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Investment Timing in Seaport Climate-Change Adaptation and Capacity Expansion Under Competition

by

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Résumé

Les ports jouent un rôle essentiel dans le commerce mondial. En tant que nœuds de transport critiques au sein des chaînes d'approvisionnement, ils contribuent au développement économique et social des communautés environnantes. Cependant, ils sont confrontés à des défis croissants liés aux incertitudes climatiques, telles que les cyclones, les ouragans et les tsunamis, ainsi qu'à la volatilité des volumes commerciaux, qui engendrent souvent des problèmes de congestion. En réponse, de plus en plus de ports réalisent conjointement des investissements en capacité et en adaptation climatique afin de renforcer leur résilience et d'assurer la continuité de leurs opérations face aux perturbations climatiques. Cette étude développe un modèle à deux périodes pour analyser les décisions de synchronisation d'investissements décisions interdépendantes en capacité et en adaptation climatique de deux ports concurrents, sous incertitude climatique et selon une structure de gouvernance portuaire de type « landlord ». Trois scénarios de synchronisation sont examinés : les deux ports investissent tôt (période 1), tard (période 2), ou l'un investit tôt et l'autre tard. Les résultats montrent que le bien-être social diminue avec l'intensité croissante des catastrophes dans les trois cas. En cas d'intensité faible, l'investissement en adaptation augmente tandis que l'investissement en capacité varie selon les scénarios, révélant l'influence des contraintes de capacité et du calendrier d'investissement. En revanche, sous forte intensité, l'investissement en adaptation augmente initialement, puis diminue au-delà d'un certain seuil, illustrant la diminution des bénéfices liés à la résilience face à des catastrophes sévères. Les stratégies proactives surpassent généralement les stratégies réactives en matière de bien-être social, en particulier sous des intensités de catastrophe faibles à modérées. L'efficacité du calendrier d'investissement dépend de l'intensité des catastrophes. Sous faible intensité, des investissements précoces maximisent le bien-être social. En cas d'intensité extrême, le bien-être social est optimal lorsque les ports investissent à des moments différents, avec un port investissant tôt sous contrainte de capacité non contraignante. Cette stratégie mixte offre une plus grande flexibilité dans l'allocation des ressources entre adaptation et capacité. Ces résultats soulignent l'importance d'une planification proactive de la résilience, d'une allocation efficiente des ressources et de stratégies d'investissement spécifiques à chaque port.

Mots clés: Synchronisation des investissements, investissement en capacité portuaire, investissement en adaptation portuaire, incertitude liée au changement climatique, intensités des catastrophes, concurrence portuaire

Méthodes de recherche: Modèle de théorie des jeux à deux périodes, Équilibre de Nash, Analyse numérique

Abstract

Ports play an important role in global trade. As critical transportation hubs in supply chain, ports contribute to both economic and social development of their nearby communities. However, ports are facing increasing challenges from climate uncertainties such as cyclones, hurricanes and tsunamis as well as fluctuating trade volumes which often lead to congestion problems. In response to these growing challenges, more ports engage in joint capacity and climate-change adaptation investments to improve resilience and ensure smooth port operations during climate-induced disruptions. This study develops a two-period model to analyze the timing decisions of two competing ports regarding the interdependent capacity and adaptation investments under climate-change uncertainty and the "landlord" port governance structure. Three investment timing cases are investigated: both ports invest early (in period 1), both ports invest late (in period 2), and one port invests early (in period 1), while the other port invests late (in period 2). The findings show that social welfare decreases with increasing disaster intensity across all three cases. Under low disaster intensity, adaptation investment increases and capacity investment varies across cases, demonstrating how investment priorities are influenced by timing and capacity constraints. However, under high disaster intensity, adaptation investment initially increases but later decreases after certain threshold which illustrates that the benefits from additional resilience planning are offset by severe disaster disruptions. Proactive investment strategies generally outperform reactive ones in maximizing social welfare, especially under low to moderate disaster intensities. The effectiveness of investment timing is associated with the range of disaster intensity. Under low disaster intensity, early investments achieve highest levels of social welfare. Under extreme disaster intensity, the highest social welfare result is achieved when two ports invest at different times with the early-investing port operating under non-binding capacity constraints. This mixed strategy provides the ports with more flexibility in allocating resources between capacity and adaptation investments. These findings emphasize the importance of proactive resilience plannings, efficient resources allocation between investments, and port-specific investment strategies.

Keywords: Investment timing, port capacity investment, port adaptation investment, climate change uncertainty, disaster intensities, port competition

Research methods: Two-period game-theoretic model, Nash equilibrium, Numerical analysis

