation and capacity investments, as well as port charges, given uncertainty about climate change and demand.

However, both Gong et al. (2020) and Xia and Lindsey (2021) only consider the decisions of a single port, abstracting away inter-port competition. In contrast, our study considers inter-port competition, as well as the ports' simultaneous decision in both capacity and adaptation. To the best of our knowledge, this is the first work that tries to link port competition, capacity, and adaptation. But unlike Xia and Lindsey (2021), our study is limited to one period, thus abstracting away investment timing.

3 The model

This section describes the model structure and presents basic assumptions. Section 3.1 characterizes shippers' demand for port services and explains the losses they can incur from congestion and climate-change induced events at the port. Section 3.2 describes the ports' objective functions based on the ownership structures and their competition behaviors.

3.1 Demand for port service

The model features two ports that compete for the same overseas customers.[1] We refer to the two ports as port i and port j. A continuum of shippers (or cargo owners) chooses between the two ports to ship goods based on their indirect or random utility, which is expressed as

$$U_n = V_n + \varepsilon_n, \tag{1}$$

where $n \in \{i, j, o\}$ represents shippers' choice, which could be port i, port j, or an outside option o, V_n is the deterministic part of the utility, and ε_n is the random or disturbance component of the utility, which represents the unobserved preferences of shippers for choice n. We assume the ε_n terms are independently and identically distributed (i.i.d.) and follow Gumbel distribution $\varepsilon_n \sim$ Gumbel (θ, σ), with cumulative distribution function

$$F(\varepsilon; \theta, \sigma) = e^{-e^{-(\varepsilon-\theta)/\sigma}}, \tag{2}$$

where θ is the location parameter and σ the scale parameter.

For $n = o$, V_o is a constant representing the deterministic utility of a generic outside option, whose characteristics may not be observable. For example, shippers may choose other transportation modes such as air or rail, or they may simply decide not to ship their cargo at all. For $n \in \{i, j\}$, the deterministic utility of choosing port n to ship one unit of cargo is given by

$$\forall n \in \{i, j\}, V_n = \mu_n - \beta\tau_n - \delta \cdot g_n(q_n, K_n) - m_n \cdot h_n(K_n, G_n, x_n), \tag{3}$$

where μ_n is the mean utility from using port n. Note that this constant μ_n can be used to capture port attributes that influence shippers' preference (such as port's hinterland connection to the final destination, proximity to the final destination and use of automation, digitization, and data-driven systems within a port for cargo tractability and operational efficiency) . The negative terms in Eq. (3) represent the generalized cost incurred by shippers of using the port, which includes (1) the service fee charged explicitly by the port $\beta\tau_n$; (2) the cost due to congestion at the port $\delta \cdot g_n(q_n, K_n)$; and (3) potential cost of damage to the cargo if a coastal natural disaster hits the port $m \cdot h_n(K_n, G_n, x_n)$. Specifically, τ_n is the service fee per unit cargo charged by port n, q_n is the traffic volume or cargo throughput at port n, K_n is the capacity investment made by port n, G_n is the adaptation to climate change investment made by port n, x_n measures the expected frequency of coastal natural disasters over a certain time span at port n, and β, m_n, δ are coefficients. The function $g_n(\cdot)$ captures the congestion level at port n, while the function $h_n(\cdot)$ captures the risk of coastal natural disasters faced by shippers at port n. See Table 1 for a notational glossary.

[1] We consider two competing ports, but our model can be generalized to a network of multiple competing ports.

Table 1: National glossary

Notation	Description
β	Coefficient of port user charge in shippers' random utility and is normalized to 1
δ	Parameter measuring port congestion cost to shippers
μ_i	Constant utility for shippers choosing port i
m_i	Intensity of damage to shippers using port i
x_i	Expected disaster frequency during the planning horizon at port i
M_i	Intensity of damage to port i
Q	Potential market demand
ε_i	Unobserved idiosyncratic utility shock for shippers choosing port i
U_i	Indirect utility of shippers choosing port i
c_{Ki}	Unit capacity investment cost of port i
c_i	Unit operating cost of port i
π_i	Expected profit of port i
W_i	Social welfare at port i
W	The overall social welfare at both ports
q_i	Traffic volume at port i
τ_i	Port charge of port i
K_i	Capacity investment of port i
G_i	Protection investment of port i
θ	Location parameter of Gumbel distribution, which is normalized to 0
σ	Scale parameter of Gumbel distribution

Note: The same description applies for port j

The congestion level at a port depends positively on port demand q_n and negatively on port capacity K_n. We assume $g_n(\cdot)$ takes the functional form in Equation (4), which is homogeneous of degree zero in volume and capacity: a standard assumption in the literature on congestible facilities (e.g., Small and Verhoef 2007, Chap. 3).

$$g_n\left(q_n, K_n\right) = \frac{q_n}{K_n}. \tag{4}$$

The same functional form has been used in, for example, De Borger and Van Dender (2006) and De Borger et al. (2007).

Following Xia and Lindsey (2021), we assume $h_n(\cdot)$, the risk of coastal natural disasters faced by shippers at the port, takes the following functional form

$$h_n\left(K_n, G_n, x_n\right) = x_n \left(\frac{G_n}{K_n}\right)^{-1}. \tag{5}$$

The investment decisions are made by the ports at the beginning of a planning horizon. Once a port has invested in capacity and adaptation, it stays with this level of capacity and adaptation for a certain period which can encompass many years until the next time it makes another investment decisions. During the period, multiple natural disasters are possible. We thus denote x_n as the expected disaster frequency during a certain period, rather than the probability of disaster. Hence, the expected disaster frequency x_n could exceed unity. This parameterx_n can be estimated from historical data on sea level rise, weather, and extreme events, and x_n is exogenous to the port. Following Xia and Lindsey (2021), protection G_i is expressed as monetary expenditure on protection measures overall (which may include seawalls, dikes, surge barriers, infrastructure elevations, etc.). Thus, the ratio G_n/K_n measures the port's adaptation cost per unit port capacity. This ratio can be a proxy for port protection level, because compared with a smaller port, a larger port would need proportionally more protection to reach the same protection level. This is consistent with Becker et al. (2017), which, by using a generic model, shows that to elevate a port against sea level rise, protection cost is proportional to port capacity. Thus, the ratio G_n/K_n is a reasonable representation of how well a port is protected rather than only G_n. A well-protected port limits operational disruptions and infrastructure damage, thus limiting the possible delays and loss of cargo value incurred by shippers. We take a reciprocal form of the port's protection level to capture the port's vulnerability. At the same time, using other decreasing functions would not change the qualitative insights of the study.

Our formulation of the disaster risk faced by shippers is consistent with the risk definition by United Nations Office for Disaster Relief (UNDRR). More specifically, UNDRR defines risk R as a function of the combined effects of hazards H, exposure E (e.g., elements at risk such as population, properties, infrastructure, or other assets), and vulnerability V of those exposed elements (see Lam and Lassa (2017) for a discussion):

$$R = H \cdot E \cdot V. \tag{6}$$

H is represented by x_n, E is represented by one unit of cargo, and V is represented by $(G_n/K_n)^{-1}$.

Our modeling of shippers' generalized cost is consistent with the existing literature. For example, Becker et al. (2018) show that some ports find that resilience (i.e., port protection level) provides a competitive advantage, since port users are more comfortable investing in a "climate-ready port". Tongzon (2009) uses a survey method to identify important factors affecting port users' port choice. The key factors found include port charge, adequate infrastructure that limits port congestion, and port's reputation for cargo damage, consistent with the three terms considered in Equation (3).

Shippers choose the alternative corresponding to the largest random utility across all available options. Specifically, shippers will choose alternative $l \in \{i, j, o\}$ if

$$V_l + \varepsilon_l \geq V_n + \varepsilon_n, \qquad \forall\, n \neq l. \tag{7}$$

We apply the following normalization. First, we let $V_o = 0$ since the inequality in Equation (7) holds if we subtract a constant to both sides of the inequality. Second, we let the location parameter of the Gumbel distribution $\theta = 0$ since shifting the error terms by a fixed distance does not change the inequality in Equation (7). Last, since the inequality holds if we multiply the utility with any positive real number, we let the price coefficient $\beta = 1$ so that the utility is measured in monetary terms, which is more straightforward in terms of interpretation. Note that this is in contrary to the multinomial logit model in which the scale parameter of the Gumbel distribution is normalized (i.e., $\sigma = 1$). However, the results of the paper remain the same. Thus, δ and m_n in Equation (3) are parameters that convert the cost of congestion and the cost of climate risk into monetary values. We assume that m_n is port-dependent to capture intensity of damage to shippers at port n, since the expected monetary cost of a natural disaster depends not only on the frequency but also on the intensity. On the contrary, we assume δ is port-independent since shippers incur the same monetary cost from delaying at either port.

The probability that l is chosen over other alternatives is (the derivation is shown in Appendix B):

$$S_l = \frac{\exp\left(\frac{V_l}{\sigma}\right)}{\sum_n \exp\left(\frac{V_n}{\sigma}\right)} = \frac{\exp\left(\frac{V_l}{\sigma}\right)}{1 + \exp\left(\frac{V_i}{\sigma}\right) + \exp\left(\frac{V_j}{\sigma}\right)}. \tag{8}$$

S_l also represents the market share of alternative l. Suppose the potential shipping demand from the overseas market is Q units of cargo. The demand system for port i and port j can be written as

$$q_i = Q \frac{\exp\left(\frac{V_i}{\sigma}\right)}{1 + \exp\left(\frac{V_i}{\sigma}\right) + \exp\left(\frac{V_j}{\sigma}\right)}, \tag{9a}$$

$$q_j = Q \frac{\exp\left(\frac{V_j}{\sigma}\right)}{1 + \exp\left(\frac{V_i}{\sigma}\right) + \exp\left(\frac{V_j}{\sigma}\right)}. \tag{9b}$$

Figure 1 illustrates the model structure.

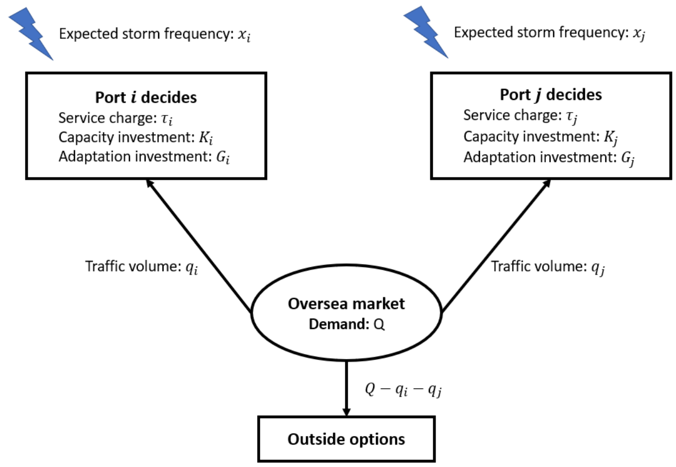


Figure 1: Model structure of the two-port system

Next, we derive the properties of the demand. We first look at how the port charge affects the port demand at the port itself and at the competing port. Let $Z_n = V_n/\sigma$. Since q_i appears on both sides of Equation (9a), we differentiate both sides of Equation (9a) with respect to (w.r.t.) τ_i and obtain

$$\frac{\partial q_i}{\partial \tau_i} = \frac{Q\exp(Z_i)}{\left(\sum_n \exp(Z_n)\right)^2}\left(\frac{\partial Z_i}{\partial \tau_i}\left(1+\exp(Z_j)\right) - \exp(Z_j)\frac{\partial Z_j}{\partial \tau_i}\right), \tag{10}$$

where $\frac{\partial Z_i}{\partial \tau_i}$ and $\frac{\partial Z_j}{\partial \tau_i}$ are expressed as

$$\frac{\partial Z_i}{\partial \tau_i} = -\frac{1}{\sigma}\left(1+\frac{\delta}{K_i}\frac{\partial q_i}{\partial \tau_i}\right), \tag{11a}$$

$$\frac{\partial Z_j}{\partial \tau_i} = -\frac{1}{\sigma}\frac{\delta}{K_j}\frac{\partial q_j}{\partial \tau_i}. \tag{11b}$$

By plugging Equation (11a) and Equation (11b) into Equation (10), we obtain one equation that contains two unknowns $\frac{\partial q_i}{\partial \tau_i}$ and $\frac{\partial q_j}{\partial \tau_i}$. Next, we differentiate both sides of Equation (9a) w.r.t. τ_j and obtain

$$\frac{\partial q_i}{\partial \tau_j} = \frac{Q\exp(Z_i)}{\left(\sum_n \exp(Z_n)\right)^2}\left(\frac{\partial Z_i}{\partial \tau_j}\left(1+\exp(Z_j)\right) - \exp(Z_j)\frac{\partial Z_j}{\partial \tau_j}\right), \tag{12}$$

where $\frac{\partial Z_i}{\partial \tau_j}$ and $\frac{\partial Z_j}{\partial \tau_j}$ are expressed as

$$\frac{\partial Z_i}{\partial \tau_j} = -\frac{1}{\sigma}\frac{\delta}{K_i}\frac{\partial q_i}{\partial \tau_j}, \tag{13a}$$

$$\frac{\partial Z_j}{\partial \tau_j} = -\frac{1}{\sigma}\left(1+\frac{\delta}{K_j}\frac{\partial q_j}{\partial \tau_j}\right). \tag{13b}$$

We thus obtain another equation that contains another two unknowns $\frac{\partial q_i}{\partial \tau_j}$ and $\frac{\partial q_j}{\partial \tau_j}$. Performing the same analysis on Equation (9b), we can thus obtain a system of four equations that contains four unknowns. The explicit expressions of the system of equations are provided in Appendix A. Solving this system of equations, we obtain the partial derivatives of demand w.r.t port pricing:

$$\frac{\partial q_i}{\partial \tau_i} = -\frac{Q\exp(Z_i)}{\Gamma}\left(\sigma\left(1+\exp(Z_j)\right)+\delta\frac{q_j}{K_j}\right) < 0, \tag{14a}$$

$$\frac{\partial q_j}{\partial \tau_j} = -\frac{Q\exp(Z_j)}{\Gamma}\left(\sigma\left(1+\exp(Z_i)\right)+\delta\frac{q_i}{K_i}\right) < 0, \tag{14b}$$

$$\frac{\partial q_i}{\partial \tau_j} = \frac{1}{\Gamma}\sigma Q \exp(Z_i)\exp(Z_j) > 0, \tag{14c}$$

$$\frac{\partial q_j}{\partial \tau_i} = \frac{1}{\Gamma}\sigma Q \exp(Z_i)\exp(Z_j) > 0, \tag{14d}$$

where the denominator Γ is

$$\Gamma = \sigma\left(\sigma\left(\sum_n \exp(Z_n)\right)^2 + Q\exp(Z_i)\frac{\delta}{K_i}(1+\exp(Z_j)) + Q\exp(Z_j)\frac{\delta}{K_j}(1+\exp(Z_i))\right) + \delta^2\frac{q_i q_j}{K_i K_j}\left(\sum_n \exp(Z_n)\right) > 0.$$

We can easily sign Equations (14a) to (14d): $\frac{\partial q_i}{\partial \tau_i} < 0$, $\frac{\partial q_j}{\partial \tau_j} < 0$, $\frac{\partial q_i}{\partial \tau_j} > 0$, and $\frac{\partial q_j}{\partial \tau_i} > 0$. Therefore, higher port charge reduces demand at own port but raises demand at its competing port. In addition, $\frac{\partial q_i}{\partial \tau_j} = \frac{\partial q_j}{\partial \tau_i}$, indicating that the pricing effect on the demand of competing port is the same for both ports.

To see how the port capacity and adaptation investments affect the port demand at the port itself and at the competing port, we perform the same analysis and obtain the following (the details can be found in Appendix A):

$$\frac{\partial q_i}{\partial K_i} = -\frac{Q\exp(Z_i)}{\Gamma}\left(\sigma(1+\exp(Z_j)) + \delta\frac{q_j}{K_j}\right)\left(m_i\frac{x_i}{G_i} - \delta\frac{q_i}{{K_i}^2}\right), \tag{15a}$$

$$\frac{\partial q_j}{\partial K_j} = -\frac{Q\exp(Z_j)}{\Gamma}\left(\sigma(1+\exp(Z_i)) + \delta\frac{q_i}{K_i}\right)\left(m_j\frac{x_j}{G_j} - \delta\frac{q_j}{{K_j}^2}\right), \tag{15b}$$

$$\frac{\partial q_i}{\partial K_j} = \frac{\sigma Q\exp(Z_i)\exp(Z_j)}{\Gamma}\left(m_j\frac{x_j}{G_j} - \delta\frac{q_j}{{K_j}^2}\right), \tag{15c}$$

$$\frac{\partial q_j}{\partial K_i} = \frac{\sigma Q\exp(Z_i)\exp(Z_j)}{\Gamma}\left(m_i\frac{x_i}{G_i} - \delta\frac{q_i}{{K_i}^2}\right), \tag{15d}$$

$$\frac{\partial q_i}{\partial G_i} = \frac{Q\exp(Z_i)}{\Gamma}\left(\sigma(1+\exp(Z_j)) + \delta\frac{q_j}{K_j}\right)\frac{m_i x_i K_i}{{G_i}^2} > 0, \tag{16a}$$

$$\frac{\partial q_j}{\partial G_j} = \frac{Q\exp(Z_j)}{\Gamma}\left(\sigma(1+\exp(Z_i)) + \delta\frac{q_i}{K_i}\right)\frac{m_j x_j K_j}{{G_j}^2} > 0, \tag{16b}$$

$$\frac{\partial q_i}{\partial G_j} = -\frac{\sigma Q\exp(Z_i)\exp(Z_j)}{\Gamma}m_j\frac{x_j K_j}{{G_j}^2} < 0, \tag{16c}$$

$$\frac{\partial q_j}{\partial G_i} = -\frac{\sigma Q\exp(Z_i)\exp(Z_j)}{\Gamma}m_i\frac{x_i K_i}{{G_i}^2} < 0. \tag{16d}$$

Apparently, $\frac{\partial q_i}{\partial G_i} > 0$, $\frac{\partial q_j}{\partial G_j} > 0$, $\frac{\partial q_i}{\partial G_j} < 0$, and $\frac{\partial q_j}{\partial G_i} < 0$. Thus, more protection investment enhances a port's competitiveness, as more shippers will be attracted to the port. One notable insight of how capacity affects demand can also be derived from an observation that $\frac{\partial q_i}{\partial K_i}$ exhibits the same sign as $\frac{\partial(\delta\cdot g_i(q_i,K_i))}{\partial K_i} - \frac{\partial(m_i\cdot h_i(K_i,\, G_i,x_i))}{\partial K_i}$ and $\frac{\partial q_j}{\partial K_i}$ exhibits the same sign as $\frac{\partial(m_i\cdot h_i(K_i,\, G_i,x_i))}{\partial K_i} - \frac{\partial(\delta\cdot g_i(q_i,K_i))}{\partial K_i}$. As a consequence, increasing the port's own capacity has two effects. Shippers experience lower congestion cost with a larger port capacity, but given the same adaptation investment, more capacity renders a port more vulnerable due to a greater exposure of assets to natural disasters, thus causing potentially more loss to shippers. If marginal congestion cost $\left(\frac{\partial(\delta\cdot g_i(q_i,K_i))}{\partial K_i}\right)$ outweighs marginal climate cost $\left(\frac{\partial(m_i\cdot h_i(K_i,\, G_i,x_i))}{\partial K_i}\right)$ increasing own capacity attracts more demand at own port and reduces demand at competing port. However, if marginal climate cost $\left(\frac{\partial(m_i \cdot h_i(K_i,\ G_i, x_i))}{\partial K_i}\right)$ outweighs marginal congestion cost $\left(\frac{\partial(\delta \cdot g_i(q_i, K_i))}{\partial K_i}\right)$, increasing own capacity can reduce demand at own port and enhances demand at competing port.

The results can be summarized in the following lemma.

Lemma 1. *(1). Higher port charge reduces demand at own port but raises demand at the competing port. For both ports, increasing or decreasing port charge exhibits the same effect on the demand of competing port. (2). More protection investment increases demand at own port but reduces demand at the competing port. (3). If marginal congestion cost outweighs marginal climate cost, more capacity investment increases demand at own port but reduces demand at the competing port; if marginal climate cost outweighs marginal congestion cost, more capacity investment reduces demand at own port but increases demand at the competing port.*

3.2 Port competition

Ports may have diverse ownership structures with different levels of private and public sector involvement, and thus different objectives in making decisions. According to World Bank (2022), there are four types of port ownership structures: service ports, tool ports, landlord ports, and fully privatized ports. Service port and tool ports mainly focus on the realization of public interests, landlord ports have a mixed character and aim to strike a balance between public and private interests, and fully privatized ports focus only on private interests. In this section, we consider two extremes: we analyze two competing ports that maximize their profit in Subsection 3.2.1, and two competing ports that maximize their respective social welfare in Subsection 3.2.2. The results of landlord ports are thus situated in between profit-maximizing ports (Subsection 3.2.1) and welfare-maximizing ports (Subsection 3.2.2), depending on the weight that the landlord ports put on public interests. In Subsection 3.2.3, we analyze the first-best outcome in which a centralized government makes decisions on behalf of the two ports with the objective of maximizing overall social welfare. We thus can compare how the equilibrium strategies of profit-maximizing competing ports and welfare-maximizing competing ports divert from the first-best outcome.

3.2.1 Profit-maximizing ports

In this subsection, we consider the competition behavior of profit-maximizing ports. Port i maximizes its own profit π_i by deciding its pricing τ_i, capacity investment level K_i, and protection investment level G_i, taking pricing τ_j, capacity K_j, and protection G_j at port j as exogenously given:

$$\max_{\{\tau_i, K_i, G_i\}} \pi_i = (\tau_i - c_i)\, q_i - M_i \cdot H_i\,(K_i, G_i, x_i) - K_i c_{K_i} - G_i, \tag{17}$$

where π_i is port i's profit, c_i is port i's unit operating cost, the function $H_i\,(K_i, G_i, x_i)$ captures the risk of coastal natural disasters faced by port i, parameter M_i converts the risk into a cost in monetary values, and c_{K_i} is the unit capacity investment cost. We take a linear form of risk and its monetary cost following port adaptation literature (Xiao et al. 2015, Wang and Zhang 2018, Xia and Lindsey 2021).

We assume the port has the same prior for the expected storm frequency x_i during the period as the shippers. In accordance with our modeling of the climate risk faced by shippers $h(\cdot)$, we formulate $H(\cdot)$ as

$$H\,(K_i, G_i, x_i) = x_i \cdot K_i \cdot \left(\frac{G_n}{K_n}\right)^{-1}, \tag{18}$$

where x_i corresponds to hazard, K_i corresponds to exposure, and $\left(\frac{G_n}{K_n}\right)^{-1}$ corresponds to vulnerability in Equation (6).