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1. Introduction

Ports are crucial transportation hubs to manage essential operations for the importation, exportation, and transshipment of cargo (Hidalgo-Gallego, 2017). Aside from their impacts on the global economy, ports also provide socioeconomic advantages for local communities through employment opportunities and infrastructure development that enhance national economic growth (Chang, 1978). However, ports face increasing challenges because of both climate change and rising port demand. Because of their location near rivers and coastal areas, ports are particularly vulnerable to natural disasters including cyclones, hurricanes, and earthquake-triggered tsunamis (Gou and Lam, 2019). Research shows that 86% of global ports are exposed to three or more climate and geological hazards, and storms create service disruptions at 40% of these ports (Verschuur et al., 2023). Moreover, the number of disaster events has increased dramatically from 100 per year during the 1970s to reach approximately 400 worldwide, exacerbating port vulnerabilities (Food and Agriculture Organization of the United Nations, 2023). This increasing frequency is combined with growing unpredictability because climate change leads to more often, intense, and variable climate extremes across the world (World Meteorological Organization, 2021). Furthermore, tropical cyclone-related ocean disasters intensify other hazards and bring ripple effects such as flooding (World Meteorological Organization, 2021). The rising natural hazards together with increased uncertainties create disruption in port operations, lead to broader economic and supply chain impacts, and affect nearby coastal communities (Izaguirre, 2021). It is therefore essential that ports invest in adaptation to enhance their resilience. Port adaptation investments consist of infrastructure improvements that include elevating port facilities, building flood barriers and seawalls, and upgrading drainage systems (Becker et al., 2018). The implementation of these adaptation strategies helps reduce vulnerabilities and maintain operational continuity during disaster events. Moreover, the advantages of adaptation investments exceed their expenses. According to Public Safety Canada (2019), every dollar spent on resilience-building leads to a reduction of ten dollars in post-disaster recovery costs. Proactive resilience planning also provides long-term resilience through strategies that protect against future extreme events. For example, Associated British Ports dedicated $2 million to construct a new lock gate which will defend against future storms (Associated British Ports, 2020). The Port Authority of New York and New Jersey established a $60 million flood protection initiative to protect their facilities together with nearby airports. The project will protect against 100-year storm events with a consideration of projected sea level rise (Port Authority of New York and New Jersey, 2022). The CLARION project, which unites the four major European ports (Rotterdam, Antwerp, Hamburg, Constanta) under the EU's Horizon Europe Programme, dedicates €6.9 million to enhance port resilience through climate-resilient quay walls, corrosion monitoring systems, flood prevention, and weather forecasting (Clarion project, 2025).

Ports are increasingly facing congestion problems due to rising demand, which illustrates the need for capacity-related investments such as improving storage areas, berths, and terminals (Bureau of Transportation Statistics, 2016). The global goods trading volume is expected to grow by 2.7% in 2024, with a projected increase of 3.0% in 2025 (World Trade Organization, 2024). As trading volumes continue to rise, ports need to consistently enhance their infrastructure to handle increasing demand and achieve higher economic returns (Munim and Schramm, 2018). By June 2024, 2.5 million TEUs (twenty-foot equivalent units) of vessel capacity were waiting offshore globally, accounting for 8.4% of the total worldwide fleet and contributing to rising freight rates (United Nations Conference on Trade and Development, 2024a). The number of port calls reached its highest level of 250,000 in 2023 due to renewed demand following the COVID-19 pandemic. This high level persisted through 2024, causing significant congestion—particularly at Asian ports, which handle 63% of global trade (Xu et al., 2021; UNCTAD, 2024b). Under the combined influence of increasing port calls and disruptions in the Red Sea, the Port of Singapore experienced wait times nearly twice the usual level from March to May 2024 (UNCTAD, 2024c). To address these challenges and ensure sustainable growth, it is important for ports to invest in infrastructure improvements. Several ports worldwide are already taking action to expand their capacity. For example, the Port of Mobile invested $200 million in the fourth stage of its terminal capacity expansion plan, which doubled the port's capacity from 500,000 to 1 million TEUs annually (Alabama Port Authority, 2024). The Port of Montreal invested more than $300 million to build the new Contrecœur terminal, which will add 1.15 million TEUs of annual capacity (Port of Montreal, 2024). The Port Authority of Rotterdam and Rotterdam World Gateway (RWG) are jointly expanding the Prinses Amaliahaven terminal, which will increase its capacity by 1.8 million TEUs (Port of Rotterdam, 2023c).

The growing worldwide shipping volumes and climate uncertainties have led ports to pursue joint investment plans for capacity expansion and climate-change adaptation measures. Ports now incorporate climate forecasts into the design of new facilities through supply chain automation and climate-adaptative planning (Becker et al., 2018). Integrating resilience into port infrastructure expansion design allows ports to adapt better to future climate disruptions at reduced costs (Mansouri, 2010). For example, the Port of Rotterdam implements the Rotterdam World Gateway (RWG) initiative, which adds two million TEUs (Port of Rotterdam, 2023a) to its capacity, and the national Delta programme uses adjustable flood barriers and reinforced dikes to manage and resist increasing water levels (Port of Rotterdam, 2023b). The Port of San Diego enhances its infrastructure and expands capacity through the Tenth Avenue Marine Terminal (TAMT) project, while simultaneously restoring coastal wetlands to minimize storm disruptions and using advanced stormwater treatment systems to protect wetlands (Port of San Diego, 2024).