The first-order conditions (FOCs) w.r.t. τ_i, K_i, G_i are given by:

$$\frac{\partial \pi_i}{\partial \tau_i} = q_i + (\tau_i - c_i)\frac{\partial q_i}{\partial \tau_i} = 0, \tag{19a}$$

$$\frac{\partial \pi_i}{\partial K_i} = (\tau_i - c_i)\frac{\partial q_i}{\partial K_i} - M_i \frac{2x_i K_i}{G_i} - c_{K_i} = 0, \tag{19b}$$

$$\frac{\partial \pi_i}{\partial G_i} = (\tau_i - c_i)\frac{\partial q_i}{\partial G_i} + M_i \frac{x_i {K_i}^2}{{G_i}^2} - c_{G_i} = 0, \tag{19c}$$

where $\frac{\partial q_i}{\partial \tau_i}$, $\frac{\partial q_i}{\partial K_i}$, and $\frac{\partial q_i}{\partial G_i}$ are expressed in Equations (14a), (15a) and (16a), respectively.

The equilibrium outcome can be solved by formulating the competition game as a complementarity problem.

$$\min_{\{\tau_i, K_i, G_i, \tau_j, K_j, G_j\}} -\left(\tau_i \frac{\partial \pi_i}{\partial \tau_i} + K_i \frac{\partial \pi_i}{\partial K_i} + G_i \frac{\partial \pi_i}{\partial G_i} + \tau_j \frac{\partial \pi_j}{\partial \tau_j} + K_j \frac{\partial \pi_j}{\partial K_j} + G_j \frac{\partial \pi_j}{\partial G_j}\right),$$

$$s.t. \frac{\partial \pi_i}{\partial \tau_i} \le 0,\ \frac{\partial \pi_i}{\partial K_i} \le 0,\ \frac{\partial \pi_i}{\partial G_i} \le 0,\ \frac{\partial \pi_j}{\partial \tau_j} \le 0,\ \frac{\partial \pi_j}{\partial K_j} \le 0,\ \frac{\partial \pi_j}{\partial G_j} \le 0, \text{ eqs. (9a) and (9b).}$$

3.2.2 Welfare-maximizing ports

In this subsection, we consider the competition behavior of welfare-maximizing ports. A welfare-maximizing port chooses port pricing, capacity, and adaptation to maximize not only its own profit, but also the consumer surplus of the shippers using this port:

$$\max_{\{\tau_i, K_i, G_i\}} W_i = \pi_i + CS_i, \tag{20}$$

where W_i denotes the social welfare of port i, which equals the profit of port i (π_i) plus the consumer surplus of shippers using port i (CS_i). Consumers' surplus is a measure of aggregate consumer welfare. Here, CS_i represents the difference between shippers' willingness to pay for port i's services and the price that they pay for it.

The consumer surplus of one shipper is $E(\max_n U_n)$. Since shippers are assumed to be homogenous, the consumer surplus of the shippers using the port is calculated as follows (the derivation is provided in Appendix B):

$$CS_i = q_i \cdot E\left(\max_n U_n\right) = q_i \cdot \ln\left(\sum_n \exp(Z_n)\right), \tag{21}$$

where $Z_n = \frac{V_n}{\sigma}$. The FOCs are given by:

$$\begin{aligned}\frac{\partial W_i}{\partial \tau_i} =& q_i + (\tau_i - c_i)\frac{\partial q_i}{\partial \tau_i} + \frac{\partial q_i}{\partial \tau_i}\ln\left(\sum_n \exp(Z_n)\right) \\ & - \frac{q_i}{\sigma \sum_n \exp(Z_n)}\left(\exp(Z_i)\frac{\delta}{K_i}\frac{\partial q_i}{\partial \tau_i} + \exp(Z_j)\frac{\delta}{K_j}\frac{\partial q_j}{\partial \tau_i} + \exp(Z_i)\right) = 0,\end{aligned} \tag{22a}$$

$$\begin{aligned}\frac{\partial W_i}{\partial K_i} =& (\tau_i - c_i)\frac{\partial q_i}{\partial K_i} - M_i\frac{2x_iK_i}{G_i} - c_{K_i} + \frac{\partial q_i}{\partial K_i}\ln\left(\sum_n \exp(Z_n)\right) \\ & - \frac{q_i}{\sigma \sum_n \exp(Z_n)}\left(\exp(Z_i)\frac{\delta}{K_i}\frac{\partial q_i}{\partial K_i} + \exp(Z_j)\frac{\delta}{K_j}\frac{\partial q_j}{\partial K_i} + \exp(Z_i)(m_i\frac{x_i}{G_i} - \delta\frac{q_i}{{K_i}^2})\right) = 0,\end{aligned} \tag{22b}$$

$$\begin{aligned}\frac{\partial W_i}{\partial G_i} =& (\tau_i - c_i)\frac{\partial q_i}{\partial G_i} + M_i\frac{x_i{K_i}^2}{{G_i}^2} - 1 + \frac{\partial q_i}{\partial G_i}\ln\left(\sum_n \exp(Z_n)\right) \\ & - \frac{q_i}{\sigma \sum_n \exp(Z_n)}\left(\exp(Z_i)\frac{\delta}{K_i}\frac{\partial q_i}{\partial G_i} + \exp(Z_j)\frac{\delta}{K_j}\frac{\partial q_j}{\partial G_i} - exp(Z_i)\, m_i\frac{x_iK_i}{{G_i}^2}\right) = 0,\end{aligned} \tag{22c}$$

where $\frac{\partial q_i}{\partial \tau_i}$, $\frac{\partial q_j}{\partial \tau_i}$, $\frac{\partial q_i}{\partial K_i}$, $\frac{\partial q_j}{\partial K_i}$, $\frac{\partial q_i}{\partial G_i}$, $\frac{\partial q_j}{\partial G_i}$ are provided in Equations (14a), (14d), (15a), (15d), (16a) and (16d) respectively. Similarly, the complementarity problem is formulated as

$$\min_{\{\tau_i,K_i,G_i,\tau_j,K_j,G_j\}} -\left(\tau_i\frac{\partial W_i}{\partial \tau_i}+K_i\frac{\partial W_i}{\partial K_i}+G_i\frac{\partial W_i}{\partial G_i}+\tau_j\frac{\partial W_j}{\partial \tau_j}+K_j\frac{\partial W_j}{\partial K_j}+G_j\frac{\partial W_j}{\partial G_j}\right),$$
$$s.t.\frac{\partial W_i}{\partial \tau_i}\le 0,\ \frac{\partial W_i}{\partial K_i}\le 0,\ \frac{\partial W_i}{\partial G_i}\le 0,\ \frac{\partial W_j}{\partial \tau_j}\le 0,\ \frac{\partial W_j}{\partial K_j}\le 0,\ \frac{\partial W_j}{\partial G_j}\le 0,\ \text{eqs. (9a) and (9b)}.$$

3.2.3 The first-best outcome

In this subsection, we consider the first-best outcome where a central government makes decisions on behalf of the two ports with the objective of maximizing overall social welfare, which equals the total profits of the two ports and the total consumer surplus of shippers using the two ports:

$$\max_{\{\tau_i,K_i,G_i,\tau_j,\ K_j,G_j\}} W=\pi_i+\pi_j+CS_i+CS_j, \tag{23}$$

where W denotes the overall welfare of all players, π_i is provided in Equation (17), CS_i is provided in Equation (21), and π_j and CS_j can be formulated symmetrically.

The FOCs are given by:

$$\begin{aligned}\frac{\partial W}{\partial \tau_i}=&\frac{\partial W_i}{\partial \tau_i}+(\tau_j-c_j)\frac{\partial q_j}{\partial \tau_i}+\frac{\partial q_j}{\partial \tau_i}\ln\left(\sum_n \exp(Z_n)\right)\\&-\frac{q_j}{\sigma\sum_n\exp(Z_n)}\left(\exp(Z_i)\frac{\delta}{K_i}\frac{\partial q_i}{\partial \tau_i}+\exp(Z_j)\frac{\delta}{K_j}\frac{\partial q_j}{\partial \tau_i}+\exp(Z_i)\right)=0,\end{aligned} \tag{24a}$$

where $\frac{\partial W_i}{\partial \tau_i}$ is expressed in Equation (22a).

$$\begin{aligned}\frac{\partial W}{\partial K_i}=&\frac{\partial W_i}{\partial K_i}+(\tau_j-c_j)\frac{\partial q_j}{\partial K_i}+\frac{\partial q_j}{\partial K_i}\ln\left(\sum_n \exp(Z_n)\right)\\&-\frac{q_j}{\sigma\sum_n\exp(Z_n)}\left(\exp(Z_i)\frac{\delta}{K_i}\frac{\partial q_i}{\partial K_i}+\exp(Z_j)\frac{\delta}{K_j}\frac{\partial q_j}{\partial K_i}+\exp(Z_i)(m_i\frac{x_i}{G_i}-\delta\frac{q_i}{{K_i}^2})\right)=0,\end{aligned} \tag{24b}$$

where $\frac{\partial W_i}{\partial K_i}$ is expressed in Equation (22b).

$$\begin{aligned}\frac{\partial W}{\partial G_i}=&\frac{\partial W_i}{\partial G_i}+(\tau_j-c_j)\frac{\partial q_j}{\partial G_i}+\frac{\partial q_j}{\partial G_i}\ln\left(\sum_n \exp(Z_n)\right)\\&-\frac{q_j}{\sigma\sum_n\exp(Z_n)}\left(\exp(Z_i)\frac{\delta}{K_i}\frac{\partial q_i}{\partial G_i}+\exp(Z_j)\frac{\delta}{K_j}\frac{\partial q_j}{\partial G_i}-exp(Z_i)\,m_i\frac{x_iK_i}{{G_i}^2}\right)=0,\end{aligned} \tag{24c}$$

where $\frac{\partial W_i}{\partial G_i}$ is expressed in Equation (22c).

The complementarity problem is expressed as:

$$\min_{\{\tau_i,K_i,G_i,\tau_j,K_j,G_j\}} -\left(\tau_i\frac{\partial W}{\partial \tau_i}+K_i\frac{\partial W}{\partial K_i}+G_i\frac{\partial W}{\partial G_i}+\tau_j\frac{\partial W}{\partial \tau_j}+K_j\frac{\partial W}{\partial K_j}+G_j\frac{\partial W}{\partial G_j}\right),$$
$$s.t.\frac{\partial W}{\partial \tau_i}\le 0,\ \frac{\partial W}{\partial K_i}\le 0,\ \frac{\partial W}{\partial G_i}\le 0,\ \frac{\partial W}{\partial \tau_j}\le 0,\ \frac{\partial W}{\partial K_j}\le 0,\ \frac{\partial W}{\partial G_j}\le 0,\ \text{eqs. (9a) and (9b)}.$$

4 Numerical analysis

Based on the equilibrium outcomes described in Section 3, we conduct numerical experiments to assess how the changes of certain parameters affect the equilibrium outcome of the three cases based on ownership structures. The details of the data and input parameters estimation are provided in Appendix C.

4.1 Symmetric scenario analysis

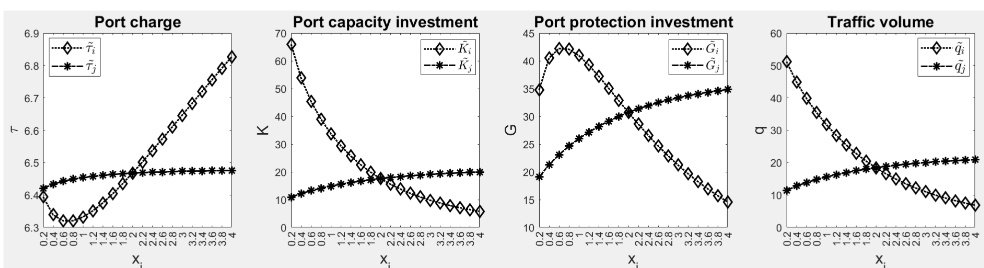
In this section, we consider a symmetric scenario, where the parameter values pertaining to both ports, namely port i and port j, are identical. This scenario corresponds to the real-world situation where two competing ports are subject to similar climate-change risks and operational characteristics. For example, Port of Vancouver and Port of Prince Rupert are both located on coastal areas and are subject to the same risk of sea-level rise of the Pacific Ocean. Port of Vancouver is the Canada's largest port by tonnage of cargo handled. Port of Prince Rupert is Canada's third busiest seaport by cargo tonnage and container volume. Serving as alternative to Port of Vancouver in Canada's west coast, Port of Prince Rupert and Port of Vancouver can be considered as competitors.

Table 2 lists the baseline parameter values for symmetric scenario. More specifically, we set the baseline value of constant utility of shippers choosing both ports as 10 to ensure that the outside option also captures a certain market share in the baseline as well as in the sensitivity analysis when the parameter is varied. Constant utility of shippers choosing a port captures the preference of shippers based on factors not explicitly considered in the utility function. A value much higher than 10 (such as 20) would lead to the two ports exactly splitting the market and shippers not choosing outside options available to transport their goods, which is not realistic. To determine the expected coastal natural disaster frequency during the planning horizon, we assume the annual disaster probability does not change within the period. Thus, the expected number of coastal disasters during the planning horizon can be calculated as $\sum_{h=0}^{N} h\ {x_a}^h (1-x_a)^{N-h} \frac{N!}{h!(N-h)!}$, where x_a is the annual disaster probability and N is the planning horizon. By assuming the annual probability of a coastal disaster is 0.1 and the planning horizon of the port encompasses 20 years, we calculate that the expected disaster frequency is 2 (thus in the baseline $x_i = x_j = 2$). Unit operating cost is sourced from the annual reports of Port of Vancouver and Port of Prince Rupert of 2020. Additionally, we refer to a few capacity investment projects recently undertaken or proposed by the ports in Canada to obtain an estimate for the unit capacity investment cost (more details in Appendix C). We assume $Q = 100$ in the baseline but we vary it widely from 50 to 150 to see its effects. The congestion cost that shippers incur due to port capacity constraint can include loss in cargo value due to depreciation/obsolescence, delivery delay penalty which results from customer dissatisfaction and reputation damage, and additional interest expenses on inventory. Since the congestion cost can be shipper-specific and can depend on the type of cargo, it is difficult to have a general estimate. We set $\delta = 4$ in the baseline but vary it widely from 1 to 10 to see its effects. We assume that the disaster intensity to shippers is $m_i = m_j = 0.5$ and the disaster intensity to the port is $M_i = M_j = 1$, as the damage cost to infrastructure is generally higher than the damage cost to cargo.

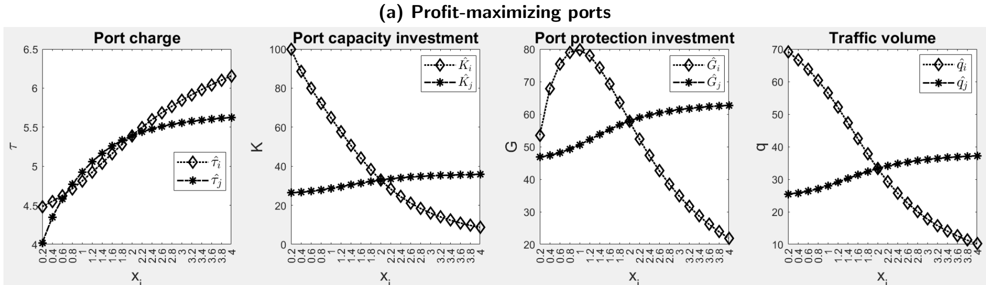
Table 2: Baseline parameter values for symmetric scenario

Constant utility for shippers	$\mu_i = \mu_j = 10$
Expected coastal disaster frequency during a port's planning horizon	$x_i = x_j = 2$
Intensity of damage to shippers	$m_i = m_j = 0.5$
Intensity of damage to the port	$M_i = M_j = 1$
Unit operating cost of the port	$c_i = c_j = 1$
Unit capacity investment cost of the port	$c_{Ki} = c_{Kj} = 1.5$
Potential market demand	$Q = 100$
Parameter measuring port congestion cost to shippers	$\delta = 4$

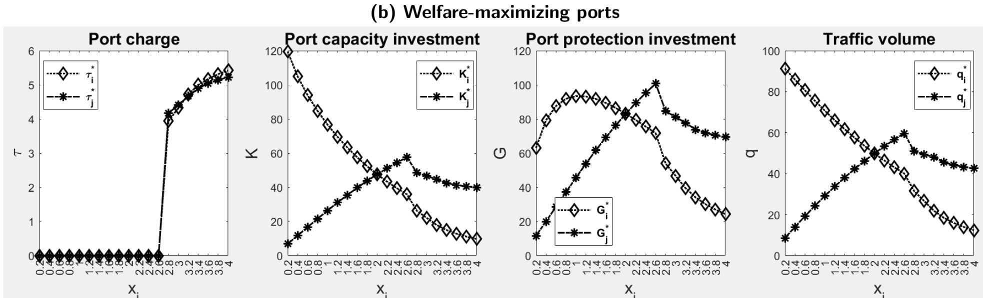
We now conduct sensitivity analyses for the parameter values. We start by analyzing two competing ports that are identical. However, as we vary certain parameters, the two ports are not symmetric anymore. Figure 2 displays the effects of varying expected disaster frequency x_i at port i under the three port ownership structures. In all figures, the symbol ˜ in the legend denotes the equilibrium outcome for profit-maximizing ports; the symbol ˆ in the legend denotes the equilibrium outcome for welfare-maximizing ports; and the symbol * in the legend denotes first-best outcome. As x_i varies from 0.2 to 4, the effect on the equilibrium outcome of capacity investment, protection investment and traffic volume are similar for profit-maximizing and welfare-maximizing ports. As x_i increases, port i would invest less in capacity because it is more likely to suffer from losses in infrastructure damage due to higher frequency and less capacity means fewer assets are at risk. On the other hand, port j would increase its capacity investment to accommodate the traffic diverting from port i to port j. The protection investment of port i is non-monotone. The protection investment first increases, then decreases with the climate risk at port i. This shows that a port will not necessarily always increase its protection investment when its climate risk intensifies. The reason is that when the climate risk is high (i.e., $x_i \geq 0.6$ under profit-maximizing ports and $x_i \geq 1$ under welfare-maximizing ports), the port would reduce its capacity investment to such an extent that the port does not need much protection investment to protect its infrastructure. But the protection investment at port j always increases since the increasing capacity investment at port j would need protection. Traffic volume at port i decreases as shippers do not find a high-climate-risk port attractive, while traffic volume at port j increases as traffic is diverted from port i to port j. Nevertheless, the reduction in port i's traffic volume outweighs the increase in port j's traffic volume, indicating less overall maritime traffic in the market.



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



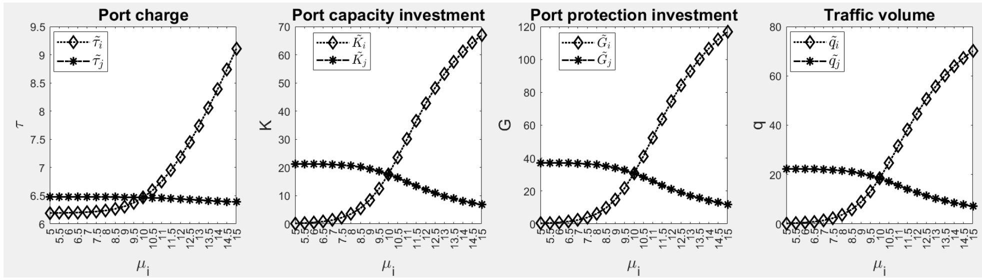
(c) First-best outcome

Figure 2: Varying expected disaster frequency x_i

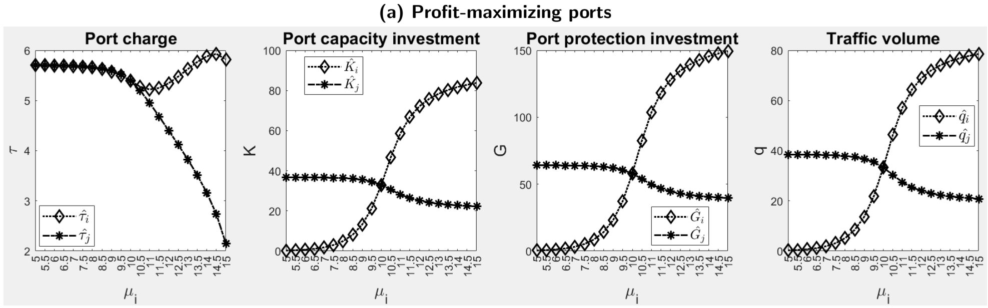
The pricing behavior is slightly different between profit-maximizing and welfare-maximizing ports. Under profit-maximizing ports, as shippers could be discouraged by the increasing climate risk at port i, port i first decreases its fees to attract traffic and compensate for increased risk for shippers. But since the capacity at port i decreases further with x_i, which causes congestion to shippers, port i is thus inclined to increase the port charge to curb congestion and regain some attractiveness to shippers. Since traffic is diverted to port j, there could be congestion at port j, but port j only increases its charge slightly as a profit-maximizing port does not care about the welfare loss of shippers due to congestion. On the contrary, under welfare-maximizing ports, the port charge at both port i and port j increases with x_i. Since port i considers the welfare of shippers who could be worse off due to the increasing climate risk at port i and the possible congestion because of decreasing port capacity, port i increases port charge. Due to the diverted traffic, port j increases the charge to reduce the congestions costs incurred by shippers. Under profit-maximizing ports, port charge varies between 6.3 and 6.8 for port i and between 6.4 and 6.5 for port j, while under welfare-maximizing ports, port charge varies between 4.5 and 6 for port i and between 4 and 5.5 for port j. Apparently, the port charge increases to a greater extent under welfare-maximizing ports, because these ports take into consideration the shippers' welfare, which includes the congestion cost. Welfare-maximizing ports invest more in capacity and protection and charge cheaper port fees than profit-maximizing ports. As a result, both the individual-port traffic volume and the overall traffic volume are higher under welfare-maximizing ports than under profit-maximizing ports.

Figure 2c depicts the first-best outcome of varying x_i. When $x_i \leq 2.6$ the port charge of both ports will be set to zero, representing the corner solution. In this range ($0.2 \leq x_i \leq 2.6$), K_i^* decreases with x_i while K_j^* increases with x_i, G_i^* first increases then decreases with x_i while G_j^* increases with x_i, and q_i^* decreases with x_i, and q_j^* increases with x_i. These insights are the same for profit and welfare-maximizing ports. Within this range, the total traffic volume under first-best outcome ($q_i^* + q_j^*$) hardly changes (i.e., $q_i^* + q_j^*$ varies only between 99.89 and 99.70) and is close to the potential market size ($Q = 100$). This occurs because the central government tries to satisfy the total potential market demand at the expense of port profits. When climate risk at port i is sufficiently large (i.e., $x_i \geq 2.8$), it is no longer optimal to satisfy all demand at the expense of port profits, and thus the equilibrium is no longer a corner solution. During this range ($2.8 \leq x_i \leq 4$), as the focus shifts from shippers' welfare to ports' profits, τ_i^* and τ_j^* both increase with x_i; K_i^* and K_j^* both decrease with x_i; G_i^* and G_j^* both decrease with x_i; q_i^* and q_j^* both decrease with x_i. This is contrary to the competition cases where the decision variables of the two ports can move in opposite directions with x_i. When the climate risk at port i is small (e.g., $x_i = 0.2$), the central government invests a lot in port i's capacity (e.g., $K_i^* = 119.5$, which is greater than $\widetilde{K}_i = 65.96$ and $\widehat{K}_i = 99.94$) and invests a lot less in port j's capacity (e.g., $K_j^* = 6.84$, which is lesser than $\widetilde{K}_j = 10.92$ and $\widehat{K}_j = 26.42$) to encourage shippers to go to port i. When the climate risk at port i is big (e.g., $x_i = 4$), the capacity investment at both port i and port j is greater than under profit/welfare-maximizing cases (e.g., $K_i^* = 9.74$, which is greater than $\widetilde{K}_i = 5.79$ and $\widehat{K}_i = 8.66$, and $K_j^* = 39.91$, which is greater than $\widetilde{K}_j = 35.86$ and $\widehat{K}_j = 19.96$). The port charge is not only a transfer between the port and shippers, but also a measure to control congestion. A higher port charge limits the traffic volume, thereby reducing congestion for the existing shippers. However, under the first-best outcome, the central government will build enough port capacity for shippers such that the port charge is set to zero because port congestion is no longer an issue.

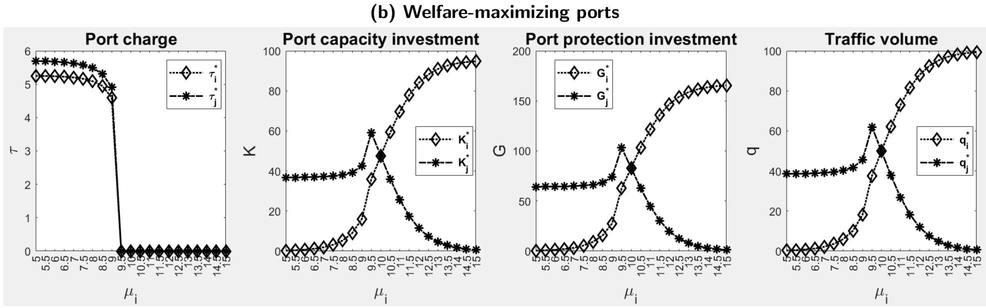
Figure 3 shows the effects of varying constant utility of shippers choosing port i, μ_i. μ_i and μ_j capture the preference of shippers based on factors not considered in the utility function. Here, $\mu_i > \mu_j$ implies that shippers prefer port i to port j if all else is equal. An increase in μ_i attracts more shippers at port i, thereby leading to an increase in port i's capacity, protection, and traffic volume. When μ_i varies from 5 to 10, the attractiveness of port i is increasing but is still less than that of port j. Thus, the capacity, protection, and traffic volume at port j decreases only slightly, because port j is still competent in the competition against port i. However, when μ_i varies from 10 to 15, port j is losing attractiveness, and thus we see a more obvious decrease in port j's capacity, protection, and



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



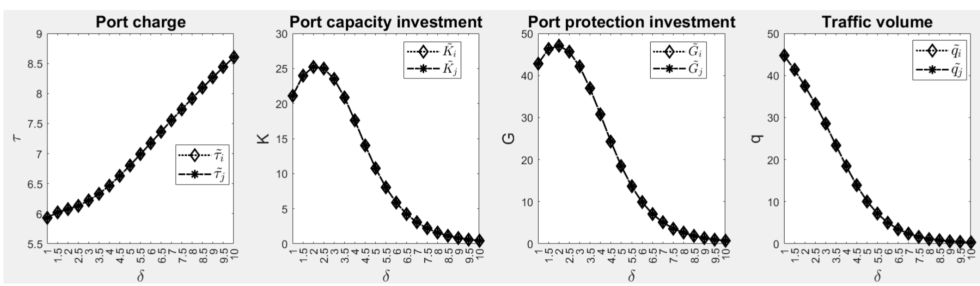
(c) First-best outcome

Figure 3: Varying constant utility for shippers $\mu_\mathbf{i}$

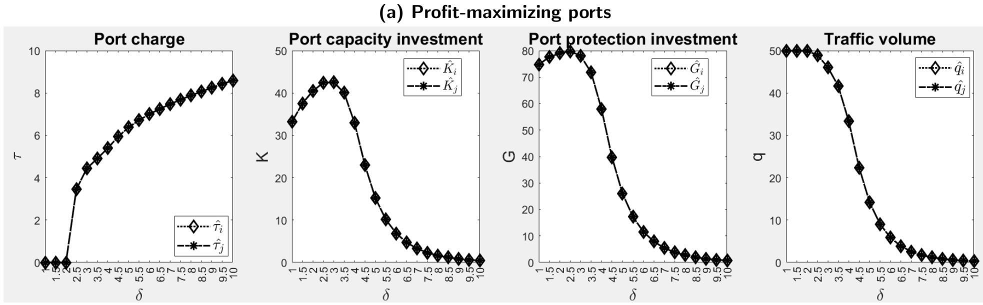
traffic volume. When μ_i is small (i.e., $\mu_i \leq 7$), the capacity, protection, and traffic at port i are close to 0. The above observations hold for both profit-maximizing and welfare-maximizing cases. However, under the welfare-maximizing case, the capacity, protection, and traffic at port i increase or decrease more when μ_i varies around the benchmark case where $\mu_i = \mu_j = 10$, while this observation does not hold in the profit-maximizing case. The pricing behavior is different under the profit-maximizing and welfare-maximizing ports. Under profit-maximizing ports, $\widetilde{\tau}_i$ increases with μ_i and the increasing trend is more obvious when $\mu_i \geq 10$, but $\widetilde{\tau}_j$ barely changes with μ_i. The increasing μ_i gives port i market power, which allows it to increase price, while port j competes with port i by adjusting capacity and protection rather than port charge. Under welfare-maximizing ports, $\widehat{\tau}_i$ and $\widehat{\tau}_j$ are roughly the same in the range of $5 \leq \mu_i \leq 10$, indicating that port i and port j compete in capacity and protection rather than price. In the range of $10 \leq \mu_i \leq 15$, $\widehat{\tau}_j$ decreases sharply with μ_i due to the loss of competitive advantage, whereas $\hat{\tau_i}$ first increases with μ_i due to the increasing market power and then decreases with μ_i due to the sharp decrease of $\widehat{\tau}_j$ (which tends to drag down $\widehat{\tau}_i$) and slower increase in $\widehat{K}_i$and $\widehat{G}_i$ (which gives port i less edge to increase price). As expected, welfare-maximizing ports charge lower fee, invest more in capacity and protection, and handle more traffic volume as compared to profit-maximizing ports.

Under the first-best outcome depicted in Figure 3c, when $9.5 \leq \mu_i \leq 15$, the equilibrium outcome is a corner solution where the pricing of both ports is 0. Within this range, K_i^*, $G_i^*$and q_i^* increases with μ_i, while K_j^*, $G_j^*$and q_j^* decreases with μ_i. The central government tries to satisfy all market demand which is evident from $q_i^* + q_j^*$ being close to 100. The increase in capacity investment, protection investment and traffic volume at port i and decrease of those at port j are symmetric since the decisions of the two ports are centralized, as opposed to welfare/profit-maximizing cases where the increase at port i exceeds the decrease at port j. When $5 \leq \mu_i \leq 9$, the equilibrium outcome becomes an interior solution. Within this range, K_i^*, $G_i^*$and q_i^* increases with μ_i. K_j^*, $G_j^*$and q_j^* also increases with μ_i (although only slightly), which is in contrast from the welfare/profit-maximizing cases where those variables of port j decrease (slightly) with μ_i. This happens because under the first-best case, port i and port j are not competing, instead they both try to satisfy more market demand. As a result, τ_i^* and τ_j^* both decrease with μ_i to attract traffic. Since $\mu_i < \mu_j$, we have $\tau_j^* > \tau_i^*$ as port j is more attractive and has the edge to charge higher fees.

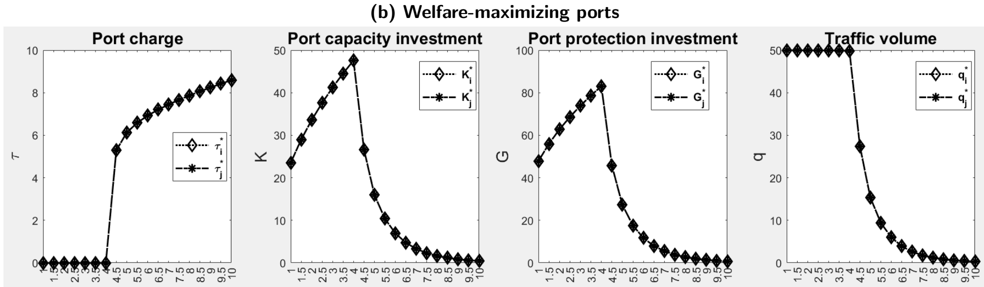
Figure 4 varies parameter δ, the congestion cost to shippers to capture the effect of shipment delays at the port. Since the ports are symmetric, varying δ results in the same outcome for port i and port j. Under profit-maximizing ports, as δ increases, ports initially increase their capacity investment to reduce the congestion costs for shippers. As δ increases further, the high congestion cost discourages the market to choose ports as an alternative, resulting in reduced demand for port services overall. As a result, ports would invest less in capacity. Protection investment changes with δ in the same way as port capacity. Port charge always increases with δ, because higher port charge reduces congestion by limiting the traffic at the ports. Traffic volume always decreases with δ as maritime transport becomes less attractive. The above results under welfare-maximizing ports are similar to profit-maximizing ports, except that when $1 \leq \delta \leq 2$, port charge of both ports is 0, indicating the equilibrium outcome is a corner solution. Within this range, each port captures half of the market.



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



(c) First-best outcome

Figure 4: Varying parameter for port congestion cost δ

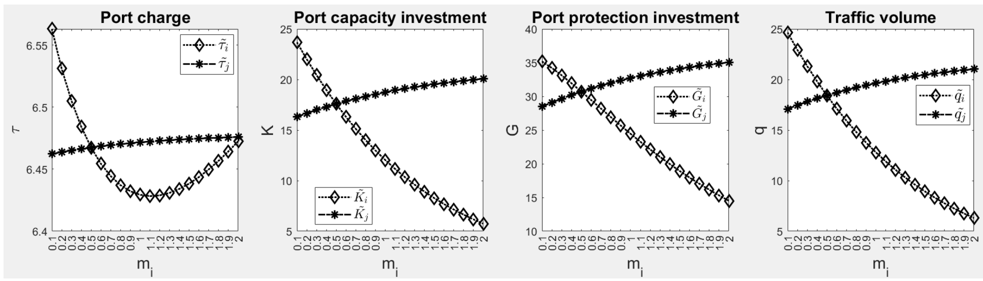
Under the first-best case, the equilibrium outcome is a corner solution in the range of $1 \leq \delta \leq 4$. Within this range, port charge is 0 and the two ports split the market equally. As δ increases, capacity investment undertaken by both ports increases which enables them to satisfy overall market demand. When $\delta > 4$, the equilbrium outcome is no longer a corner solution because satisfying overall market demand is not optimal. Within this range, similar to the profit-maximizing and welfare-maximizing cases, port capacity investment, protection investment and traffic volume decrease with δ, while the port charge increases with δ. Under both welfare-maximizing and the first-best cases, the ports charge lower fees, invest more in capacity and protection investment, and handle more traffic volume than profit-maximizing ports. Last, we compare the equilibrium under welfare-maximizing case and first-best case. When $1 \leq \delta \leq 2$, the equilibrium is a corner solution under both cases. Thus, the port charge is 0 and the two ports split the market. When $2 < \delta \leq 8$, the ports under welfare-maximizing case charge higher fees and handle less traffic than the ports under first-best. When $\delta \leq 3$, the ports under welfare-maximizing case invest more in capacity and protection than the ports under first-best case. This is because when the congestion cost to shippers is small ($\delta \leq 3$), it is not necessary for the ports to engage in congestion pricing and the equilibrium outcome is more likely to be a corner solution where the port charge becomes 0. Since congestion is not an issue, the ports try to satisfy all market demand. As the ports under welfare-maximizing case compete, they overinvest in capacity and protection, compared with ports who coordinate under first-best case, to attract shippers. When $3 < \delta \leq 8$, the congestion becomes an issue as the cost to shippers is high. The ports under first-best case are more willing to address the congestion issue and thus invest more in capacity and protection than the ports under welfare-maximizing case. When $8 < \delta \leq 10$, the congestion cost to shippers is extremely high, which renders maritime transport unattractive. Within this range, the difference between first-best case and welfare-maximizing case is negligible as both invest little in capacity and protection due to the shrink in demand.

Figure 5 shows the effects of varying the intensity of damage to shippers choosing port i m_i, which quantifies the expected damage suffered by shippers in monetary value. Under both profit-maximizing and welfare-maximizing ports, a higher m_i reduces the capacity investment, protection investment, and traffic volume at port i. On the other hand, capacity investment, protection investment, and traffic volume increases in port j since it appeals more to shippers and demand builds up. The reduction in these variables at port i outweighs the increase in those at port j in terms of absolute magnitude.

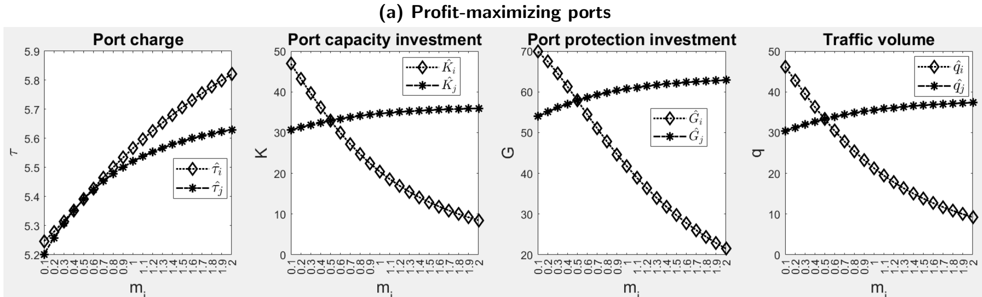
The pricing behavior is different under profit-maximizing and welfare-maximizing cases. Under profit-maximizing ports, $\widetilde{\tau}_i$ initially decreases as the port tries to attract traffic by reducing price. Subsequently, as m_i increases and the port invests less in capacity, the port increases $\widetilde{\tau}_i$ to control congestion. $\widetilde{\tau}_j$ slightly increases with m_i since port j attracts increasingly more shippers. Under welfare-maximizing port, port charge at both ports increases with m_i to control congestion since capacity at port i reduced a lot and capacity at port j does not increase as much. The four variables (pricing, capacity, protection, and traffic) also vary in a wider range under welfare-maximizing case than under profit-maximizing case.

Under the first-best case, when $m_i \leq 0.9$, the equilibrium outcome is a corner solution where the port charge is 0. Within this range, the two ports try to satisfy the overall market demand as the total traffic volume is close to 100. Intuitively, as m_i increases, capacity investment, protection investment and traffic volume decrease at port i and increase at port j. When $m_i \geq 1$, the equilibrium outcome is an interior solution. Within this range, consistent with the observation for welfare-maximizing and profit-maximizing ports, capacity investment, protection investment and traffic volume at port i decrease further with m_i. However, we first see a slight increase of capacity investment, protection investment and traffic volume at port j because port j still wants to take the traffic lost by port i. But as m_i further increases, an attempt to satisfy the market demand is not optimal since the increase in consumer welfare cannot outweigh the loss in profit. As a result, capacity investment, protection investment and traffic volume at port j then decrease with m_i. This is contrary to the welfare and profit maximizing cases where capacity, protection and traffic volume at port j always increase with

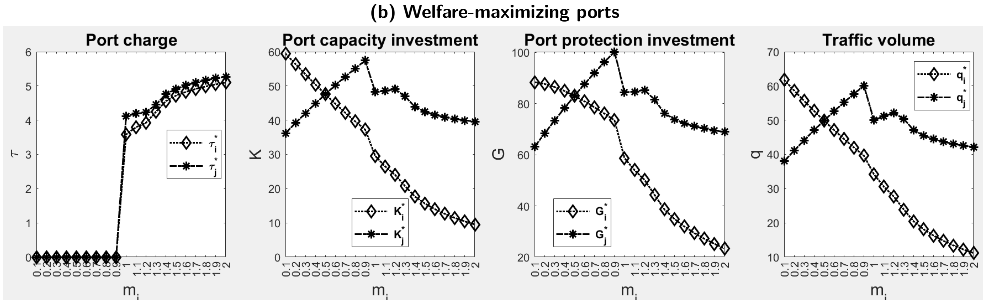
m_i due to competition. Similar to the welfare-maximizing case, port charge of the two ports increases with m_i.



(a) Profit-maximizing ports



(b) Welfare-maximizing ports

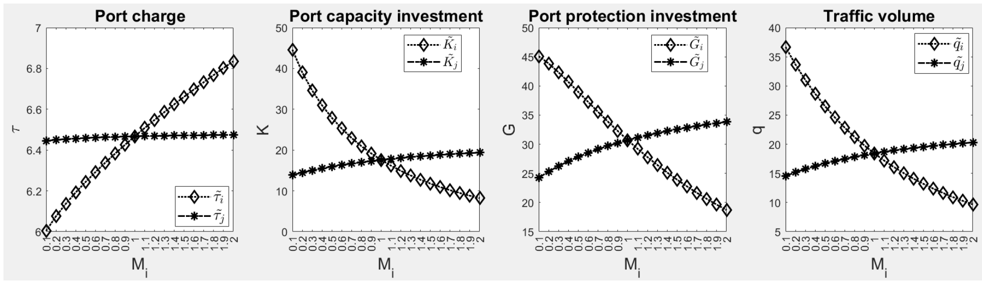


(c) First-best outcome

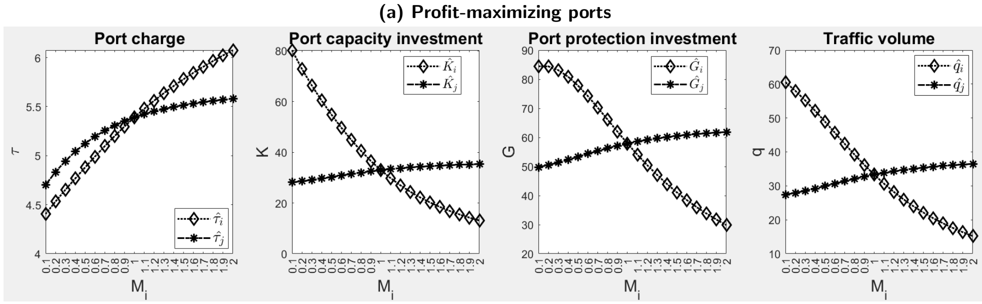
Figure 5: Varying intensity of damage to shippers $\mathbf{m_i}$

Figure 6 depicts the effects of varying the intensity of damage to port i M_i, which quantifies the expected damage suffered by the port in monetary value. Under both profit-maximizing and welfare-maximizing ports, as M_i increases, capacity investment, protection investment, and traffic volume decrease at port i and increase at port j. The reduction in these variables at port i outweighs the increase in those at port j in terms of absolute magnitude. Port charge of both ports under both cases increases with M_i, although τ_j increases very slightly. The four variables vary in a wider range under the welfare-maximizing case than under the profit-maximizing case.

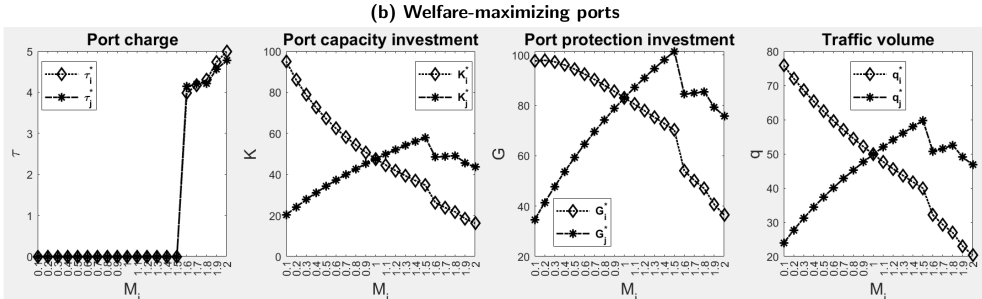
Under the first-best case, when $M_i \leq 1.5$, the equilibrium outcome is a corner solution where port charge is 0. Within this range, the two ports try to satisfy the overall market demand as the total traffic volume is close to 100. As M_i increases, port j appeals more to shippers than port i. As a result, K_i^*, G_i^* and q_i^* decreases with M_i, while K_j^*, G_j^* and q_j^* increases with M_i. When $M_i \geq 1.6$, the equilibrium outcome is an interior solution. Within this range, consistent with the observation for welfare and profit-maximizing ports, capacity investment, protection investment and traffic volume at port i decreases further with M_i. Initially, capacity investment, protection investment and traffic volume at port j increases as the port attempts to take up the traffic lost by port i. But as M_i further increases, trying to satisfy the market demand is not optimal, since the increase in consumer welfare cannot outweigh the lost in profit. As a result, capacity investment, protection investment and traffic volume at both ports decline with M_i. Similar to the welfare-maximizing case, port charge of the two ports increases with M_i.