The timing of investment plays a vital role in port capacity and adaptation decisions because early and late investments create different advantages and disadvantages that affect long-term investment outcomes' efficiency and effectiveness. Ports can invest in adaptation early to gain protective advantages from proactive resilience strategies. According to UNCTAD (2022), proactive planning is more effective at reducing climate disruptions when dealing with repeated risks such as anticipated climate events, rapid demand surges, capacity shortages caused by congestion, and port operational inefficiencies. The Canadian Climate Institute (2022) reports that proactive strategies help decrease coastal flooding expenses by 90%. Alternatively, ports may delay adaptation investments because they need to understand how climate disruptions will affect their operations. Ports can wait until the uncertainties become clearer by delaying investments (Truong et al., 2024). Another reason ports delay investments is that adaptation projects generate less profit than standard investments because they focus on cost reduction rather than revenue generation (United Nations Environment Programme, 2016). In addition, adaptation investments often involve significant upfront costs. For example, elevation strategies, which raise the height of infrastructure to improve resilience against sea-level rise, can cost between US $30 million and $200 million per square kilometre of port area (RTI International & Environmental Defense Fund, 2022). Additional barriers, such as regulatory policies, political instability, and economic and institutional weaknesses in various country settings can further increase the upfront costs (Climate Investment Funds, 2010). These high expenditures may be difficult to justify if climate disruptions do not occur. However, delaying adaptation investments will make ports vulnerable to climate change and potentially result in huge economic losses due to disruptions and shipping delays. Current annual storm-related damages are estimated at nearly $3 billion but could reach $25.3 billion per year by 2100 without adaptation investments (RTI International & Environmental Defense Fund, 2022). Meanwhile, early capacity investments enable ports to handle more vessels, which can significantly reduce congestion, boost trade, and generate positive spillover effects for neighboring ports (Brancaccio et al., 2024). It was also noted by Brancaccio et al. (2024) that adding capacity for one more vessel reduced congestion by 4% at the investing port and 0.6% at nearby ports. However, early investments in port infrastructure can lead to lock-in problems, where decision-makers continue inefficient projects due to excessive commitments, causing reduced flexibility and increased cost overruns (Cantarelli, 2010). In contrast, delayed capacity investments offer greater flexibility in aligning port capacity with actual market demand under uncertainty, helping to avoid risks of overcapacity or undercapacity (International Transport Forum, 2018). Both insufficient and excessive capacity expansion without a clear consideration of demand lead to high unit costs, congestion, and reduced competitiveness (Notteboom et al., 2022c). Nevertheless, delaying capacity expansions can result in increased congestion, which influences shipping rates, and delivery times and causes inefficiencies throughout the entire supply chain (Vizion, 2025).

The globalization of goods and services, the expansion of global supply chain networks, shifts in inter-port relations, and improved port-hinterland connections have intensified competition among ports (Notteboom et al., 2022b). Competition offers incentives for ports to strategically prioritize capacity and adaptation investments to improve their market positions, capture greater market share, and limit the expansion of competing ports (Musso et al., 2006). It directly influences critical decisions such as port pricing, adaptation strategies, and capacity investments, which are key determinants of port performance in competitive environments (Ishii et al., 2013; Itoh and Zhang, 2023). Increased port competition also benefits customers through expanded service choices, lower prices, and greater social welfare (Luo et al., 2022). Moreover, several studies highlight that inter-port competition influences investment decisions. Competition can lead to larger adaptation investments to mitigate climate disruptions (Wang and Zhang, 2018). It also accelerates investment timing, which leads to earlier—but not necessarily larger—capacity expansion investments (Balliauw et al., 2019; Randrianarisoa and Zhang, 2019). However, excessive competition forces ports to make trade-offs between long-term infrastructure investments, including capacity expansion and equipment upgrades, and short-term operational efficiency required by shipping companies to minimize dock time (Cheon et al., 2018). As a result, ports may either over-invest in capacity, which can lead to financial losses from unused resources, or delay investments to prioritize short-term efficiency, which can cause congestion (Heaver, 1995).

The study employs a two-period model to analyze investment-timing strategies, considering interdependent capacity and adaptation investments, the landlord port ownership structure[1], inter-port competition, and uncertainties in disaster intensity. Specifically, three investment timing cases are considered: both ports investing early in period 1 (Case I), both ports investing late in period 2 (Case II), and one port investing early in period 1 while the other invests late in period 2 (Case III). Adaptation and capacity investment decisions are made by the Port Authority with the objective of maximizing social welfare, while the Terminal Operator sets the port service charge to maximize profit, subject to the constraint that throughput volume must not exceed the capacity established by the Port Authority. Closed-form equilibrium outcomes for the three cases are derived. Numerical analysis is conducted by varying the disaster intensity parameter to illustrate the impact of investment-timing decisions on social welfare and to examine how disaster intensity affects capacity and adaptation investment choices.

The study presents several key findings. First, as disaster intensity increases, social welfare declines across all cases. Under low disaster intensity, adaptation investment often increases, and capacity investment differs across cases. This reflects how ports adjust resilience and expansion investment priorities based on investment timing and capacity constraints. However, when disaster intensity becomes high, adaptation investment initially increases but eventually decreases because of diminishing marginal returns, which the benefits from additional resilience fail to offset the

[1] According to Notteboom et al. (2022a), five types of port governance structures exit: public service ports, tool ports, landlord ports, corporatized ports, and private service ports. Public service ports are fully owned and operated by the government, whereas private service ports are fully privatized with only public sector supervision. Tool ports are still operated by the public but allow private cargo handling, while corporatized ports operate like private enterprises but remain publicly owned. Compared to corporatized and private service ports, landlord ports maintain public ownership of port land and regulations. In contrast to public service ports and tool ports, landlord ports maintain private sector decisions on operations and infrastructure maintenance. As the most common port model globally, accounting for more than 80% of ports, landlord ports provide an effective balance between public governance and private efficiency by keeping port land and regulations under public ownership and port infrastructure, operations and maintenance under private control by terminal operators (Notteboom and Haralambides, 2020). Therefore, this study focuses only on landlord port governance structure.

impacts of severe disruptions. Second, proactive investments generally achieve better performance than delayed investments, leading to higher investment levels, especially under low- to moderate-disaster intensities. Third, investment-timing decisions are influenced by the range of disaster intensities. When disaster intensity is low, early investments by both ports result in the highest social welfare. In contrast, under high disaster intensity, Case III, where one port invests early with non-binding capacity constraint in period 2 and the other port invests late with binding capacity constraint, achieves the highest level of social welfare. This suggests that non-binding capacity constraints give ports greater flexibility in adjusting investment decisions, improving their ability to cope with extreme disaster disruptions.