(a) Profit-maximizing ports



(b) Welfare-maximizing ports

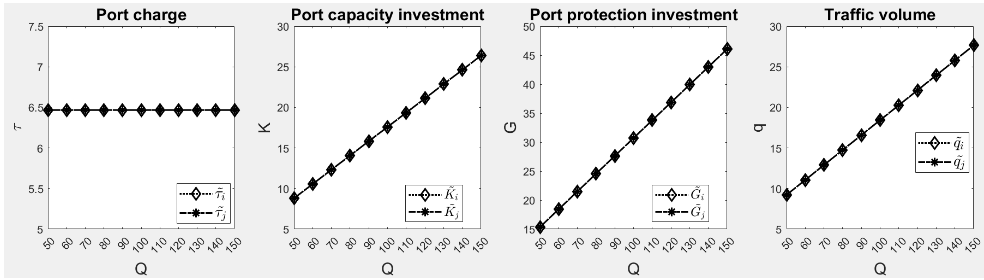


(c) First-best outcome

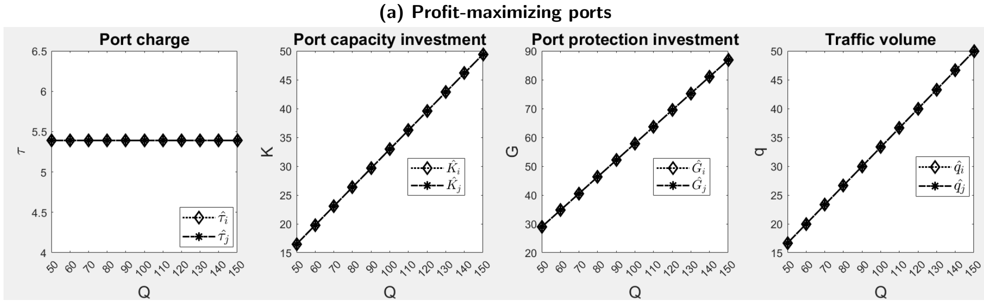
Figure 6: Varying intensity of damage to port $\mathbf{M_i}$

Figure 7 reveals the effects of varying potential market demand, Q. Under all three cases, as Q increases, both ports' capacity and protection investment increase strongly, as does traffic volume on account of new shippers entering the market. The ports compete fiercely to attract shippers by offering enhanced capacity and ensuring better protection against climate change induced events and disasters. Port charge under all cases is invariant to Q. This implies that both ports finance their investments without increasing the port charge as it would entail losing the competitive edge to the competitor. The port charge is always set to 0 under first-best outcome.

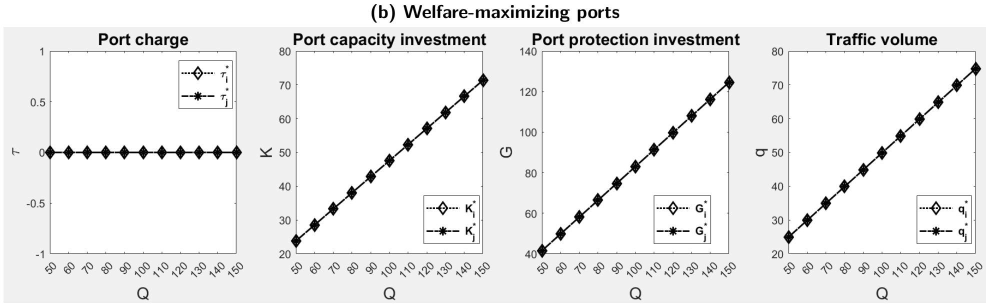
Figure 8 varies the unit operating cost of port i, c_i. As c_i increases, port i increases its port charge as it becomes more expensive to operate the port, thereby causing shippers to prefer port j over port i. Given irreversibility of investments, port i will reduce capacity investment as demand shrinks. The port also holds back on protection to avoid overinvesting because the amount of capacity requiring protection declines with c_i. Conversely, increased demand of port j amongst shippers leads to a slight increase in its port charge under welfare-maximizing case, whereas the charge of port j remain mostly invariant under profit-maximizing case as they do not care about the congestion cost incurred by shippers. With marginal increase in charge of port j being considerably lower than that of port i, port j retains its competitive edge over port i as c_i varies. Port j slightly increases capacity and protection investment to accommodate the increased demand and defend larger capacity. These



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



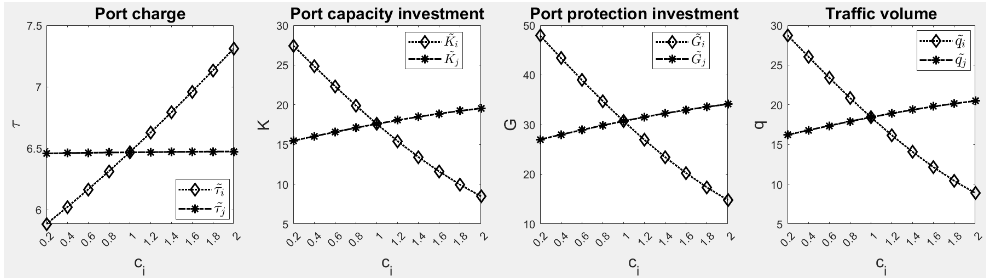
(c) First-best outcome

Figure 7: Varying potential market demand Q

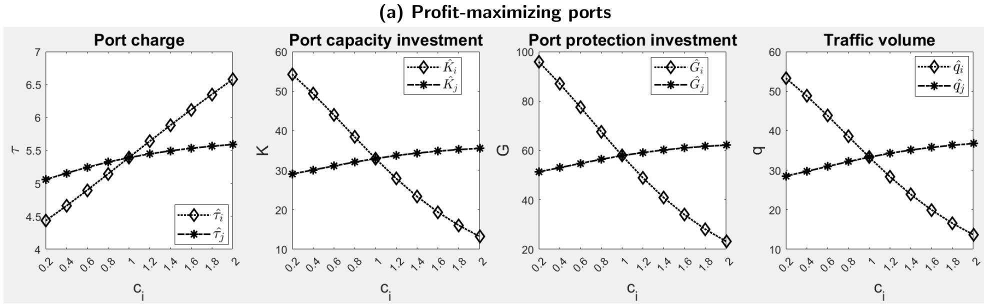
insights hold under both welfare-maximizing and profit maximizing ports. But the variables vary in a wider range under welfare-maximizing ports.

Under the first-best case, when $c_i \leq 1.4$, the equilibrium outcome is a corner solution where the ports try to satisfy the overall market demand. Within this range, port charge is 0 and total traffic volume is close to 100. When $c_i \geq 1.6$, the equilibrium outcome is an interior solution. Within this range, contrary to the welfare and profit maximizing cases, the capacity investment, protection investment and traffic volume of both ports decrease with c_i as the ports under first-best case coordinate. However, charges levied by both ports increases with c_i, consistent with welfare and profit maximizing cases.

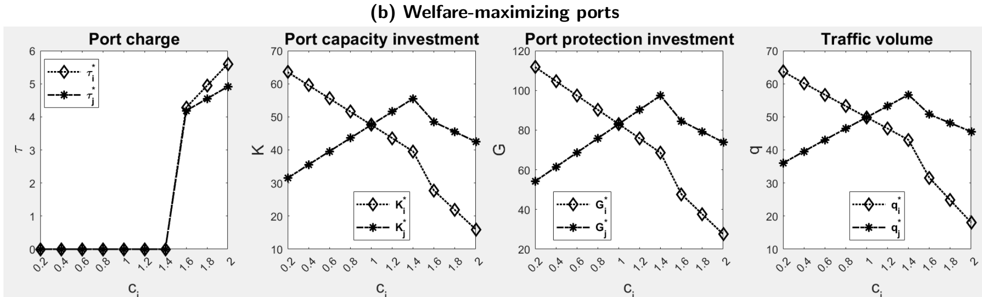
The effects of varying unit capacity investment cost of port i, c_{ki}, are shown in Figure 9. As c_{ki} rises, intuitively port i decreases its capacity investment, which leads to the decrease in port i's protection as well. Consequently, shippers start to prefer port j over port i. Port j thus embarks on capacity enhancement projects to compete with port i. Port j's adaptation investment also increases as capacity requiring protection increases with c_{ki}. Nevertheless, the reduction in port i's capacity outweighs the increase in port j's capacity, indicating less overall capacity in the market. Reduced traffic volume compels the port i to increase its port charge to maintain its profitability margin. Port j's charge slightly increases as excess demand for the port builds up. These observations are the same under both welfare-maximizing and profit maximizing ports, despite that the charge of port j under welfare-maximizing case increases to a greater extent than under profit-maximizing case due to the consideration of shippers' welfare.



(a) Profit-maximizing ports



(b) Welfare-maximizing ports

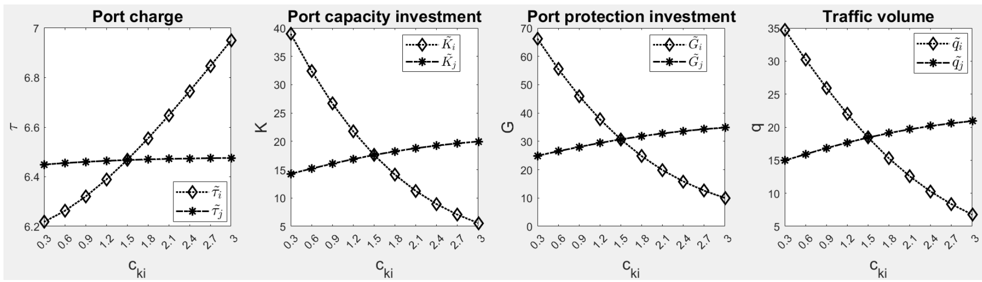


(c) First-best outcome

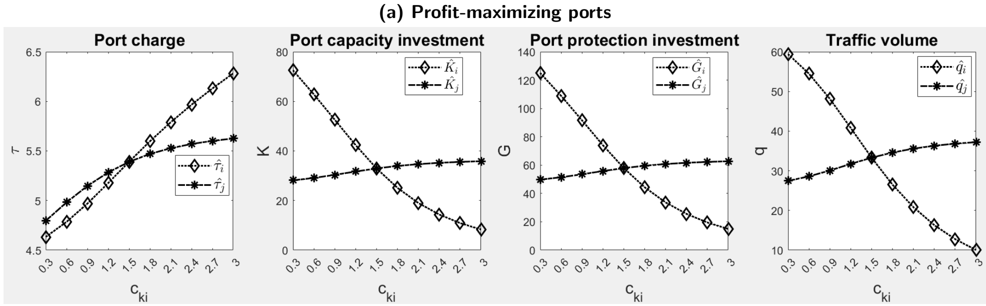
Figure 8: Varying unit operating cost $\mathbf{c_i}$

Under the first-best case, when $c_{ki} \leq 1.8$, the equilibrium outcome is a corner solution where port charge is 0 and total traffic volume is close to 100. When $c_{ki} \geq 2.1$, the equilibrium outcome is an interior solution. Within this range, contrary to the welfare and profit maximizing cases, the capacity investment, protection investment and traffic volume of both ports decrease with c_{ki} due to coordination. The charges levied by both ports increases with c_{ki}, consistent with welfare and profit maximizing cases.

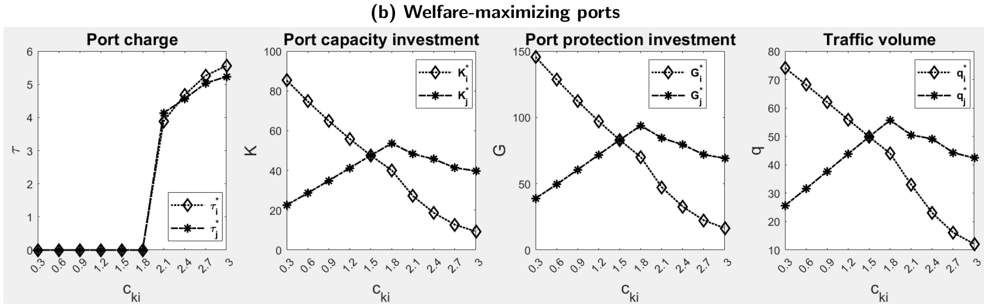
Figure 10 shows the effect of varying σ, which measures the heterogeneity in the error term of the random utility function and provides insights on how well the behavior of shippers can be predicted. We assume $\sigma = 1$ in the baseline. Larger σ indicates higher heterogeneity in the error term implying increased difficulty in behavior prediction. With a bigger σ, capacity investment undertaken by both ports decrease because of the effect of unknown factors on shippers' choice. Protection investment also decreases as the amount of capacity requiring protection declines with σ. Traffic volume in general decreases with σ, except when σ is small and the two ports try to satisfy overall market demand. The above observations are similar under the three cases. Under welfare-maximizing case, when $\sigma \leq 0.6$, the ports find it easier to predict shippers' choice behavior and thus try to satisfy overall market demand, demonstrated by $\widehat{q}_i$ and $\widehat{q}_j$ are both close to 50. At $\sigma = 0.2$ and $\sigma = 0.4$, capacity and protection further increase compared to the scale at $\sigma = 0.6$, which warrants the ports to raise their port charge as the enhanced capacity and protection increase shippers' willingness to pay. When $\sigma > 0.6$, port charge increases with σ as congestions poses concerns due to reduced capacity. This observation also applies for profit-maximizing ports. Note that the port charges under profit-maximizing cases always



(a) Profit-maximizing ports



(b) Welfare-maximizing ports

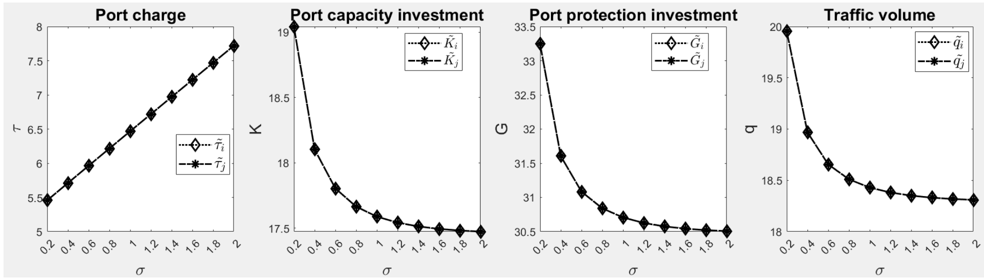


(c) First-best outcome

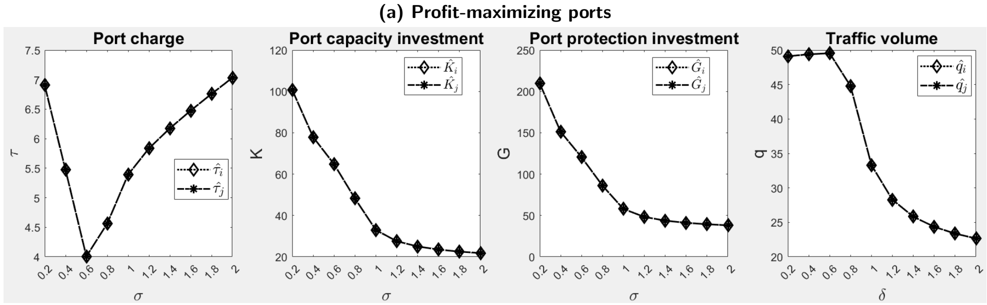
Figure 9: Varying unit capacity investment cost c_{ki}

increase with σ, as profit-maximizing ports never consider satisfying overall market demand. Under first-best case, when $\sigma \leq 1$, the equilibrium outcome is a corner solution. The ports under first-best keep their port charge at 0 despite trying to satisfy overall market demand, contrary to the ports under welfare-maximizing case. When $\sigma > 1$, the equilibrium outcome is an interior solution with insights similar to the welfare-maximizing case.

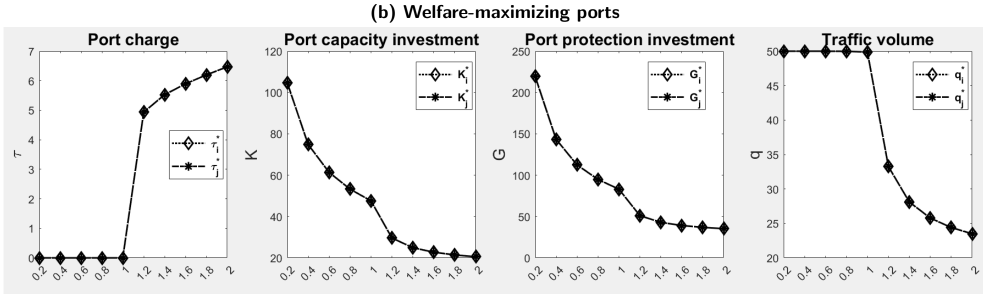
We now vary port-specific parameters relating to expected disaster frequency, constant utility attained by shippers, and the disaster intensity to shippers to the ports simultaneously. We vary expected disaster frequency of both ports, x_i and x_j, simultaneously indicating a global deterioration of the climate in Figure 11. With the increase in both x_i and x_j, the ports reduce their investment in capacity because they are more likely to suffer from losses in infrastructure damage and less capacity means fewer assets are at risk. The protection investment of both ports is non-monotone. The ports first increase their protection investment as higher climate risk warrants more protection. But after the climate risk exceeds a certain range, their protection investment reduces, because they invest in substantially less capacity that requires protection. Port charge of both ports increases with climate risk to ensure congestion is at an acceptable level given the decline in capacity. Consequently, traffic volume decreases with x_i and x_j. The above insights apply for both profit and welfare maximizing cases. However, at $x_i = x_j = 0.2$, the equilibrium outcome under welfare-maximizing case is a corner solution where port charge is 0 and the two ports split the market. Additionally, port charge, capacity investment, protection investment and traffic volume vary within a wider range under welfare-maximizing case than under profit-maximizing case.



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



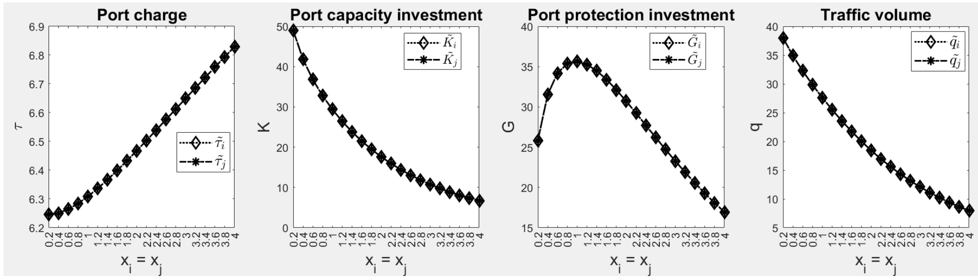
(c) First-best outcome

Figure 10: Varying σ

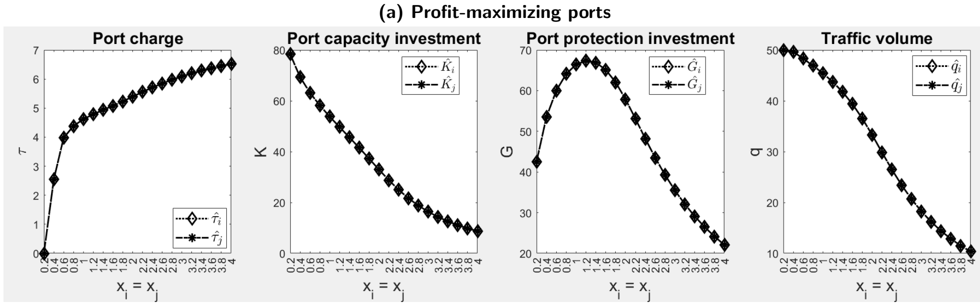
Under the first-best case, when $0.2 \leq x_i = x_j \leq 2$, the equilibrium outcome is a corner solution. Within this range, port capacity decreases slightly with climate risk, whereas port protection increases substantially to ensure protection of the ports and the shippers. The traffic volume q_i^* and q_j^* both stay at 50 to split the total market. When $x_i = x_j > 2$, it is no longer optimal for the ports to satisfy overall market demand. The insights within this range are similar to the profit and welfare maximizing cases.

Figure 12 varies constant utility attained by shippers choosing both ports, μ_i and μ_j . As μ_i and μ_j increase, the ports become more attractive than other alternatives for shippers. The ports thus increase capacity and protection investment to accommodate the increased demand, leading to an increase in traffic volume. The above insights are the same under profit and welfare maximizing ports, but pricing behavior is different. Under profit-maximizing case, since ports enjoy more market power, port charge increases in order to obtain more profit margin, whereas under welfare-maximizing case, port charge decreases in order to satisfy more market demand. In particular, when $13 \leq \mu_i = \mu_j \leq 15$, the equilibrium outcome becomes a corner solution, and thus port charge is set to 0 and traffic volume of each port is close to 50.

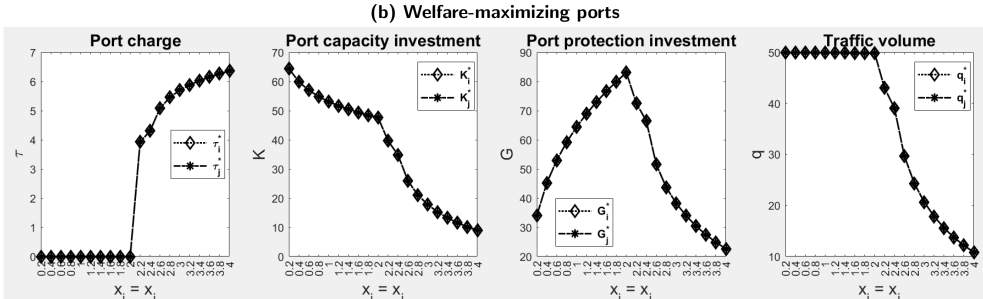
Under first-best case, when $\mu_i = \mu_j \geq 10$, the equilibrium outcome is a corner solution where port charge is 0. Within this range, capacity and protection investments remain constant, implying sufficient port capacity and protection to satisfy the overall market. When $\mu_i = \mu_j < 10$, the insights resemble the welfare-maximizing case.



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



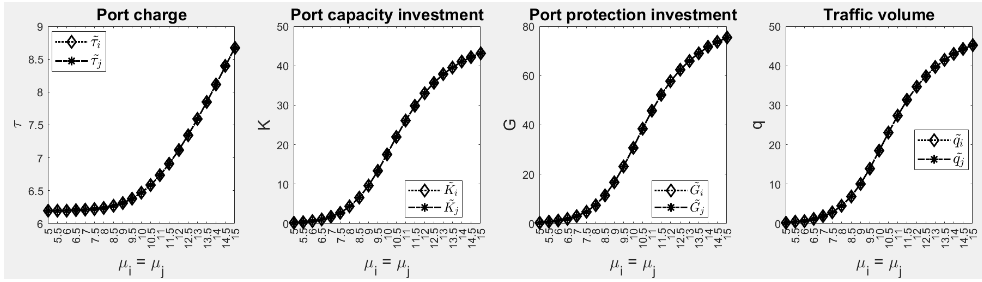
(c) First-best outcome

Figure 11: Varying expected disaster frequency of both ports, x_i and x_j

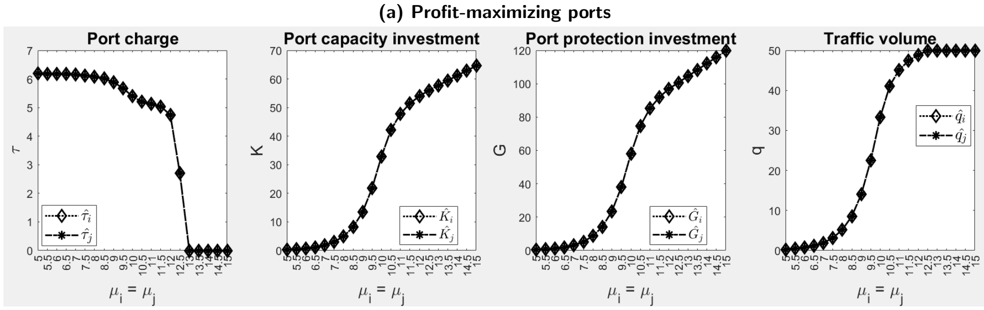
We examine the effect of the overall increase in the intensity of damage to shippers choosing both ports, m_i and m_j in Figure 13. As m_i and m_j increase, capacity, protection, and traffic volume at both ports decrease under profit and welfare maximizing cases. However, pricing behavior is different. Under profit-maximizing case, as m_i and m_j increase, ports initially reduce their charge to attract traffic and subsequently increase it as an attempt to control congestion as capacity is further reduced. On the contrary, ports under welfare-maximizing case always increase their charge with m_i and m_j to control congestion since capacity is substantially reduced. The four variables vary in a wider range under welfare-maximizing case than under profit-maximizing case.

Under first-best case, when $m_i = m_j \leq 0.6$, the equilibrium outcome is a corner solution. Within this range, port charge is kept at 0 and traffic volume of each port is kept at 50. Capacity investment remains almost invariant because when the capacity invested is adequate to meet overall market demand, the ports do not have incentive to further increase capacity as m only affects shippers. But to protect shippers, ports increase protection investment. When $m_i = m_j > 0.7$, the equilibrium outcome is an interior solution wherein the ports no longer try to satisfy overall market demand. Consequently, capacity and protection investments undertaken by both ports decline with m_i and m_j. Moreover, consistent with the welfare-maximizing case, port charge increases with m_i and m_j within this range. As a result, q_i^* and q_j^* reduce as well.

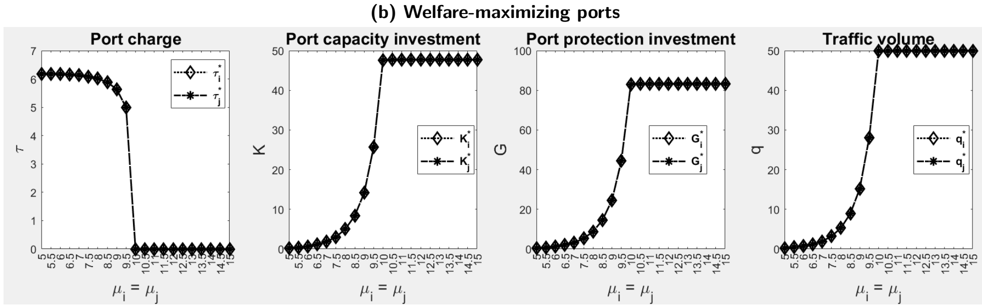
We examine the effect of the overall increase in intensity of damage to both ports, M_i and M_j in Figure 14. The insights from varying M_i and M_j in all cases resemble those from varying m_i



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



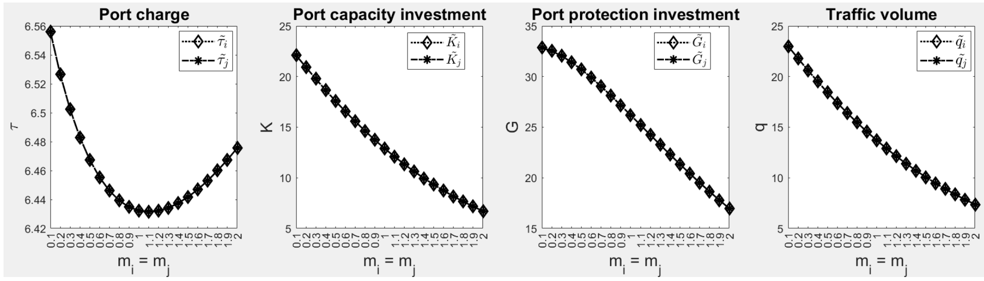
(c) First-best outcome

Figure 12: Varying constant utility for shippers choosing both ports, μ_i and μ_j

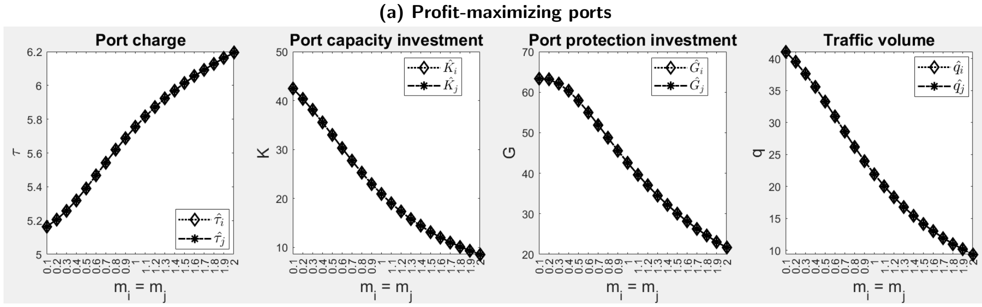
and m_j, with three exceptions First, for profit-maximizing ports, the port charge increases with M_i and M_j while port charge is non-monotone with m_i and m_j. This can be attributed to M being a port-wise parameter while m being a user-wise parameter. In such a situation, reducing port charge is effective in attracting traffic since it counters the effect of an increasing m, but is not effective when the parameter in change is M. Second, for welfare-maximizing ports, the protection investment is non-monotone with M_i and M_j while protection investment decrease with m_i and m_j. As M_i and M_j increases, $\widehat{G}_i$and $\widehat{G}_j$ initially increases slightly with M till $M_i = M_j = 0.3$, and subsequently declines. This happens because the ports first increase their protection investment to counter higher intensity of damage. But after such vulnerability exceeds a certain range, their protection investment reduces, because they invest in substantially less capacity that requires protection. Last, port capacity investment always decreases with M_i and M_j, but remains almost invariant with m_i and m_j in the range of corner solutions. The first-best equilibrium outcome is a corner solution when $M_i = M_j \leq 1.1$.

4.1.1 Asymmetric scenario analysis

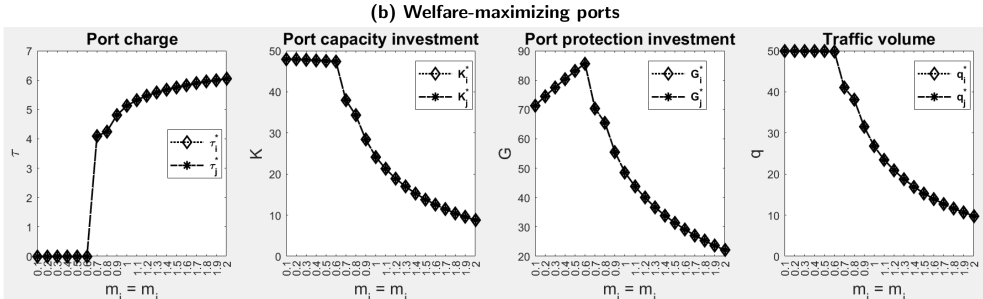
We now consider the asymmetric scenario, where the assumed values of a few parameters pertaining to both ports are different. This scenario corresponds to a real-world situation where competing ports could be subject to different climate risks. For instance, Port of Rotterdam and Port of Antwerp are competitors. Overseen by the Port of Rotterdam Authority, Port of Rotterdam is the largest port in Europe with throughput of 468.7 million tonnes in 2021. The Port of Antwerp-Bruges is Europe's second-largest seaport and handles around 290 million tonnes of international maritime cargo every



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



(c) First-best outcome

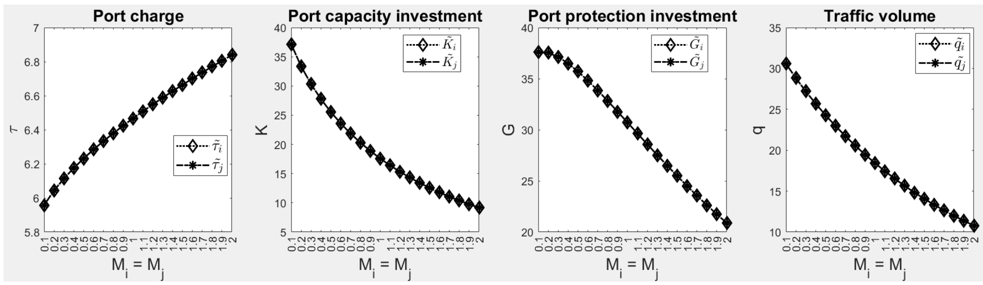
Figure 13: Varying intensity of damage to shippers choosing both ports, $\mathbf{m_i}$ and $\mathbf{m_j}$

year. However, since Port of Rotterdam is located on the North Sea, while Port of Antwerp-Bruges is situated on the estuary of the river Scheldt, Port of Rotterdam is subject to higher climate risk due to sea level rise and flooding than Port of Antwerp. On the contrary, Port of Rotterdam might have a better strategic location due to its adjacence to deep water. The asymmetric numerical analysis thus tries to capture such a scenario and serves as a robustness check to show that the insight from symmetric analysis also holds in the asymmetric scenario.

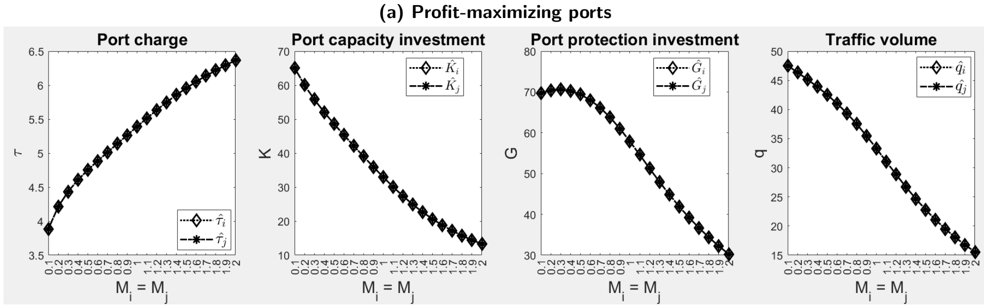
Table 3 lists the parameter values for asymmetric equilibrium. In our baseline parameters, we assume $\mu_i = 10 < \mu_j = 16$ to indicate that shippers attain higher constant utility from choosing port j, thereby implying shippers' preference for port j over port i if all else being equal. We also assume $x_i = 2 < x_j = 6$, suggesting port j and its users to be subjected to higher climate risk. We also choose a higher m_j and M_j further implying higher climate risk at port j. The other parameters are kept the same as in the symmetric case.

We now conduct computational numerical experiments to investigate the impact of varying key parameters on port charge, level of capacity investment, level of adaptation investment and traffic volume in asymmetric case setting.

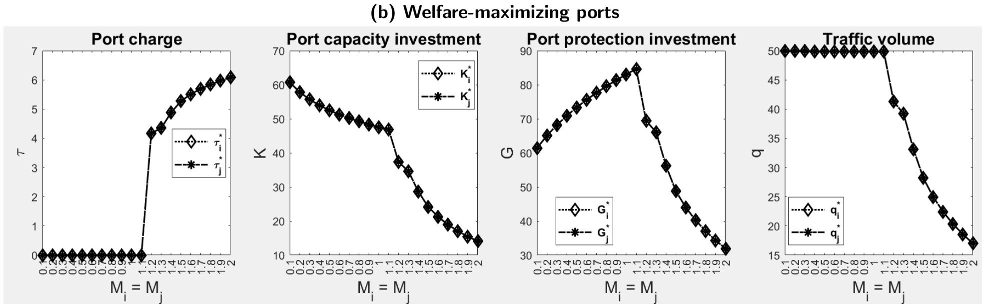
Figure 15 varies expected disaster frequency at port i, x_i. The insights are largely the same as Figure 2 in the symmetric scenario. Specifically, at port i, capacity investment decreases with x_i, protection is non-monotone, while traffic volume decreases; at port j, capacity, protection, and traffic all increase with x_i. But a few points are worth noting. First, the effect of x_i on $\widehat{\tau}_j$ is not monotone: $\widehat{\tau}_j$



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



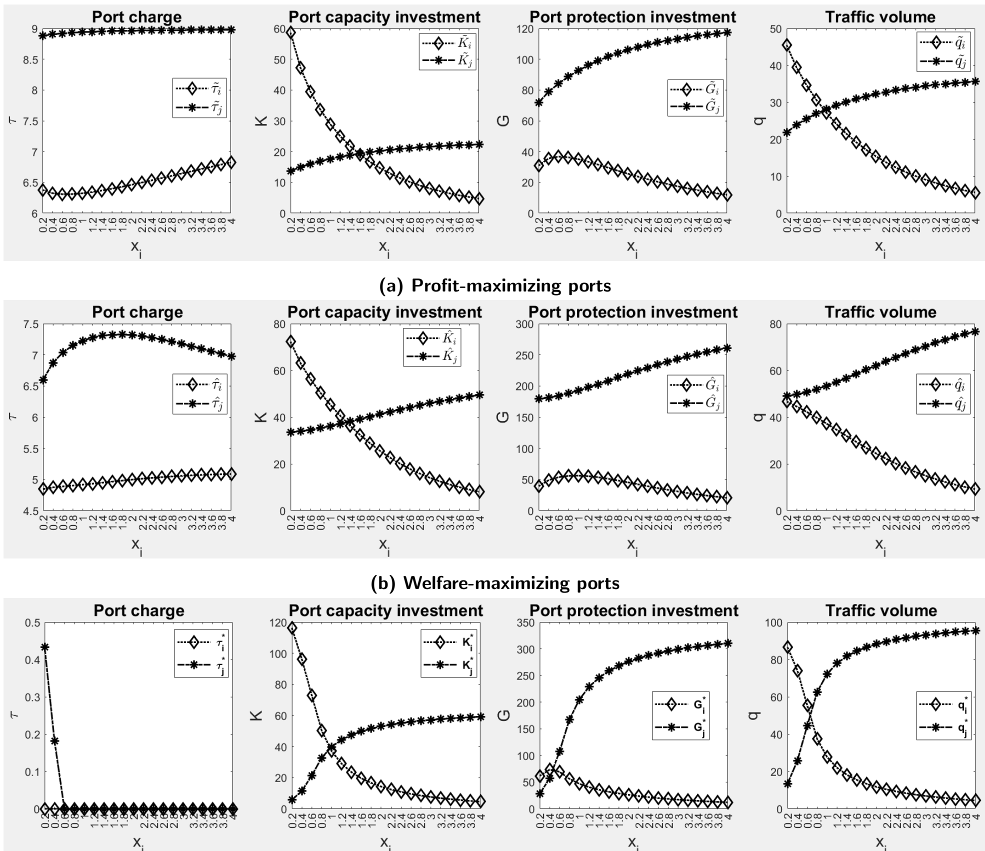
(c) First-best outcome

Figure 14: Varying intensity of damage to both ports, $\mathbf{M_i}$ and $\mathbf{M_j}$

Table 3: Baseline parameter values for asymmetric scenario

Constant utility for shippers	$\mu_i = 10;\ \mu_j = 16$
Expected coastal disaster frequency during a port's planning horizon	$x_i = 2;\ x_j = 6$
Intensity of damage to shippers	$m_i = 0.5;\ m_j = 1$
Intensity of damage to the port	$M_i = 1;\ M_j = 3$
Unit operating cost of the port	$c_i = c_j = 1$
Unit capacity investment cost of the port	$c_{Ki} = c_{Kj} = 1.5$
Potential market demand	$Q = 100$
Parameter measuring port congestion cost to shippers	$\delta = 4$

first increases then declines with x_i. As x_i increases from 0.2 to 1.6, the decrease in $\widehat{K}_i$ is substantial but increase in $\widehat{K}_j$ is minimal. This happens because the competitive advantage of port j is still not strong enough to warrant substantial increase in $\widehat{K}_j$. Consequently, port j increases $\widehat{\tau}_j$ to resolve the congestion issues that arise due to shift in traffic from port i to port j and inadequate $\widehat{K}_j$. However, when x_i increases from 1.6 to 4, $\widehat{K}_i$ decreases at a slower rate but $\widehat{K}_j$ increases further, making capacity constraint at port j less of an issue which warrants the reduction in $\widehat{\tau}_j$. Second, the equilibrium outcome under first-best case is mostly corner solution. When $x_i \leq 0.4$, the charge at port j becomes positive to further encourage shippers to use port i. Third,$\widehat{K}_j$ is more than twice the scale of $\widetilde{K}_j$, and consequently, $\widehat{G}_j$ is also more than twice the scale of $\widetilde{G}_j$. This is because $\mu_j > \mu_i$, so letting more users use port j would give more consumer surplus, which is consistent with the objective function of maximizing welfare. Last, in the range where $x_i \leq 1$, K_j^*, G_j^* and K_i^* vary at a faster rate than in the



(a) Profit-maximizing ports

(b) Welfare-maximizing ports

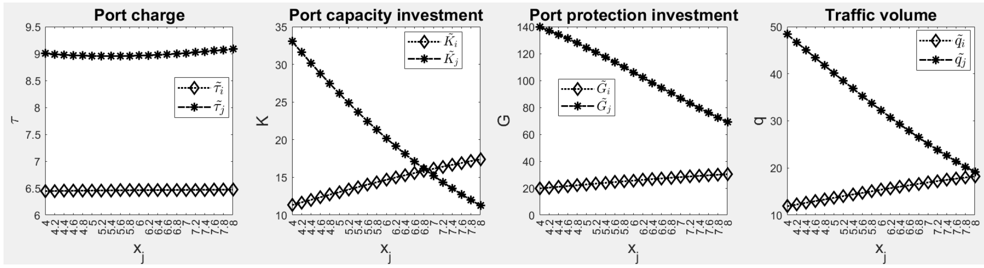
(c) First-best outcome

Figure 15: Varying expected disaster frequency $\mathbf{x_i}$

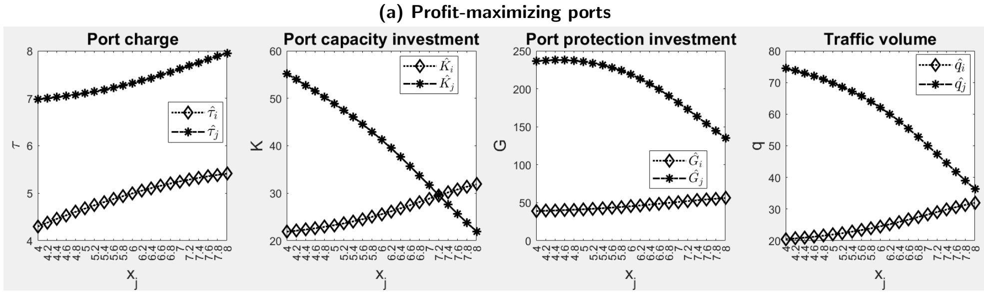
range $x_i > 1$. This is because when x_i is small (i.e., $x_i \leq 1$), the central government encourages the use of port i by increasing the capacity investment at port i and simultaneously reducing the capacity and protection investment at port j.

Figure 16 displays the effect of varying expected disaster frequency at port j, x_j. The results are quite intuitive. For all three cases, the increase in x_j results in the reduction of capacity and traffic at port j and the increase of capacity, protection, and traffic at port i. The protection of port j decreases in general, although some slight non-monotonicity can be observed for the welfare-maximizing and first-best case. In terms of pricing, the port charges under profit-maximizing case remain largely invariant, indicating the ports compete more in capacity and protection than price. The ports charges under welfare-maximizing case increases with x_j, which reflects that the ports practice congestion pricing to control congestion. Under first-best case, the outcome is always a corner solution with price set at 0.

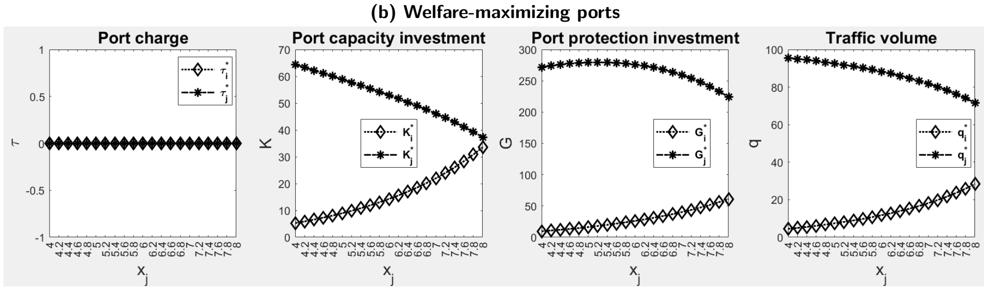
Figure 17 varies constant utility attained by shippers choosing port i, μ_i. For all three cases, with the increase in μ_i, port i becomes more attractive for shippers leading to the increase in capacity, protection, and traffic volume at port i, while these variables at port j decrease. Under both profit and welfare maximizing cases, increased demand for port i leads to an increase in port i's service charge, which increases the port's profit margin and limit ports given the increase in traffic. However, under welfare-maximizing case, the effect of μ_i on $\widehat{\tau}_j$is not monotone. Initially, when $5 \leq \mu_i \leq 10.5$, port j increases $\widehat{\tau}_j$ to reduce the congestion as capacity decreases. Subsequently, when $11 \leq \mu_i \leq 15$, the port decreases $\widehat{\tau}_j$ to attract traffic although traffic volume still falls. Under profit-maximizing case, port j just slightly reduces $\widetilde{\tau}_j$ to attract traffic. Under the first-best case, the central government



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



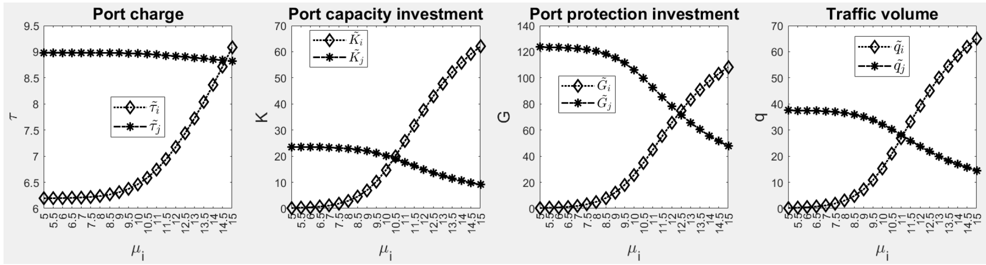
(c) First-best outcome

Figure 16: Varying expected disaster frequency $\mathbf{x_j}$

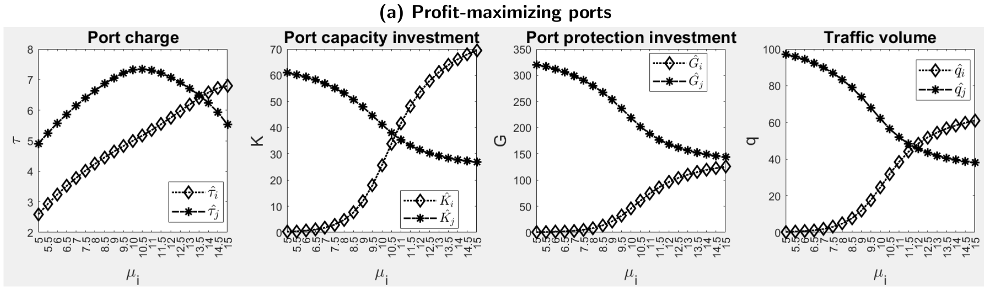
builds enough port capacity for shippers such that the port charge is set to zero as congestion is no longer an issue. Under profit-maximizing case, the reduction in $\widetilde{q}_j$ is outweighed by the increase in $\widetilde{q}_i$ implying overall increase in the traffic volume in the market, whereas under welfare-maximizing and first-best cases, the changes in traffic volume for the two ports are more symmetric.