The remainder of the study is structured as follows: Section 2 presents a review of the relevant literature. Section 3 introduces the basic model. Section 4 conducts a numerical analysis. Finally, Section 5 concludes the key findings and outlines directions for future research.

2. Literature review

The study is related to two major research streams: port capacity investment and port adaptation investment.

2.1 Port capacity investment

Since uncertainty associated with demand, economic conditions, or disasters plays an important role in analyzing port capacity investment decisions, numerous studies have developed mathematical models to optimize the pricing, timing, and scale of capacity investments, mostly under demand uncertainty. For instance, Tan et al. (2015) construct a Hotelling-location framework to determine optimal service pricing, capacity, and location for inland ports under continuous demand, uncertain river conditions, and congestion. Allahviranloo and Afandizadeh (2008) apply a fuzzy integer programming model to optimize port development investment, while considering capacity constraints and uncertain cargo demand predictions across optimistic growth and pessimistic decline scenarios. Dekker et al. (2011) develop an optimal control framework to determine the timing and size of efficient port expansion investments under conditions of demand uncertainty and economies of scale for investment decisions. In addition to optimization models, real options models serve as dynamic tools for analyzing capacity investment timing under uncertainty. Balliauw et al. (2019) examine the timing and size of capacity investments of two heterogeneous competing ports, while accounting for demand uncertainty and provide suggestions for different ownership structures. Balliauw et al. (2020) assess the optimal scale and timing for building a new port that considers demand uncertainty and customer waiting time preferences, showing that ports with more wait time sensitive customers should delay capacity expansion projects. By extending this real-options analysis, Balliauw (2021) evaluate how different capacity investment options affect the timing and scale of capacity projects between a new capacity project and a completed port expansion project, while incorporating uncertain construction timelines and demand uncertainty. Guo et al. (2021) develop a stepwise model to examine optimal port capacity investment decisions and exit strategies for ports under uncertain demand and congestion in port cluster settings. With the same objective, Guo and Jiang (2022) present a multistage model to help ports choose between continuing or abandoning capacity expansion projects, while aiming to optimize their resource allocation within any port cluster under demand uncertainty. Chen and Liu

(2016) examine how demand uncertainty and congestion influence risk-averse ports' capacity expansion and pricing decisions when facing trade-offs between stability and efficiency. Beyond the context of ports, Gao and Driouchi (2013) incorporates Knightian uncertainty into real options analysis to show how decision makers' attitudes affect the timing of rail transit investment and population thresholds for investment, while applying this to Xiamen, China to improve rail transportation efficiency. Xiao et al. (2013) analyze how demand uncertainty influences capacity investment decisions in competitive multi-airport environments, showing that airports build larger capacities when capital costs are low during uncertain times. Zheng et al. (2020) study the optimal airlines' investment timing in exclusive airport terminals (ETs) under Knightian uncertainty and competition, and demonstrate how government subsidies modify private investments' incentives to achieve social optimality.

Many studies focus on how competitive dynamics between ports influence capacity investment and pricing strategies. Anderson et al. (2008) discuss how ports in Busan and Shanghai react to each other's capacity investment strategies to protect their market shares. Under a multi-port competition setting, Yeo and Song (2006) provide a competitiveness assessment tool to analyze and rank the competitiveness of Asian ports under the Hierarchical Fuzzy Process framework. The study identifies capacity, infrastructure facility, location, service quality, and profitability as important factors in gaining a competitive advantage over rival ports. Luo et al. (2012) employ a two-stage game model to study the impacts of structural transitions from monopoly to duopoly on pricing and irreversible capacity investment decisions. Wan and Zhang (2013) analyze the relationship between road congestion and seaport competition within the Cournot framework and illustrate how road capacity expansion and congestion tolls impact seaport competitive dynamics. Cheng and Yang (2017) compare capacity investment decisions at ports whose objectives differ—profit-oriented versus GDP-oriented. Talley and Ng (2021) develop a cargo port choice equilibrium model that simultaneously analyze the decisions of both shippers and port service providers, enabling policymakers to observe how policy changes and competition influence capacity investments and trade volume in the entire port network.