Figure 18 shows the effect of varying constant utility attained by shippers choosing port j, μ_j. An increase in μ_j results in the increase in capacity, protection, and traffic volume at port j, whereas these three variables decrease at port i. This observation applies for both profit and welfare maximizing cases and the first-best case when the equilibrium outcome is a corner solution. Under profit-maximizing case, $\widetilde{\tau}_j$ increases with μ_j to exploit the market power port j has, while $\widetilde{\tau}_i$ hardly changes. Under welfare-maximizing case, $\widehat{\tau}_i$ always decreases with μ_j due to the loss of attractiveness of port i to shippers. However, port j initially decreases $\widehat{\tau}_j$ to attract demand as the capacity invested increases substantially when $\mu_j \leq 16.5$. When $16.5 \leq \mu_j \leq 19.5$, the invested capacity slows down, which results in the increase in $\widehat{\tau}_j$ to deal with congestion. But when $\mu_j \geq 19.5$, the invested capacity again catches up, combined with the sharp price cut at port j, resulting in the reduction in $\widehat{\tau}_j$. Under the first-best case, the equilibrium outcome is an interior solution when $\mu_j < 15$. Within this range, capacity investment, protection investment and traffic volume of both ports increase with μ_j, while port charge decreases with μ_j as the ports coordinate to attract more shippers overall.

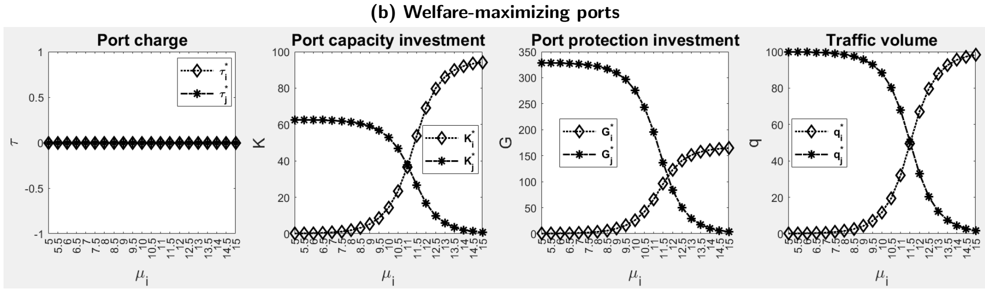
Figure 19 varies congestion cost to shippers, δ. Since the ports are asymmetric, varying delta results in different magnitude of such variations in port i and port j. The changes in these variables are more drastic for port j as compared to port i. Under profit-maximizing ports, as δ increases, both port i and port j witness reduced realized traffic volume as shippers start to explore other external alternatives



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



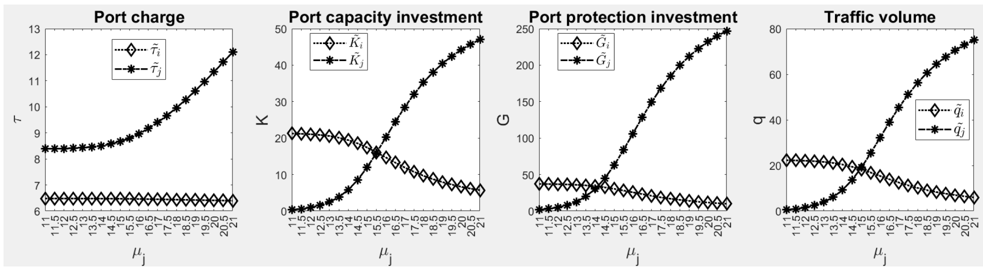
(c) First-best outcome

Figure 17: Varying constant utility for shippers μ_i

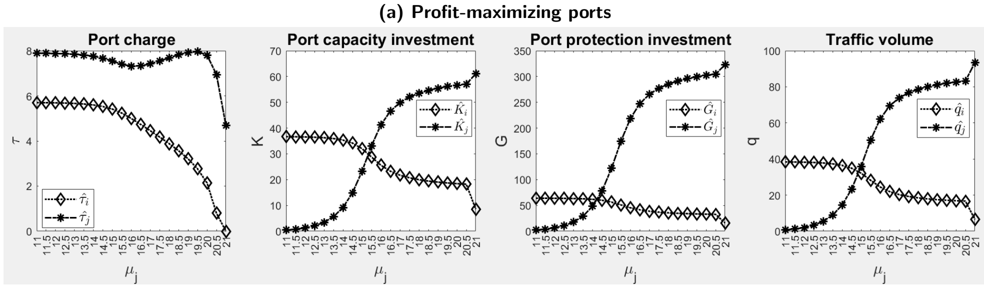
available to them. Capacity investment of both ports is non-monotone. If δ is small, undertaking capacity investment is optimal when δ increases since it reduces congestion costs for shippers. If δ is large, benefits of reducing congestion are muted as traffic volume is modest. As amount of capacity requiring protection varies with δ, adaptation investment undertaken by both ports to defend its larger facilities varies with δ in a similar manner. The pricing behaviour of the two ports largely varies. As δ increases, port i increases respective port charge since higher port charge reduces congestion. Port j, on the other hand, initially reduces $\tau_j^{\sim}$ to stimulate demand when $1 \leq \delta \leq 3.5$. Afterwards, $\tau_j^{\sim}$ increases as δ increases to curb congestion.

The results under welfare-maximizing ports are similar to profit-maximizing ports, except that when $1 \leq \delta \leq 2.5$, port charge of both ports is 0 and port j 's traffic volume is closer to 100, indicating that the equilibrium outcome is a corner solution. As $\delta > 2.5$, the insights for capacity investment, protection investment and traffic volume resemble profit-maximizing case. Within this range, unlike profit-maximizing case, port charge of both ports under welfare-maximizing case increases with δ, because higher port charge reduces congestion by limiting the traffic at the ports.

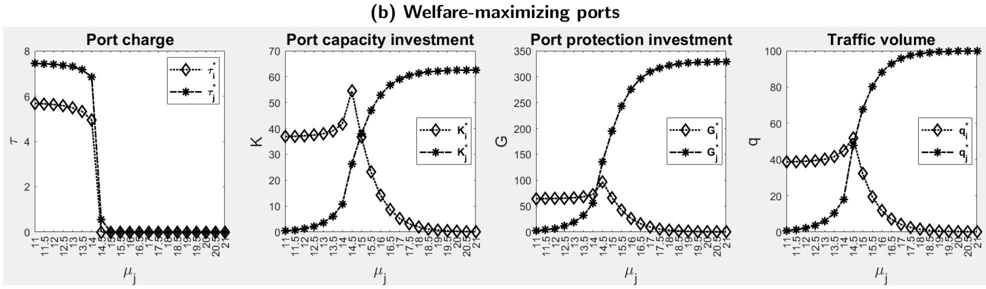
Under the first-best case, the equilibrium outcome is a corner solution in the range of $1 \leq \delta \leq 4.5$, where port charge is 0. Within this range, as δ increases, capacity and protection investment undertaken by both ports increases to accommodate the traffic. When $\delta > 4.5$, the equilbrium outcome is no longer a corner solution because satisfying overall market demand is not optimal. Within this range, capacity investment, protection investment and traffic volume decrease with δ, while port charge increases with δ.



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



(c) First-best outcome

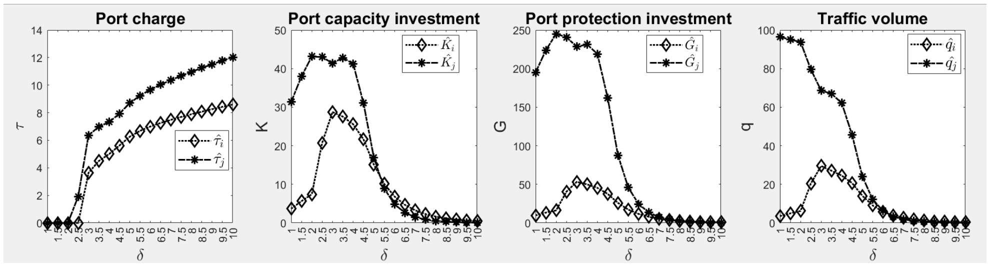
Figure 18: Varying constant utility for shippers μ_j

Figure 20 shows the effects of varying the intensity of damage to shippers choosing port i, m_i. For all three cases, capacity, protection, and traffic at port i decreases with m_i, but these variables increase with m_i at port j. The port charge under the profit-maximizing case remains largely invariant, but under the welfare-maximizing case it decreases with m_i to compensate for the higher intensity of damage to shippers. The equilibrium outcome always remains to be a corner solution under first-best case, which leads to zero port charge.

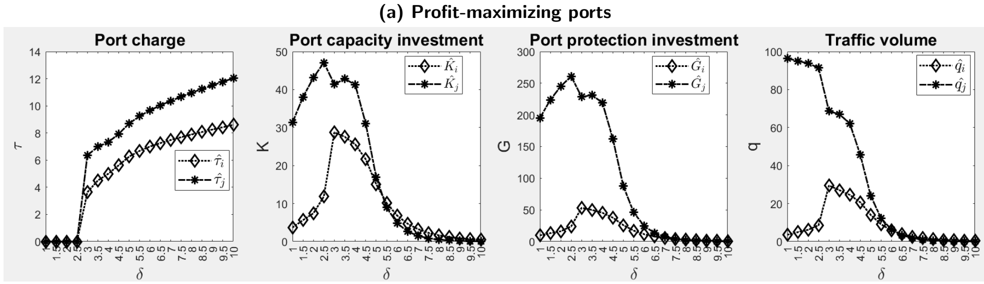
Figure 21 displays the effects of varying intensity of damages to shippers choosing port j, m_j. The insights are largely the same as Figure 20 of varying m_i, but a few points worth noting. First, some slight nonmonotonicity (inverted U-shape) can be observed for protection investment under welfare-maximizing and first-best cases. Second, $\widetilde{\tau}_j$ decreases with m_j, while $\widetilde{\tau}_i$ does not vary much with m_i in Figure 20. Since port j faces higher climate risk than port i (i.e., $x_j > x_i$ in the baseline), the marginal increase in m_j disadvantages port j to a greater extent than the marginal increase in m_i on port i. Thus, with increasing m_j in Figure 21, apart from the reduction in capacity and protection, port j also reduces service charge to compete with port i. Last, $\widehat{\tau}_i$ increases with m_j to handle the congestion due to the demand shifted from port j, while $\widehat{\tau}_j$ exhibits a slight U-shape as port j first tries to recapture traffic and later has to deal with congestion due to the substantial cut in capacity.

Figure 22 varies the intensity of damage to port i, M_i. The insights are the same as Figure 6 in the symmetric case, and thus are not repeated here.

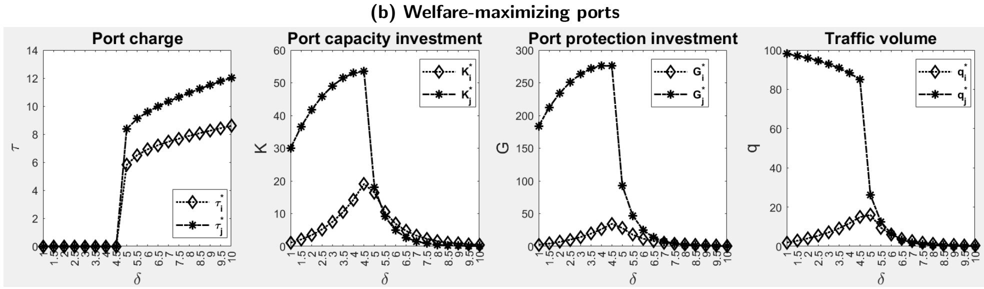
Figure 23 displays the effects of varying intensity of damage to port j, M_j. The insights are mostly the same as Figure 21, with two points worth noting. First, $\widetilde{\tau}_j$ increases with M_j, but $\widetilde{\tau}_j$ decreases



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



(c) First-best outcome

Figure 19: Varying parameter for port congestion cost δ

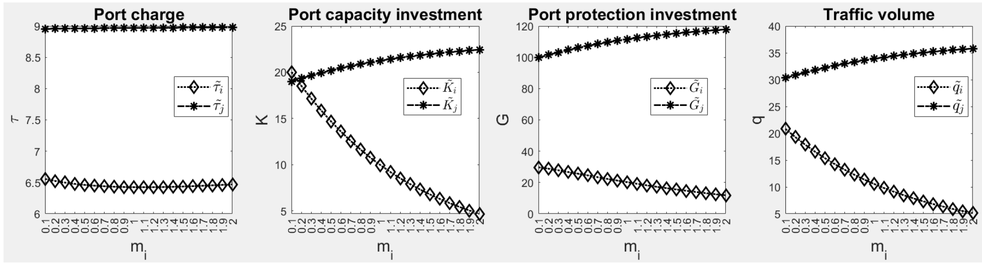
with m_j. Since changes in M_j does not affect shippers' demand for port j, port j can increase $\widetilde{\tau}_j$ to maintain its profit margin. Second, $\widehat{\tau}_j$ increases with M_j, but $\widehat{\tau}_j$ exhibits a slight U-shape with m_j. Again, since changes in M_j does not affect shippers' demand, port j does not reduce port charge to compensate for or attract shippers.

4.2 Managerial implications

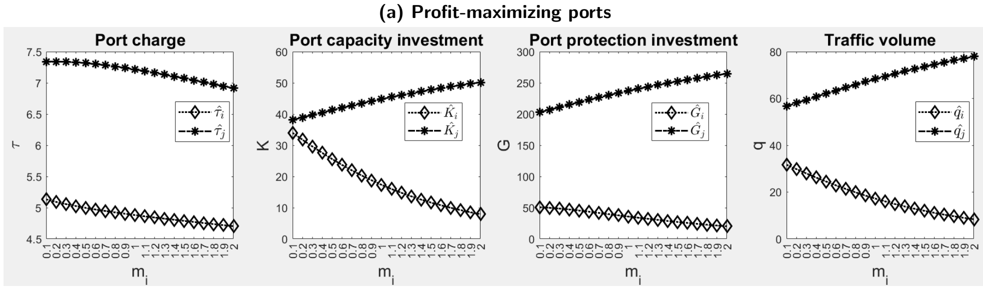
From our analysis in Section 4.1 and 4.2, we demonstrate the following managerial implications.

First, when a port faces higher climate risk either due to higher disaster frequency or higher damage intensity, this port would invest less in capacity to expose fewer assets at risk. However, this port will not necessarily always increase its protection investment, because when the climate risk is sufficiently high, the port would substantially cut capacity investment, which warrants less protection investment. Its competing port, however, would increase investment in capacity to capture the shift in demand from the port that entails higher climate risk. The protection investment at the competing port also increases to ensure the increased capacity infrastructure is protected. The traffic volume decreases at the high-risk port but increases at its competing port. Nevertheless, the overall traffic volume decreases with the deterioration in climate risk at one port, indicating the negative impact of climate change on maritime industry.

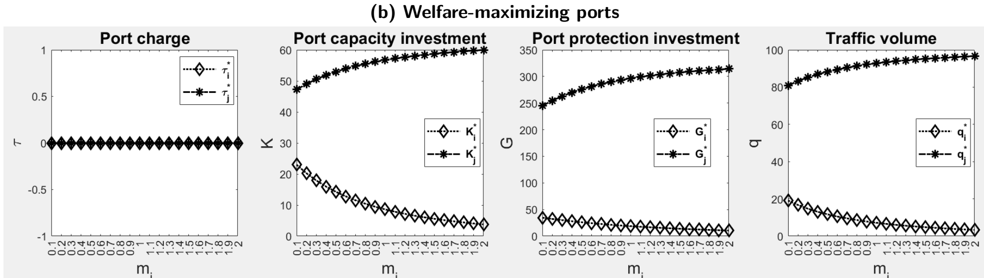
Second, welfare-maximizing and first-best ports invest more in both protection and capacity but charge less service fees than profit-maximizing ports. Welfare-maximizing ports are more inclined to increase port charge than profit-maximizing ports when congestion occurs, because welfare-maximizing



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



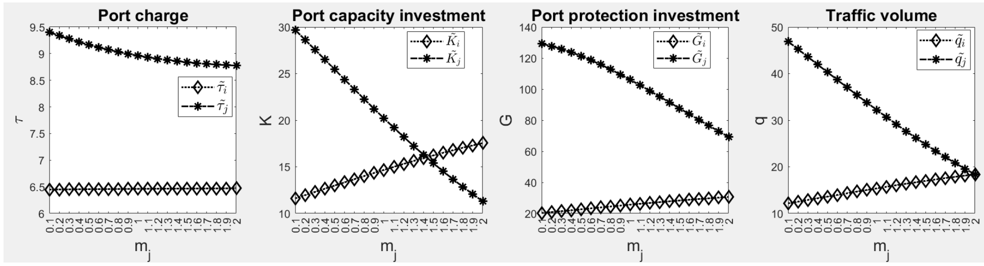
(c) First-best outcome

Figure 20: Varying intensity of damage to shippers $\mathbf{m_i}$

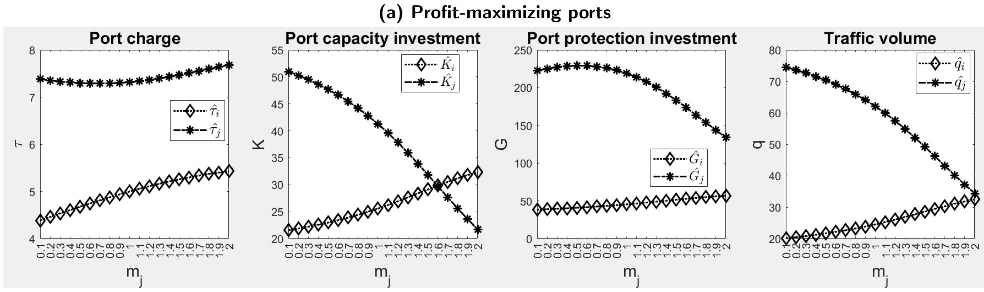
ports consider the welfare of shippers which is negatively affected by congestion. The comparison of equilibrium strategies between welfare-maximizing ports and first-best ports is not always clear. When the climate risk at one port is very small, the central government would prioritize the investments at this port, while discouraging shippers from using the other port. As a result, the capacity and protection investments at the low-risk port would be larger but the two investments at the other port would be smaller under the first-best case than under welfare-maximizing case. But if climate risk at both ports is high, the capacity and protection investments under first-best case would surpass those under welfare-maximizing case, implying that with deteriorating climate risk, ports under competition would underinvest in capacity and protection compared with ports under coordination.

Third, corner solutions where port charges are set to zero occur most often in the first-best case, occur sometimes in the welfare-maximizing case, and rarely occur in the profit-maximizing case. Corner solutions occur because the ports try to satisfy all market demand at the expense of their profits. Corner solutions are more likely to occur when the ports can easily attract shippers. This happens when (1) the climate risk is low, (2) constant utility of using the port is high, (3) congestion cost to shippers is low, (4) unit operating cost or unit capacity investment cost is low, and (5) the randomness associated with shippers' behavior is small.

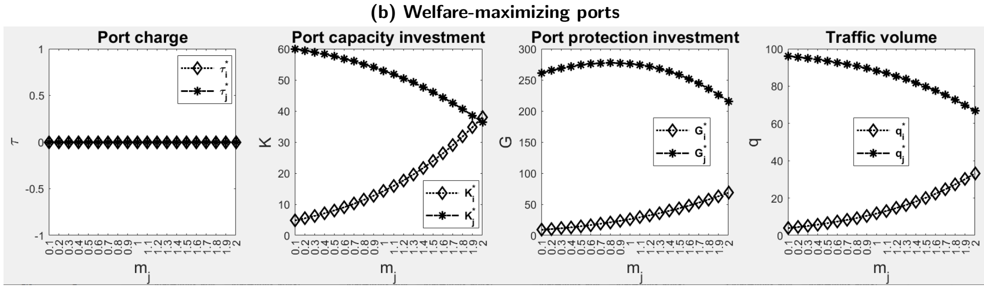
Fourth, the effect of shippers' congestion cost on port capacity and protection investments is non-monotone. Shippers incur higher congestion cost when the delay at the port causes shippers more late delivery penalties or more losses to their cargo value due to depreciation or obsolescence. When shippers' congestion cost is relatively high, ports would invest more in capacity to deal with capacity constraint. Protection investment would also increase to protect the capacity infrastructure from



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



(c) First-best outcome

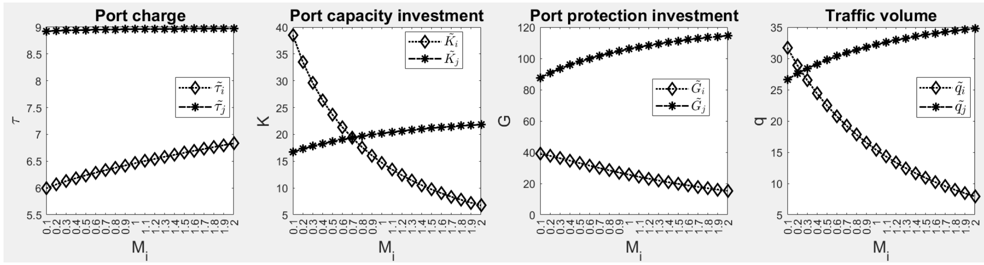
Figure 21: Varying intensity of damage to shippers $\mathbf{m_j}$

climate risk. However, when the congestion cost is sufficiently high, shippers would switch to other transportation modes and demand for port services would decline. Consequently, ports reduce investments in capacity and protection. When the congestion cost is very low, inter-port competition can lead welfare-maximizing ports to overinvest in capacity and protection as they strive to attract shippers, compared to the ports who coordinate under the first-best case.