Multiple research studies analyze how different port ownership structures and vertical integration influence capacity investment decisions. De Borger et al. (2008) demonstrate how congestible duopolistic markets affect public investment in hinterland capacity and private port pricing strategies, which result in changes to hinterland congestion, competitive pricing, and overall welfare in European ports. Xiao et al. (2012) investigate how different port ownership structures influence capacity investments, pricing strategies, and congestion under various competition scenarios to impact social welfare. Zheng and Negenborn (2014) compare centralized versus decentralized regulation under imperfect information through agency theory and Stackelberg framework, showing decentralized regulation leads to better port efficiency, higher port demand, and social welfare. Wan et al. (2016) analyze how different coalition structures in landside accessibility investments influence social welfare under port competition, showing different port ownership structures (private or public) ports affect the social welfare outcomes. While both Zhu et al. (2019) and Jiang et al. (2021) analyze the effects of vertical integration between terminal operators and shipping lines on capacity investment and port pricing, they produce different social welfare outcomes. Zhu et al. (2019) suggest that vertical integration improves social welfare through enhanced infrastructure, which reduces congestion. Conversely, Jiang et al. (2021) believe that integration diminishes social welfare by allowing shipping lines to gain excessive control over port operations.

2.2 Port adaptation investment

Extensive research has explored the perceptions, actions, and strategies of various stakeholders regarding climate risks, resilience, and port adaptation investment. Interviews and surveys conducted by Becker et al. (2012), Ng et al. (2018), and Mclean and Becker (2021) illustrate that ports need holistic and integrated strategies to collect information and develop long-term, proactive resilience plans. Case studies by Becker and Caldwell (2015) on two American ports and by Ng et al. (2013) on four Australian ports demonstrate that collaborative adaptation strategies and a clear understanding of regional vulnerabilities are essential. Becker et al. (2013, 2018) explain how infrastructure, policy frameworks, and adaptation investments enhance port resilience from the global viewpoint. In particular, Becker et al. (2018) expand the global knowledge base of port resilience through financial and risk-management strategies, while advocating customized risk assessments for specific ports. In addition to port studies, Wang et al. (2020b) perform a critical analysis of climates risks affecting road and rail systems across various locations to develop resilience planning and adaptation strategies.

Several studies use economic models to evaluate the timing and scale of adaptation investments. Xiao et al. (2015) develop an integrated model for landlord ports, which incorporates information accumulation with disaster uncertainties and investment spillovers to determine the optimal timing of adaptation investments. Randrianarisoa and Zhang (2019) create a two-period model to analyze the optimal timing and scale of adaptation investments, while considering climate uncertainty, competition, and information accumulation over time. Jiang et al. (2020) apply an economic model to evaluate the relative effectiveness of climate change mitigation (CCM) and climate change adaptation (CCA) strategies across different market conditions. Wang et al. (2022) develop a two-period model to examine how competition and different risk attitudes influence the size and timing of adaptation investments within an integrated seaport and dry port system.

Various studies have investigated how competition or cooperation among ports influence adaptation strategies. Asadabadi and Miller-Hooks (2018) develop a deterministic, game-theoretic model of a co-opetitive port network to evaluate protective infrastructure investments' resilience benefits. Asadabadi and Miller-Hooks (2020) use a stochastic framework with various unpredictable disaster scenarios to help stakeholders who operate under both competitive and co-opetitive circumstances. Chen et al. (2018) use a network game-theoretic model to examine how port-hinterland container transportation networks (PHCTNs) become more resilient against man-made unconventional emergency events (MUEEs) through adaptation investments in a co-opetitive setting. Wang and Zhang (2018) examine how inter-port competition or cooperation influences adaptation investments in two competing public ports that share a common hinterland under Knightian uncertainty. By introducing governance structure to the analysis, Wang et al. (2020a) demonstrate how terminal operators' governance structures influence adaptation strategies under asymmetric disaster uncertainties and inter- or intra-port competition. Itoh and Zhang (2023) analyze independent and simultaneous disaster risks at two competing ports and propose a framework to balance private and public investment responsibilities.

Several studies illustrate the impacts of government policies on port adaptation investments and resilience planning. Pauw et al. (2022) show that government intervention to deal with market information asymmetries leads to increased private-sector funding for port adaptation projects. Zheng et al. (2021a; 2021c) examine the effects of two common regulatory instruments—subsidies and minimum-investment quotas—on adaptation investments. Zheng et al. (2021c) focus on a two-port network with asymmetric disaster impacts to demonstrate that minimum-investment quotas with adaptation-sharing produce greater adaptation investments than subsidies. Conversely, Zheng et al. (2021a) incorporate climate ambiguity, diverse risk attitudes and inter-port spillovers to show that the most suitable instrument depends on uncertainty levels and port-specific risk preferences. Zheng et al. (2022a) analyze how a subsidy impacts port adaptation investment when both government assessments and disasters are uncertain, showing that the presence of these uncertainties discourages the subsidy's effectiveness. Zheng et al. (2022b) develop a two-port economic model to analyze how public versus confidential government disclosure policies with a subsidy influence adaptation investments and social welfare.

2.3 Joint port capacity and adaptation investments

In Section 2.1, although many studies using economic models have examined the timing and scale of port capacity investment under demand uncertainty, congestion, pricing strategies, competition, and governance structures, most of them focus on single-period competitive settings. These studies overlook the interdependence between capacity and adaptation investments, and they do not consider how disaster uncertainty influences investment timing decisions in a multi-period framework. Similarly, the studies in Section 2.2 analyze the optimal scale and timing of adaptation investments under climate uncertainty, but they emphasize information accumulation, competition, or market dynamics rather than the interaction between capacity and adaptation investment decisions.

Limited research has analyzed the joint capacity and adaptation investment decisions. Gong et al. (2020) demonstrate an analytical model to analyze the trade-off between port capacity expansion and adaptation investments under uncertainty and budget constraints. However, their model focuses on investment decisions within a single-period, single-port setting and does not consider investment timing decisions. Xia and Lindsey (2021) and Xia et al. (2024) illustrate integrated capacity and adaptation investments under climate uncertainty. The former study analyzes optimal time and size of joint investments under information accumulation in a non-competitive setting, whereas the latter explores the impacts of inter-port competition and climate disruptions on joint investment decisions without considering the timing of investments. Wang et al. (2023) develop a two-period model to analyze the optimal timing and size of joint capacity and adaptation investments by port authorities under risk-sensitive behaviour and disaster uncertainty. However, their study focuses on single port setting without considering inter-port competition and how terminal operators make decisions in response to port authorities' investment decisions. This study bridges these gaps by developing a two-period model that analyzes the timing of joint capacity and adaptation investments under climate uncertainty, inter-port competition and interactions between port authorities and terminal operators.

Table 1 presents a summary of key factors considered or omitted in the papers reviewed in Section 2 on port investments that utilize game-theoretic modeling approaches. The key factors considered are port competition, investment periods, information updating, ownership structure and types of uncertainty.

Table 1: Summary of reviewed papers using game-theoretic modeling approaches

Paper	Capacity investment	Adaptation investment	Competition	Investment horizon	Information	Port structure[2]	Uncertainty
Allahviranloo and Afandizadeh (2008)	√	×	×	Multi-period (finite-horizon)	×	×	Uncertainty in cargo demand forecast
De Borger et al. (2008)	√	×	Two competing ports	Two	Full	Landlord	×
Dekker et al. (2011)	√	×	×	Multi-period (finite-horizon)	×	Public	Uncertainty in demand forecast
Luo et al. (2012)	√	×	Two competing ports	Two	Full	Landlord	×
Gao and Driouchi (2013)	√	×	×	Continuous time (infinite-horizon)	Incomplete	Public	Uncertainty in population growth forecast

[2] Definitions of the port structures are provided in the footnote in Section 1.

Xiao et al. (2013)	√	×	Two competing airports	Two	×	Mixed (public and private)	Uncertainty in future demand
Wan and Zhang (2013)	√	×	Two competing ports	Two	Full	Mixed (public and private)	×
Zheng and Negenborn (2014)	√	×	Competing terminals within a single port	One	Asymmetric (centralization) and full (decentralization)	×	×
Tan et al. (2015)	√	×	×	One	×	Private	×
Xiao et al. (2015)	×	√	×	Two	Information accumulation	Landlord	Climate uncertainty
Chen and Liu (2016)	√	×	Two competing ports	Two	Incomplete (stage 1) and full (stage 2)	×	Demand uncertainty
Asadabadi and Miller-Hooks (2018)	×	√	Multi-port co-opetition[3]	One	Information sharing	×	Disruption uncertainty

[3] Co-opetition is when companies collaborate and compete at the same time (Brandenburger and Nalebuff, 1996). It shows that business performance involves not only outperforming rivals but also cooperating to gain mutual benefits.

Chen et al. (2018)	×	√	Multi-port co-opetition	One	Full	×	Man-made unconventional emergency events (MUEEs)
Wang and Zhang (2018)	×	√	Two competing ports	Discrete time (early and late)	Information accumulation	Landlord	Climate uncertainty
Balliauw et al. (2019)	√	×	Two competing ports	Continuous time (infinite-horizon)	Information accumulation	×	Demand uncertainty
Randrianarisoa and Zhang (2019)	×	√	Two competing ports	Two	Information accumulation	Landlord	Climate uncertainty
Zhu et al. (2019)	√	×	Intra-port competition	Discrete time	Full	Landlord	×
Asadabadi and Miller-Hooks (2020)	×	√	Multi-port co-opetition	One	Full	×	Disruption uncertainty
Balliauw et al. (2020)	√	×	×	Continuous time (infinite-horizon)	Full	×	Demand uncertainty

Gong et al. (2020)	√	√	×	Discrete time	Full	×	Demand and disaster uncertainty
Jiang et al. (2020)	×	√	Two competing ports	One	Full	×	×
Wang et al. (2020a)	×	√	Two competing ports	Discrete time	Information accumulation	Landlord	Disaster occurrence uncertainty
Zheng et al. (2020)	√	×	Intra-airport competition	Continuous time (infinite-horizon)	Full	×	Demand uncertainty with ambiguity
Balliauw (2021)	√	×	×	Continuous time (infinite-horizon)	Full	×	Demand uncertainty
Guo et al. (2021)	√	×	Multi-port competition within cluster	Continuous time (stepwise investment)	×	Public	Demand uncertainty
Jiang et al. (2021)	√	×	Two competing ports	Multi-stage	Full	×	×

Xia and Lindsey (2021)	√	√	×	Two	Information accumulation	Landlord	Climate and demand uncertainty
Guo and Jiang (2022)	√	×	Multi-port competition within cluster	Continuous time (multi-stage)	Full	Public	Demand uncertainty
Wang et al. (2022)	×	√	Seaport-dry port competition in shared hinterland	Two	Information accumulation	×	Risk occurrence ambiguity
Itoh and Zhang (2023)	×	√	Two competing ports	One	Full	Public, private, landlord comparison	Disaster occurrence uncertainty
Xia et al. (2024)	√	√	Two competing ports	One	×	Mixed (public and private)	Climate uncertainty
This study	√	√	Two competing ports	Two	×	Landlord	Climate uncertainty

3. The model

The model considers two competing ports A and B that compete under the landlord port ownership structure. Each port, A and B, consists of a Port Authority (PA) and a Terminal Operating Company (TOC). The PAs is responsible for developing port infrastructure and making investment decisions on behalf of the regional or national government (Verhoeven, 2010). Acting as a "landlord", the PA leases port infrastructure to the TOC, who is responsible for port operations (Notteboom, 2007). Since the PA considers public interests when making investment decisions, we assume its objective is to maximize social welfare, whereas the TOC, as a private entity, aims to maximize profit by setting the port service charge, taking into account the investments made by the PA (WorldBank, 2007).