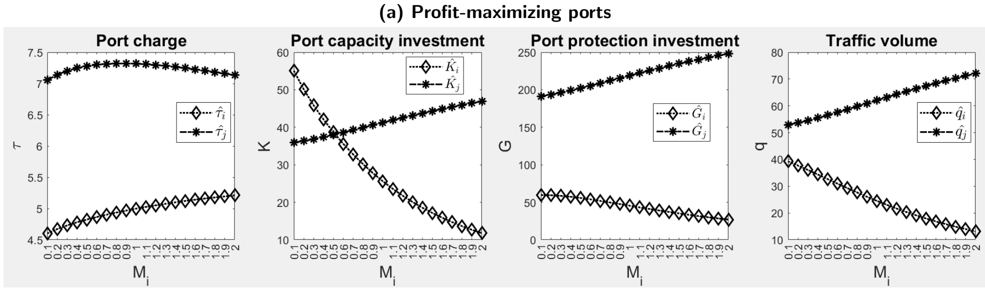
Last, the market size of cargo transportation positively affects port capacity and protection investment, as well as maritime traffic volume, but does not affect port service charge. If shippers' behavior exhibits only small randomness, it will intensity the inter-port competition, leading to the increase in both ports' investments in capacity and protection, as well as the reduction in port service fees. If the constant utility of shippers using one port increases, the port will invest more in capacity and protection, while capacity and protection investments at its competing port will decrease. If the unit operating or capacity investment cost increases, the port reduces capacity and protection investments, but the competing port will increase the investments. In general, the pricing behavior of ports under the three ownership structures exhibits distinct features depending on the prevailing factors, such as exercising market power, limiting congestion, attracting shippers, or satisfying market demand.

5 Conclusion

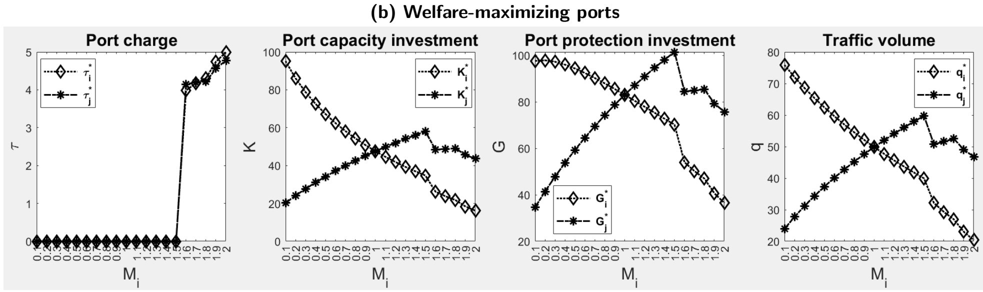
Seaports play a vital role in global maritime commerce. Yet, due to their location in low-lying coastal and riverine areas, seaports are highly vulnerable to climate-change induced events including sea level rise, severe tropical storms, inland flooding, droughts, and extreme heat events. The past decade has



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



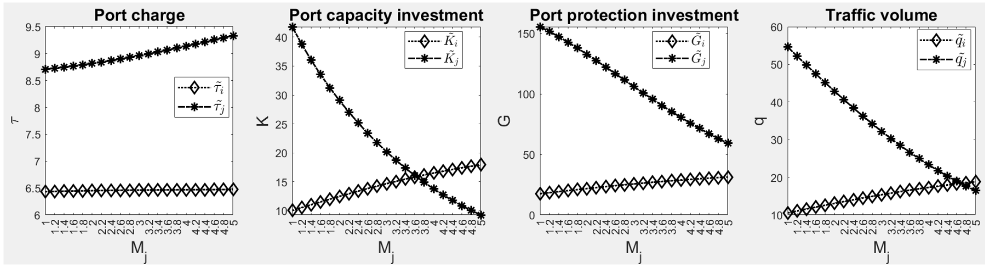
(c) First-best outcome

Figure 22: Varying intensity of damage to port $\mathrm{M_i}$

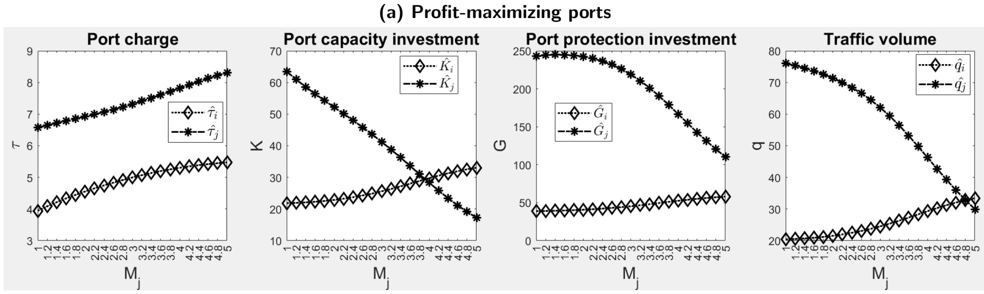
witnessed substantial costs to global economy and welfare due to the occurrence of natural disasters and climate-change related disruptions. These losses are expected to intensify in coming years with the worsening climate situation. Such vulnerabilities necessitate seaports to undertake investment in adaptation against climate-change induced events to ensure continuity in supply chains and to become more responsive, resilient, and agile. Despite rising intensity and frequency of climate-change induced events, global seaborne trade has been increasing rapidly. In addition to adaptation to climate change, seaports undertake investment in capacity to accommodate the future needs of the maritime transport, to minimize delays due to congestion, and to stay competitive. Driven by globalization, trade liberalization, and technological advancement, port competition has intensified in the past decade inducing ports to become more responsive to the needs of shippers and other stakeholders. Thus, the investment and pricing decisions undertaken by seaports can be largely influenced by inter-port competition.

Against this background, we develop a game theoretic model to investigate a seaport's strategic decisions on capacity and adaptation investments in conjunction with service charge, considering inter-port competition and uncertainty about climate-change induced events. The model features two seaports and a continuum of shippers. We consider three cases of competition based on port ownership structures: profit-maximizing ports, welfare-maximizing ports, and first-best outcome where a central government makes decisions on behalf of the two ports with the objective of maximizing overall welfare.

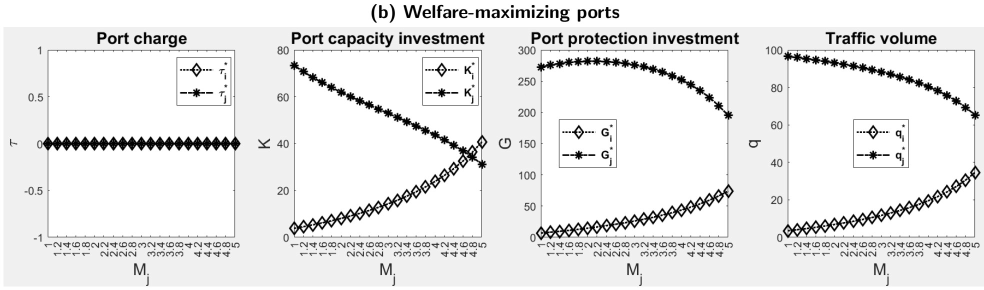
We demonstrate the following findings. First, when faced with higher climate risk, a port tends to invest less in capacity, but does not necessarily invest more in protection, as less capacity may warrant less protection. Its competing port, however, would increase capacity and protect to take up the



(a) Profit-maximizing ports



(b) Welfare-maximizing ports



(c) First-best outcome

Figure 23: Varying intensity of damage to port $\mathrm{M_j}$

demand. Second, welfare-maximizing and first-best ports invest more in both protection and capacity but charge less service fees than profit-maximizing ports. When the climate risk at one port is low, the central government would prioritize investments of one port over the other, resulting in a considerably higher investment level at the low-risk port and lower investment level at the high-risk port, compared to the welfare-maximizing case. When the climate risk at one port is high, inter-port competition would lead to underinvestment in both capacity and protection, compared to the ports who coordinate under the first-best case. Third, under both welfare-maximizing and first-best cases, corner solutions can happen where port charges are set to zero, indicating the ports try to satisfy all market demand at the expense of their profits. Corner solutions arise when shippers can be easily attracted to the ports, which can be reflected by factors such as low climate risk, high constant utility, low congestion cost, low unit operating or investment cost, or limited randomness in shippers' behavior. Fourth, the effect of shippers' congestion cost on port capacity and protection investments is non-monotone. When the congestion cost is very low, inter-port competition can lead welfare-maximizing ports to overinvest in capacity and protection, compared with the ports under coordination. Last, the pricing behavior of ports under the three ownership structures exhibits different features depending on the prevailing factors, such as exercising market power, limiting congestion, attracting shippers, or satisfying market demand.

Several extensions can be considered as future research directions. First, we can incorporate investment timing as part of the decisions. Since investing too early or too late can both bring catastrophic consequences, the model could be extended in this direction. In addition, as scientific research about climate change evolves over time, ports can accumulate more information about their climate risk and modify their investment decisions. This aspect also has not been considered in the model. Second, the model does not incorporate the vertical relationship between port authority and terminal operators within a port. The objective of a port considered in this study is either profit-maximizing (thus a privatized port) or welfare-maximizing (thus a public port). In practice, most ports operate under the landlord port model where the port authority decides investment levels with public interests in mind and leases the port facilities to private terminal operators who are profit oriented. There can also be intra-port competition among the terminal operators. Thus, the model could be generalized in this direction. Last, the model considers only two competing ports and could be extended to consider a network of maritime ports with possible co-opetition. In our two-port model, each port has three decision variables (port charge, capacity investment, and protection investment). The best response function of each decision variable is a function of the other two decision variables of the port itself and the three decision variables of the competing ports. Extending the model to multiple ports would make the computation more complicated but should still be numerically feasible.

Appendices

A Derivations of port demand properties

The partial derivatives of port demand to port price can be solved by the system of equations:

$$\begin{aligned}
&\frac{\partial q_i}{\partial \tau_i}\left(\left(\sum_n \exp(Z_n)\right)^2 \sigma + Q\exp(Z_i)\frac{\delta}{K_i}(1+\exp(Z_j))\right) - Q\exp(Z_i)\exp(Z_j)\frac{\delta}{K_j}\frac{\partial q_j}{\partial \tau_i} \\
&\quad + Q\exp(Z_i)(1+\exp(Z_j)) = 0, \\
&\frac{\partial q_j}{\partial \tau_j}\left(\left(\sum_n \exp(Z_n)\right)^2 \sigma + Q\exp(Z_j)\frac{\delta}{K_j}(1+\exp(Z_i))\right) - Q\exp(Z_i)\exp(Z_j)\frac{\delta}{K_i}\frac{\partial q_i}{\partial \tau_j} \\
&\quad + Q\exp(Z_j)(1+\exp(Z_i)) = 0, \\
&\frac{\partial q_i}{\partial \tau_j}\left(\left(\sum_n \exp(Z_n)\right)^2 \sigma + Q\exp(Z_i)\frac{\delta}{K_i}(1+\exp(Z_j))\right) - Q\exp(Z_i)\exp(Z_j)\frac{\delta}{K_j}\frac{\partial q_j}{\partial \tau_j} \\
&\quad - Q\exp(Z_i)\exp(Z_j) = 0, \\
&\frac{\partial q_j}{\partial \tau_i}\left(\left(\sum_n \exp(Z_n)\right)^2 \sigma + Q\exp(Z_j)\frac{\delta}{K_j}(1+\exp(Z_i))\right) - Q\exp(Z_i)\exp(Z_j)\frac{\delta}{K_i}\frac{\partial q_i}{\partial \tau_i} \\
&\quad - Q\exp(Z_j)\exp(Z_i) = 0.
\end{aligned}$$

To solve the partial derivatives of port demand to port capacity, differentiate both sides of Equation (9a) w.r.t. K_i, we obtain

$$\frac{\partial q_i}{\partial K_i} = \frac{Q\exp(Z_i)}{\left(\sum_n \exp(Z_n)\right)^2}\left(\frac{\partial Z_i}{\partial K_i}(1+\exp(Z_j)) - \exp(Z_j)\frac{\partial Z_j}{\partial K_i}\right), \tag{A1a}$$

where $\frac{\partial Z_i}{\partial \tau_i}$ and $\frac{\partial Z_j}{\partial \tau_i}$ are expressed by

$$\frac{\partial Z_i}{\partial K_i} = -\frac{1}{\sigma}\left(m\frac{x_i}{G_i} - \delta\frac{q_i}{{K_i}^2} + \frac{\delta}{K_i}\frac{\partial q_i}{\partial K_i}\right). \tag{A1b}$$

$$\frac{\partial Z_j}{\partial K_i} = -\frac{1}{\sigma}\frac{\delta}{K_j}\frac{\partial q_j}{\partial K_i}. \tag{A1c}$$

By plugging in Equations (A1b) and (A1c) into Equation (A1a), we could obtain one equation that contains two unknowns $\frac{\partial q_i}{\partial K_i}$ and $\frac{\partial q_i}{\partial K_j}$. Next, differentiate both sides of Equation (9a) w.r.t. K_j, we obtain

$$\frac{\partial q_i}{\partial K_j} = \frac{Q \exp(Z_i)}{\left(\sum_n \exp(Z_n)\right)^2} \left(\frac{\partial Z_i}{\partial K_j} \left(1 + \exp(Z_j)\right) - \exp(Z_j) \frac{\partial Z_j}{\partial K_j} \right), \tag{A2a}$$

where $\frac{\partial Z_i}{\partial \tau_j}$ and $\frac{\partial Z_j}{\partial \tau_j}$ are expressed by

$$\frac{\partial Z_i}{\partial K_j} = -\frac{1}{\sigma} \frac{\delta}{K_i} \frac{\partial q_i}{\partial K_j}, \tag{A2b}$$

$$\frac{\partial Z_j}{\partial K_j} = -\frac{1}{\sigma} \left(m \frac{x_j}{G_j} - \delta \frac{q_j}{{K_j}^2} + \frac{\delta}{K_j} \frac{\partial q_j}{\partial K_j} \right). \tag{A2c}$$

The following system of equations can be solved to obtain the partial derivatives of port demand to port capacity:

$$\begin{aligned}
&\frac{\partial q_i}{\partial K_i} \left(\left(\sum_n \exp(Z_n) \right)^2 \sigma + Q \exp(Z_i) \frac{\delta}{K_i} \left(1 + \exp(Z_j)\right) \right) - Q \exp(Z_i) \exp(Z_j) \frac{\delta}{K_j} \frac{\partial q_j}{\partial K_i} \\
&\quad + Q \exp(Z_i) \left(1 + \exp(Z_j)\right) (m \frac{x_i}{G_i} - \delta \frac{q_i}{{K_i}^2}) = 0, \\
&\frac{\partial q_j}{\partial K_j} \left(\left(\sum_n \exp(Z_n) \right)^2 \sigma + Q \exp(Z_j) \frac{\delta}{K_j} \left(1 + \exp(Z_i)\right) \right) - Q \exp(Z_i) \exp(Z_j) \frac{\delta}{K_i} \frac{\partial q_i}{\partial K_j} \\
&\quad + Q \exp(Z_j) \left(1 + \exp(Z_i)\right) (m \frac{x_j}{G_j} - \delta \frac{q_j}{{K_j}^2}) = 0, \\
&\frac{\partial q_i}{\partial K_j} \left(\left(\sum_n \exp(Z_n) \right)^2 \sigma + Q \exp(Z_i) \frac{\delta}{K_i} \left(1 + \exp(Z_j)\right) \right) - Q \exp(Z_i) \exp(Z_j) \frac{\delta}{K_j} \frac{\partial q_j}{\partial K_j} \\
&\quad - Q \exp(Z_i) \exp(Z_j) (m \frac{x_j}{G_j} - \delta \frac{q_j}{{K_j}^2}) = 0, \\
&\frac{\partial q_j}{\partial K_i} \left(\left(\sum_n \exp(Z_n) \right)^2 \sigma + Q \exp(Z_j) \frac{\delta}{K_j} \left(1 + \exp(Z_i)\right) \right) - Q \exp(Z_i) \exp(Z_j) \frac{\delta}{K_i} \frac{\partial q_i}{\partial K_i} \\
&\quad - Q \exp(Z_j) \exp(Z_i) (m \frac{x_i}{G_i} - \delta \frac{q_i}{{K_i}^2}) = 0.
\end{aligned}$$

To solve the partial derivatives of port demand to port adaptation investment, differentiate both sides of Equation (9a) w.r.t. G_i, we obtain

$$\frac{\partial q_i}{\partial G_i} = \frac{Q \exp(Z_i)}{\left(\sum_n \exp(Z_n)\right)^2} \left(\frac{\partial Z_i}{\partial G_i} \left(1 + \exp(Z_j)\right) - \exp(Z_j) \frac{\partial Z_j}{\partial G_i} \right), \tag{A3a}$$

where $\frac{\partial Z_i}{\partial \tau_i}$ and $\frac{\partial Z_j}{\partial \tau_i}$ are expressed by

$$\frac{\partial Z_i}{\partial G_i} = \frac{1}{\sigma} \left(m \frac{x_i K_i}{{G_i}^2} - \frac{\delta}{K_i} \frac{\partial q_i}{\partial G_i} \right), \tag{A3b}$$

$$\frac{\partial Z_j}{\partial G_i} = -\frac{1}{\sigma} \frac{\delta}{K_j} \frac{\partial q_j}{\partial G_i}. \tag{A3c}$$

Differentiate both sides of Equation (9a) with respect to (w.r.t.) G_j, we obtain

$$\frac{\partial q_i}{\partial G_j} = \frac{Q\exp(Z_i)}{\left(\sum_n \exp(Z_n)\right)^2}\left(\frac{\partial Z_i}{\partial G_j}(1+\exp(Z_j)) - \exp(Z_j)\frac{\partial Z_j}{\partial G_j}\right), \tag{A4a}$$

where $\frac{\partial Z_i}{\partial \tau_j}$ and $\frac{\partial Z_j}{\partial \tau_j}$ are expressed by

$$\frac{\partial Z_i}{\partial G_j} = -\frac{1}{\sigma}\frac{\delta}{K_i}\frac{\partial q_i}{\partial G_j}, \tag{A4b}$$

$$\frac{\partial Z_j}{\partial G_j} = \frac{1}{\sigma}\left(m\frac{x_j K_j}{{G_j}^2} - \frac{\delta}{K_j}\frac{\partial q_j}{\partial G_j}\right). \tag{A4c}$$

The following system of equations can be solved to obtain the partial derivatives of port demand to port adaptation investment:

$$\begin{aligned}
&\frac{\partial q_i}{\partial G_i}\left(\left(\sum_n \exp(Z_n)\right)^2\sigma + Q\exp(Z_i)\frac{\delta}{K_i}(1+\exp(Z_j))\right) - Q\exp(Z_i)\exp(Z_j)\frac{\delta}{K_j}\frac{\partial q_j}{\partial G_i}\\
&\quad - Q\exp(Z_i)(1+\exp(Z_j))\,m\frac{x_i K_i}{{G_i}^2} = 0,\\
&\frac{\partial q_j}{\partial G_j}\left(\left(\sum_n \exp(Z_n)\right)^2\sigma + Q\exp(Z_j)\frac{\delta}{K_j}(1+\exp(Z_i))\right) - Q\exp(Z_i)\exp(Z_j)\frac{\delta}{K_i}\frac{\partial q_i}{\partial G_j}\\
&\quad - Q\exp(Z_j)(1+\exp(Z_i))\,m\frac{x_j K_j}{{G_j}^2} = 0,\\
&\frac{\partial q_i}{\partial G_j}\left(\left(\sum_n \exp(Z_n)\right)^2\sigma + Q\exp(Z_i)\frac{\delta}{K_i}(1+\exp(Z_j))\right) - Q\exp(Z_i)\exp(Z_j)\frac{\delta}{K_j}\frac{\partial q_j}{\partial G_j}\\
&\quad + Q\exp(Z_i)\exp(Z_j)\,m\frac{x_j K_j}{{G_j}^2} = 0,\\
&\frac{\partial q_j}{\partial G_i}\left(\left(\sum_n \exp(Z_n)\right)^2\sigma + Q\exp(Z_j)\frac{\delta}{K_j}(1+\exp(Z_i))\right) - Q\exp(Z_i)\exp(Z_j)\frac{\delta}{K_i}\frac{\partial q_i}{\partial G_i}\\
&\quad + Q\exp(Z_j)\exp(Z_i)\,m\frac{x_i K_i}{{G_i}^2} = 0.
\end{aligned}$$

B Derivations of choice probability and consumer surplus

B.1 Derivation of choice probability

The probability that alternative l is chosen is

$$P_l = P\left(V_l + \varepsilon_l \geq V_n + \varepsilon_n\ ,\ \forall\ n \neq l\right) = P\left(\varepsilon_n \leq V_l + \varepsilon_l - V_n,\ \forall\ n \neq l\right).$$

Since ε_n is i.i.d., and $\varepsilon_n \sim$ Gumbel $(0,\ \sigma)$, conditional on the value of ε_l, the probability that l is chosen is

$$P_l\,|\varepsilon_l \ = \prod_{n \neq l} F(V_l + \varepsilon_l - V_n).$$

The unconditional probability is

$$P_l = \int_{-\infty}^{+\infty}\prod_{n\neq l} F\left(V_l + \varepsilon_l - V_n\right) f(\varepsilon_l) d\varepsilon_l = \int_{-}^{+}\prod_{n\neq l} e^{-e^{-\frac{V_l+\varepsilon_l-V_n}{\sigma}}}\cdot\frac{1}{\sigma}e^{-\left(\frac{\varepsilon_l}{\sigma}+e^{-\frac{\varepsilon_l}{\sigma}}\right)} d\varepsilon_l.$$

Let $e^{-\frac{\varepsilon_l}{\sigma}} = a_l \in (0, +\infty)$, the probability can be written as

$$P_l = -\int_{-}^{+} \prod_{n \neq l} e^{-a_l \cdot e^{-\frac{V_l - V_n}{\sigma}}} \cdot e^{-a_l} da_l.$$

Let $e^{-a_l} = b_l \in (0, 1)$, the probability can be written as

$$P_l = \int_0^1 \prod_{n \neq l} b_l^{\cdot e^{-\frac{V_l - V_n}{\sigma}}} db_l = \int_0^1 b_l^{\sum_{n \neq l} e^{-\frac{V_l - V_n}{\sigma}}} db_l = \left. \frac{b_l^{\sum_{n \neq l} e^{-\frac{V_l - V_n}{\sigma}} + 1}}{\sum_{n \neq l} e^{-\frac{V_l - V_n}{\sigma}} + 1} \right|_0^1 = \frac{1}{\sum_{n \neq l} e^{-\frac{V_l - V_n}{\sigma}} + 1}$$

$$= \frac{e^{\frac{V_l}{\sigma}}}{\sum_{n \neq l} e^{\frac{V_n}{\sigma}} + e^{\frac{V_l}{\sigma}}} = \frac{e^{\frac{V_l}{\sigma}}}{\sum_n e^{\frac{V_n}{\sigma}}}.$$

B.2 Derivation of consumer surplus

To derive the consumer surplus of a single port user $E(\max_n U_n)$, we first derive the CDF of $\max_n U_n$.

$$P\left(\max_n U_n < c\right) = P(U_n < c, \forall\, n) = P(\varepsilon_l < c - V_n, \forall\, n) = \prod_n F(c - V_n) = e^{-\sum_n e^{-\frac{c - V_n}{\sigma}}},$$

where the function $F(\cdot)$ is the CDF of Gumbel $(0, \sigma)$. We denote the CDF of $\max_n U_n$ as

$$F(c) = e^{-\sum_n e^{-\frac{c - V_n}{\sigma}}}.$$

We next derive the PDF of $\max_n U_n$

$$f(c) = F^{'}(c) = \frac{1}{\sigma} e^{-\sum_n e^{-\frac{c - V_n}{\sigma}}} \cdot \sum_n e^{-\frac{c - V_n}{\sigma}}.$$

Thus,

$$E\left(\max_n U_n\right) = \int_{-\infty}^{+\infty} c f(c) dc = \int_{-\infty}^{+\infty} \frac{1}{\sigma} \cdot c \cdot e^{-\sum_n e^{-\frac{c - V_n}{\sigma}}} \cdot \sum_n e^{-\frac{c - V_n}{\sigma}} dc$$

$$= \int_{-\infty}^{+\infty} \frac{1}{\sigma} \cdot c \cdot e^{-\sum_n e^{\frac{V_n}{\sigma}} \cdot e^{-\frac{c}{\sigma}}} \cdot \sum_n e^{\frac{V_n}{\sigma}} \cdot e^{-\frac{c}{\sigma}} dc.$$

Let $\sum_n e^{\frac{V_n}{\sigma}} = e^{ln(\sum_n e^{\frac{V_n}{\sigma}})}$, $E(\max_n U_n)$ can be written as

$$E\left(\max_n U_n\right) = \int_{-\infty}^{+\infty} \frac{c}{\sigma} \cdot e^{-\left(\left(\frac{c}{\sigma} - ln(\sum_n e^{\frac{V_n}{\sigma}})\right) + e^{-(\frac{c}{\sigma} - ln(\sum_n e^{\frac{V_n}{\sigma}}))}\right)} dc.$$

Let $\frac{c}{\sigma} - \ln\left(\sum_n e^{\frac{V_n}{\sigma}}\right) = x$,

$$E\left(\max_n U_n\right) = \ln\left(\sum_n e^{\frac{V_n}{\sigma}}\right) + \sigma \int_{-\infty}^{+\infty} x \cdot e^{-(x + e^{-x})} dx = \ln\left(\sum_n e^{\frac{V_n}{\sigma}}\right) + \sigma\gamma,$$

where the equality follows because $\int_{-\infty}^{+\infty} x \cdot e^{-(x+e^{-x})} dx$ is the mean of standard Gumbel distribution, which is γ, the Euler constant. Since $\sigma\gamma$ is a constant and does not affect the competition outcome, we remove it from the consumer surplus.

C Parameter values

C.1 Operating cost of handling one metric tonne of cargo of Prince Rupert Port Authority and Vancouver Fraser Port Authority in 2020

Table C1: Operating cost per metric tonne of cargo of Prince Rupert Port Authority in 2020

Particulars	Prince Rupert Port Authority
Operating expenses including salaries and employment benefits, amortization, operating and administrative expenses, federal stipend, professional and consulting fees, payments in lieu of taxes and maintenance and repairs	CAD 37,675,000
Cargo volume (Total tonnage)	32.45 million metric tonnes
Unit operating cost of handling 1 metric tonne of cargo	1.16 CAD/tonne

Source: Port of Prince Rupert (2020)

Table C2: Operating cost per metric tonne of cargo of Vancouver Fraser Port Authority in 2020

Particulars	Vancouver Fraser Port Authority
Operating expenses including salaries and employment benefits, depreciation, operating and administrative expenses, professional fees and consulting services, dredging, payments in lieu of taxes and maintenance and repairs	CAD 146,418,000
Cargo volume (Total tonnage)	145 million metric tonnes
Unit operating cost of handling 1 metric tonne of cargo	1.00977 CAD/tonne

Source: Port of Vancouver (2020)

Average cost of handling 1 metric tonne of cargo is CAD 1.08. We round down this value to CAD 1 for the numerical analysis. Thus, in the baseline, we set $c_i = c_j = 1$.

C.2 Capacity investment cost per quintal of cargo

We consider capacity investment projects being undertaken by Vancouver Fraser Port Authority and Port of Montreal. With one port located on east coast and other on west coast of Canada, they provide a glimpse of cost of capacity construction of ports within the nation.

- Roberts Bank Terminal 2 project led by Vancouver Fraser Port Authority: It is a proposed new maritime container terminal at Roberts Bank in Delta, British Columbia. It is currently undergoing a federal review by an independent panel. With an estimated cost of CAD 2 billion, the project will be funded by the port authority and private investment. If approved and built, Roberts Bank Terminal 2 would provide 2.4 million TEUs of container capacity. As per the project's expected timelines, its construction could take approximately six years and could be operational by the early-2030s (if approved as expected). Since shipping companies normally load up to 24000 kilograms (or 24 metric tonnes) of cargo in a TEU (Menon, 2022) and the planning horizon is 20 years, the estimated unit capacity investment cost per tonne and per year (without discounting) is CAD 1.74 ($= 2000/(2.4 * 24 * 20)$).
- Construction of a new container terminal in Contrecœur by Port of Montreal: This new terminal is expected to boost the growth of the container market in Quebec and Eastern Canada. The construction cost of the terminal is estimated to be CAD 850 million. It is expected to be fully up and running by 2026 with the capacity to handle 1.15 million TEUs per year. The estimated unit capacity investment cost per tonne and per year (without discounting) is CAD 1.54 ($= 850/(1.15 * 24 * 20)$).

We round down this value to CAD 1.5 for the numerical analysis. Thus, in the baseline, we set $c_{Ki} = c_{Kj} = 1.5$.

References

Allahviranloo, M. and Afandizadeh, S., 2008. Investment optimization on port's development by fuzzy integer programming. European Journal of Operational Research, 186(1):423–434.

AltaGas, 2016. Ridley Island Propane Export Facility: Project Description. https://www.altagas.ca/sites/default/files/2016-07/AltaGas%20Propane%20Export%20Facility%20Project%20Description_Final.pdf. Accessed December 2022.

Anderson, C.M., Park, Y.A., Chang, Y.T., Yang, C.H., Lee, T.W. and Luo, M., 2008. A game-theoretic analysis of competition among container port hubs: the case of Busan and Shanghai. Maritime Policy & Management, 35(1):5–26.

Asadabadi, A. and Miller-Hooks, E., 2018. Co-opetition in enhancing global port network resiliency: A multi-leader, common-follower game theoretic approach. Transportation Research Part B: Methodological, 108:281–298.

Balliauw, M., Kort, P.M. and Zhang, A., 2019. Capacity investment decisions of two competing ports under uncertainty: A strategic real options approach. Transportation Research Part B: Methodological, 122:249–264.

Balliauw, M., Kort, P.M., Meersman, H., Van de Voorde, E. and Vanelslander, T., 2020a. The case of public and private ports with two actors: capacity investment decisions under congestion and uncertainty. Case Studies on Transport Policy, 8(2):403–415.

Balliauw, M., Kort, P.M., Meersman, H., Smet, C., Van De Voorde, E. and Vanelslander, T., 2020b. Port capacity investment size and timing under uncertainty and congestion. Maritime Policy & Management, 47(2):221–239.

Becker, A., Inoue, S., Fischer, M. and Schwegler, B., 2012. Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators. Climatic change, 110(1):5–29.

Becker, A.H., Acciaro, M., Asariotis, R., Cabrera, E., Cretegny, L., Crist, P., Esteban, M., Mather, A., Messner, S., Naruse, S. and Ng, A.K., 2013. A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. Climatic change, 120(4):683–695.

Becker, A., A. Hippe and E. McLean, 2017. Cost and materials required to retrofit US seaports in response to sea level rise: A thought exercise for climate response. Journal of Marine Science and Engineering 5(3):44. https://www.mdpi.com/2077-1312/5/3/44. Accessed April 2021.

Becker, A., Ng, A., McEvoy, D., Mullet, J., 2018. Implications of climate change for shipping: Ports and supply chains. Wiley Interdisciplinary Reviews: Climate Change, 9(2):e508. https://doi.org/10.1002/wcc.508. Accessed Aug 2022.

Burkett, V. and Davidson, M., 2012. Coastal impacts, adaptation, and vulnerabilities. Island Press.

Chen, H.C. and Liu, S.M., 2016. Should ports expand their facilities under congestion and uncertainty?. Transportation Research Part B: Methodological, 85:109–131.

Chen, H.C., Lee, P.T.W., Liu, S.M. and Lee, T.C., 2017. Governments' sequential facility investments and ports' pricing under service differentiation and uncertainty. International Journal of Shipping and Transport Logistics, 9(4):417–448.

Cong, L.Z., Zhang, D., Wang, M.L., Xu, H.F. and Li, L., 2020. The role of ports in the economic development of port cities: Panel evidence from China. Transport Policy, 90:13–21.

Cronin, 2021. Long Beach seawall to be replaced. https://www.gloucestertimes.com/news/local_news/long-beach-seawall-to-be-replaced/article_86e47f3f-70eb-52c0-bd57-bb66f73e270c.html. Accessed December 2022.

De Borger, B. and Van Dender, K., 2006. Prices, capacities and service levels in a congestible Bertrand duopoly. Journal of Urban Economics, 60(2):264–283.

De Borger, B., Dunkerley, F. and Proost, S., 2007. Strategic investment and pricing decisions in a congested transport corridor. Journal of Urban Economics, 62(2):294–316.

De Borger, B., Proost, S. and Van Dender, K., 2008. Private port pricing and public investment in port and hinterland capacity. Journal of Transport Economics and Policy (JTEP), 42(3):527–561.

De Monie, G., Rodrigue, J.P. and Notteboom, T., 2011. Economic cycles in maritime shipping and ports: the path to the crisis of 2008. Integrating seaports and trade corridors, pp.13–30.

Devanney III, J.W. and Tan, L.H., 1975. The relationship between short-run pricing and investment timing: The port pricing and expansion example. Transportation Research, 9(6):329–337.

EESI, 2020. Ports Leading the Way on Mitigation and Resilience. https://www.eesi.org/briefings/view/111720transportation. EESI (Environnemental and Energy Study Institute). Accessed December 2022.

Esteban, M., Webersick, C. and Shibayama, T., 2009, February. Estimation of the economic costs of non adapting Japanese port infrastructure to a potential increase in tropical cyclone intensity. In IOP Conference Series. Earth and Environmental Science (Vol. 6, No. 32). IOP Publishing.

Gao, Y. and Driouchi, T., 2013. Incorporating Knightian uncertainty into real options analysis: Using multiple-priors in the case of rail transit investment. Transportation Research Part B: Methodological, 55:23–40.

Gong, L., Xiao, Y.B., Jiang, C., Zheng, S. and Fu, X., 2020. Seaport investments in capacity and natural disaster prevention. Transportation Research Part D: Transport and Environment, 85:102367.

Grenadier, S.R., 2002. Option exercise games: An application to the equilibrium investment strategies of firms. The Review of Financial Studies, 15(3):691–721.

Hossain, T., Adams, M. and Walker, T.R., 2021. Role of sustainability in global seaports. Ocean & Coastal Management, 202:105435.

Housni, F., Boumane, A., Rasmussen, B.D., Britel, M.R., Barnes, P., Abdelfettah, S. and Maurady, A., 2022. Environmental sustainability maturity system: An integrated system scale to assist maritime port managers in addressing environmental sustainability goals. Environmental Challenges, 7:100481.

Huisman, K.J. and Kort, P.M., 2015. Strategic capacity investment under uncertainty. The RAND Journal of Economics, 46(2):376–408.

ILO, 2021. ILO Sectoral Brief: COVID-19 and the port sector. ILO (International Labour Organization) publication. https://www.ilo.org/wcmsp5/groups/public/---ed_dialogue/---sector/documents/briefingnote/wcms_810868.pdf. Accessed December 2022.

Ishii, M., Lee, P.T.W., Tezuka, K. and Chang, Y.T., 2013. A game theoretical analysis of port competition. Transportation Research Part E: Logistics and Transportation Review, 49(1):92–106.

ITF, 2017. ITF (International Transport Forum) Transport Outlook 2017, OECD Publishing, Paris, https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2017/international-freight_9789282108000-6-en. Accessed December 2022.

ITF, 2019. ITF (International Transport Forum) Transport Outlook 2019, OECD Publishing, Paris, https://doi.org/10.1787/transp_outlook-en-2019-en. Accessed December 2022.

Izaguirre, C., Losada, I.J., Camus, P., Vigh, J.L. and Stenek, V., 2021. Climate change risk to global port operations. Nature Climate Change, 11(1):14–20. https://www.nature.com/articles/s41558-020-00937-z. Accessed December 2022.

Jansson, J.O. and Shneerson, D., 1982. Port economics (Vol. 8). MIT press.

Jiang, C., Zheng, S., Ng, A.K., Ge, Y.E. and Fu, X., 2020. The climate change strategies of seaports: Mitigation vs. adaptation. Transportation Research Part D: Transport and Environment, 89:102603.

Kauppila, J., Martinez, L., Merk, O. and Benezech, V., 2016. Capacity to grow: Transport infrastructure needs for future trade growth. Paris: OECD/International Transport Forum. https://www.itf-oecd.org/sites/default/files/docs/future-growth-transport-infrastructure.pdf. Accessed December 2022.

Lam, J.S.L. and Lassa, J.A., 2017. Risk assessment framework for exposure of cargo and ports to natural hazards and climate extremes. Maritime Policy & Management, 44(1):1–15.

Lin, Y., Ng, A.K., Zhang, A., Xu, Y. and He, Y., 2020. Climate change adaptation by ports: the attitude of Chinese port organizations. Maritime Policy & Management, 47(7):873–884.

Luo, M., Liu, L. and Gao, F., 2012. Post-entry container port capacity expansion. Transportation Research Part B: Methodological, 46(1):120–138.

Menon, H., 2022. What is TEU in Shipping – Everything You Wanted to Know. Marine Insight.

Ng, A.K., Chen, S.L., Cahoon, S., Brooks, B. and Yang, Z., 2013. Climate change and the adaptation strategies of ports: The Australian experiences. Research in Transportation Business & Management, 8:186–194.

Ng, A.K., Zhang, H., Afenyo, M., Becker, A., Cahoon, S., Chen, S.L., Esteban, M., Ferrari, C., Lau, Y.Y., Lee, P.T.W. and Monios, J., 2018. Port decision maker perceptions on the effectiveness of climate adaptation actions. Coastal Management, 46(3):148–175.

Ng, K.Y.A., Becker, A., Cahoon, S., Chen, S.L., Earl, P. and Yang, Z. eds., 2015. Climate change and adaptation planning for ports. London: Routledge.

Nicholls, R.J., Brown, S., Hanson, S. and Hinkel, J., 2010. Economics of coastal zone adaptation to climate change (World Bank Discussion Papers, 10) Washington, US. International Bank for Reconstruction and Development / World Bank 48pp.

Nishimura, K.G. and Ozaki, H., 2007. Irreversible investment and Knightian uncertainty. Journal of Economic Theory, 136(1):668–694.

Niu, Y., Zhou, L. and Zou, Z., 2019. A model of capacity choice under Knightian uncertainty. Economics Letters, 174:189–194.

Noritake, M. and Kimura, S., 1983. Optimum number and capacity of seaport berths. Journal of Waterway, Port, Coastal, and Ocean Engineering, 109(3):323–339.

Notteboom, T. and Siu Lee Lam, J., 2014. Dealing with uncertainty and volatility in shipping and ports. Maritime Policy & Management, 41(7):611–614.

Notteboom, T., Pallis, T. and Rodrigue, J.P., 2021. Disruptions and resilience in global container shipping and ports: the COVID-19 pandemic versus the 2008–2009 financial crisis. Maritime Economics & Logistics, 23(2):179–210.

Nursey-Bray, M., Blackwell, B., Brooks, B., Campbell, M.L., Goldsworthy, L., Pateman, H., Rodrigues, I., Roome, M., Wright, J.T., Francis, J. and Hewitt, C.L., 2013. Vulnerabilities and adaptation of ports to climate change. Journal of Environmental Planning and Management, 56(7):1021–1045.

OECD, 2012. Strategic Transport Infrastructure Needs to 2030, OECD Publishing, Paris, https://www.oecd-ilibrary.org/economics/strategic-transport-infrastructure-needs-to-2030_9789264114425-en. Accessed December 2022.

Patel, M., 2021. Impact Evaluation of Major Hurricanes on Designated Southeast Coast Counties of USA Using Multivariate Analysis and Forecasting. Doctoral dissertation, The University of Alabama at Birmingham.

Peters, H.J., 2001. Developments in global seatrade and container shipping markets: their effects on the port industry and private sector involvement. International Journal of Maritime Economics, 3(1):3–26.

Port of Long Beach, 2021. The making of a state-of-the-art terminal. https://polb.com/port-info/news-and-press/the-making-of-a-state-of-the-art-terminal-08-26-2021/. Accessed December 2022.

Port of Prince Rupert, 2020. 2020 Annual Report. https://2020.rupertport.com/. Accessed January 2023.

Port of Montreal, 2023. The Port of Montreal's expansion: Construction of the new terminal in Contrecœur. https://www.port-montreal.com/en/the-port-of-montreal/projects/terminal-in-contrecoeur. Accessed March 2023.

Port of Vancouver, 2020. Vancouver Fraser Port Authority Financial Report 2020. https://www.portvancouver.com/wp-content/uploads/2021/06/2020-Financial-Report.pdf. Accessed January 2023.

Port of Vancouver, 2023. Roberts Bank Terminal 2 Project. https://www.robertsbankterminal2.com/projectfacts/. Accessed March 2023.

Randrianarisoa, L.M. and Zhang, A., 2019. Adaptation to climate change effects and competition between ports: Invest now or later?. Transportation Research Part B: Methodological, 123:279–322.

Randrianarisoa, L.M., Wang, K. and Zhang, A., 2020. Insights from recent economic modeling on port adaptation to climate change effects. Maritime transport and regional sustainability, pp.45–71.

Small, K.A., Verhoef, E.T., 2007. The Economics of Urban Transportation. Routledge, London.

Smit, H.T., 2003. Infrastructure investment as a real options game: the case of European airport expansion. Financial Management, pp.27–57.

Thomas, D., 2012. Port Authority Nixes 25 Feet Elevation for Gulfport. Port of Gulfport Restoration Program. http://www.portofthefuture.com/news-headlines/port-authority-nixes-25-feet-elevation-for-gulfport/. Accessed December 2022.

Tongzon, J.L., 2009. Port choice and freight forwarders. Transportation Research Part E: Logistics and Transportation Review, 45(1):186-195.

UNCTAD, 2017. Review of Maritime Transport 2017. United Nations publication. https://unctad.org/system/files/official-document/rmt2017_en.pdf. Accessed December 2022.

UNCTAD, 2021a. Trade and Development Report 2021. United Nations publication. https://unctad.org/system/files/official-document/tdr2021_en.pdf. Accessed December 2022.

UNCTAD, 2021b. Review of Maritime Transport 2021. UNCTAD United Nations publication. https://unctad.org/system/files/official-document/rmt2021_en_0.pdf. Accessed December 2022.

Van Houtven, G., Gallaher, M., Woollacott, J. and Decker, E., 2022. Act Now or Pay Later: The Costs of Climate Inaction for Ports and Shipping. RTI International. https://safety4sea.com/wp-content/uploads/2022/03/EDF-The-Costs-of-Climate-Inaction-for-Ports-and-Shipping-2022_03.pdf. Accessed December 2022.

Verschuur, J., Koks, E.E. and Hall, J.W., 2020. Port disruptions due to natural disasters: Insights into port and logistics resilience. Transportation research part D: Transport and Environment, 85:102393.

Wang, B., Chin, K.S. and Su, Q., 2022. Prevention and adaptation to diversified risks in the seaport–dry port system under asymmetric risk behaviors: Invest earlier or wait?. Transport Policy.

Wang, K. and Zhang, A., 2018. Climate change, natural disasters and adaptation investments: Inter-and intra-port competition and cooperation. Transportation Research Part B: Methodological, 117:158–189.

Wang, K., Yang, H. and Zhang, A., 2020. Seaport adaptation to climate change-related disasters: terminal operator market structure and inter-and intra-port coopetition. Spatial Economic Analysis, 15(3):311–335.

World Bank, 2022. Port Reform Toolkit PPIAF, World Bank, 2nd Edition. https://ppp.worldbank.org/public-private-partnership/library/port-reform-toolkit-ppiaf-world-bank-2nd-edition. Accessed December 2022.

Xia, W. and Lindsey, R., 2021. Port adaptation to climate change and capacity investments under uncertainty. Transportation Research Part B: Methodological, 152:180–204.

Xiao, Y., Fu, X. and Zhang, A., 2013. Demand uncertainty and airport capacity choice. Transportation Research Part B: Methodological, 57:91–104.

Xiao, Y., Ng, A.K., Yang, H. and Fu, X., 2012. An analysis of the dynamics of ownership, capacity investments and pricing structure of ports. Transport Reviews, 32(5):629–652.

Xiao, Y.B., Fu, X., Ng, A.K. and Zhang, A., 2015. Port investments on coastal and marine disasters prevention: Economic modeling and implications. Transportation Research Part B: Methodological, 78:202–221.

Yang, Z., Ng, A.K., Lee, P.T.W., Wang, T., Qu, Z., Rodrigues, V.S., Pettit, S., Harris, I., Zhang, D. and Lau, Y.Y., 2018. Risk and cost evaluation of port adaptation measures to climate change impacts. Transportation Research Part D: Transport and Environment, 61:444–458.

Zhang, A., 2009. The impact of hinterland access: conditions of rivalry between ports, in Port Competition and Hinterland Connections, OECD Publishing, Paris, https://doi.org/10.1787/9789282102251-6-en.

Zhen, L., Zhuge, D., Murong, L., Yan, R. and Wang, S., 2019. Operation management of green ports and shipping networks: overview and research opportunities. Frontiers of Engineering Management, 6(2):152–162.

Zheng, S., Fu, X., Wang, K. and Li, H., 2021a. Seaport adaptation to climate change disasters: Subsidy policy vs. adaptation sharing under minimum requirement. Transportation research part E: logistics and transportation review, 155:102488.

Zheng, S., Wang, K., Li, Z.C., Fu, X. and Chan, F.T., 2021b. Subsidy or minimum requirement? Regulation of port adaptation investment under disaster ambiguity. Transportation Research Part B: Methodological, 150:457–481.