This study develops a two-period, two-stage model to examine the capacity and adaptation investment decisions of PAs and the pricing strategies of TOCs at two competing ports under disaster uncertainty. The study assumes that both the PAs and TOCs have full knowledge of the demand and cost functions which allows the model to be solved by backward induction in Section 3.2.2. A complete list of the mathematical notations used in the following model is provided in Appendix A.1.

The model is structured as follows:

Regarding investment timing, the PAs of the two competing ports, A and B, can choose to invest either in period 1 or period 2. Each period represents a planning horizon for port infrastructure investments, typically spanning 15–20 years, depending on the port. To examine the trade-off between early and delayed investment, we assume that a port can invest in either period 1 or period 2, but not both. Three investment timing scenarios are introduced and analyzed:

Case I: both ports (A and B) invest in period 1.

Case II: both ports (A and B) invest in period 2.

Case III: one port invests in period 2, while the other port invests in period 2.

Within each period, the model unfolds in two stages:

Stage 1: At the beginning of the period, the PAs of ports A and B determine the optimal capacity and adaptation investment levels to maximize their respective social welfare.

Stage 2: Based on the investment decisions made by the PAs, the TOCs at ports A and B determine port charge while ensuring that throughput volume does not exceed the available port capacity. This capacity includes the initial capacity plus any additional capacity resulting from investments made by the PA at the beginning of the period. The TOCs aim to maximize their own profit. If the PAs do not invest at the beginning of the period, the available capacity remains equal to the initial capacity. We therefore disregard any depreciation of available capacity in subsequent periods.

3.1 Demand function for port service

Following Singh and Vives (1984), this study assumes that a representative shipper has a quadratic utility function U_t when choosing between port A and port B. This function shows diminishing returns which as traffic volume increases, the marginal utility decreases and it also allows for substitution between two ports.

$$U_t = a(q_{At} + q_{Bt}) - \frac{1}{2}b({q_{At}}^2 + {q_{Bt}}^2 + 2rq_{At}q_{Bt}), \tag{1}$$

where q_{it} is the traffic volume at port i ($i = A, B$) in period t ($t = 1, 2$), and a, b, and r are positive parameters.

The representative shipper maximizes its net utility NU_t by choosing q_{At} and q_{At}:

$$NU_t = U(q_{At}, q_{Bt}) - \tau_{At}q_{At} - \tau_{Bt}q_{Bt}, \tag{2}$$

where τ_{it} represents the port charge set by the TOC at port i ($i = A, B$) in period t ($t = 1, 2$). We assume that the full cost incurred by shippers when using a port consists solely of the port service charge. However, the model could be extended to incorporate additional costs, such as congestion costs (e.g., De Borger and Van Dender, 2006; Xiao et al., 2012; Balliauw et al., 2019) and disaster-related damage costs (Xia and Lindsey, 2021; Xia et al., 2024), which may also impact shippers' decisions.

By applying the first-order conditions (FOCs), i.e., $\frac{\partial NU}{\partial q_{At}} = 0$ and $\frac{\partial NU}{\partial q_{Bt}} = 0$, the inverse demand functions can be derived as follows:

$$\tau_{At} = a - bq_{At} - rq_{Bt} \tag{3}$$

$$\tau_{Bt} = a - bq_{Bt} - rq_{At} \tag{4}$$

The parameter a represents the maximum willingness to pay when there is no demand (or the price at which the demand drops to 0). The parameter b represents the price sensitivity to own demand. The parameter r $(0 < r < b)$ represents the degree of substitutability between the services of ports A and B. When $r = 0$, the two ports provide completely differentiated services, representing a market scenario where each operates as a monopoly without competition. In contrast, when $r = b$, the two ports provide homogeneous services, reflecting a fully competitive market. Similar parameters are used in Caravaggio and Sodini (2018), Balliauw et al. (2019), and Zheng et al. (2020, 2021b, 2021c) to illustrate the degree of differentiation and product heterogeneity within maritime and aviation markets.

By rearranging Eq. (3) and (4), the demand functions are derived as follows:

$$q_{At} = \frac{a}{(b+r)} - \frac{b}{(b-r)(b+r)}\tau_{At} + \frac{r}{(b-r)(b+r)}\tau_{Bt} \tag{5}$$

$$q_{Bt} = \frac{a}{(b+r)} - \frac{b}{(b-r)(b+r)}\tau_{Bt} + \frac{r}{(b-r)(b+r)}\tau_{At} \tag{6}$$

For model tractability, the demand function is assumed to remain the same across both periods. However, the model could be extended to incorporate period-dependent parameters (e.g., a_t, b_t, r_t) to capture different demand features of the two periods.

3.2 Case I: Both ports invest in period 1

3.2.1 Problem formulation

Stage 1: PAs' social welfare maximization problem

Suppose the port i $(i = A$ or $B)$ start with an initial capacity $\overline{K_i}$ and adaptation $\overline{I_i}$. The initial capacity $\overline{K_i}$ represents the maximum cargo volume that port i can handle within a given period. The adaptation investment $\overline{I_i}$ represents the financial resources allocated to enhancing the port's resilience against natural disasters. Bekker et al. (2013) suggest that adaptation includes both hard interventions, such as constructing storm surge barriers, enhancing drainage systems, and elevating infrastructure, and soft interventions such as emergency plans, conservation programs and improved decision support systems. Hass and Wentland (2023) illustrate that there is a lack of agreements upon the standardized methodologies to recognize climate change adaptation. Unlike capacity, which can be measured in standardized units, such as millions of TEUs (Twenty-Foot Equivalent Units) per year, adaptation strategies cannot be quantified with a single unit. Therefore, the adaptation investments in this study are defined as the total expenditures incurred in adaptation strategies.

Since in Case I, the PAs of both ports invest in period 1 and no investment in period 2 will be made, the available capacity and adaptation in both periods are $\overline{K_i} + K_{i1}$ and $\overline{I_i} + I_{i1}$, assuming no depreciation on the physical infrastructure. As stated earlier, the objective of the PAs for both ports are to maximize social welfare by determining the capacity and adaptation investment levels in period 1.

$$\max_{\{K_{i1}, I_{i1}\}} SW_i = SW_{i1} + \beta\, SW_{i2}, \tag{7}$$

where SW_i is the social welfare of port i, which includes the social welfare in period 1 (SW_{i1}) and period 2 (SW_{i2}), and β is the discount factor.

Social welfare of port i in period t SW_{it} is calculated as the sum of consumer surplus CS_{it}, the profit of TOC π_{it} minus the expected costs associated with disasters D_{it}, capacity investment $c_k\, K_{it}$, adaptation investment I_{it}.

$$SW_{it} = CS_{it} + \pi_{it} - D_{it} - c_k\, K_{it} - I_{it}, \tag{8}$$

where c_k is the unit capacity investment cost.

The total consumer surplus, $CS_{At} + CS_{Bt}$, is represented by the net utility defined in Eq. (2). Since each port prioritizes its own consumers, the consumer surplus for each port is defined as follows:

$$CS_{it} = aq_{it} - \frac{1}{2} b\, {q_{it}}^2 - r\, q_{it} q_{-it} - \tau_{it} q_{it}, \tag{9}$$

where the subscript $-i$ denotes the port other than port i. The detailed derivation is provided in Appendix A.2.

The study assumes that no operating costs are incurred by the TOC to focus on the influence of capacity and adaptation investments on revenues. The TOC's profit function is defined as:

$$\pi_{it} = \tau_{it} q_{it}, \tag{10}$$

The expected disaster damage cost in period 1 D_{i1} is defined as:

$$D_{i1} = E_{x_1}\,[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_i)]^+, \tag{11}$$

where x_1 is the disaster intensity during period 1 and θ ($\theta > 1$) is the effectiveness in adaptation investment. This shows that every \$1 invested in adaptation brings more than \$1 benefits in disaster damage reduction which offer incentives for PAs to invest in adaptation planning. $(\bar{K}_i + K_{i1})$ is the available capacity of port i at the beginning of period 1 after the investment by the PA. $(\bar{K}_i + K_{i1})x_1$ represents the vulnerability of a port, as greater handling capacity increases exposure to natural disasters due to the extensive physical infrastructure at risk and the intensity of the disaster further amplifies the port's vulnerability. However, the port's vulnerability can be reduced by adaptation investments. If the adaptation investment $\theta(\bar{I}_i + I_i)$ is sufficient to fully offset potential damage $(\bar{K}_i + K_{i1})x_1$, the resulting damage is zero. Thus, the positive part function $[\cdot]^+$ is applied to ensure that the disaster costs are non-negative. Since x_1 is a random variable, the expectation is taken with respect to x_1.

Since the ports do not make further investment in period 2, available capacity and adaptation in period 2 is still $(\bar{K}_i + K_{i1})$ and $(\bar{I}_i + I_i)$ respectively. The expected disaster damage cost for port i in period 2 D_{i2} is thus defined as:

$$D_{i2} = E_{x_2}\,[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_i)]^+, \tag{12}$$

where x_2 is the disaster intensity in period 2, which is a random variable.

By rearranging the terms, the PA's objective function can be written as:

$$\begin{aligned}\max_{\{K_{i1}, I_{i1}\}} SW_i = &\left(\frac{1}{2} q_{i1}(a + \tau_{i1}) - \ E_{x_1}\,[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_i)]^+ - c_k K_{i1} - I_{i1}\right) \\ &+ \beta\left(\frac{1}{2} q_{i2}(a + \tau_{i2}) - \ E_{x_2}\,[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})]^+\right).\end{aligned} \tag{13}$$

Stage 2: TOCs' profit maximization problem

The TOC of port i maximizes its profits in each period, subject to the capacity constraint:

$$\max_{\{\tau_{it}\}} \pi_{it} = \tau_{it} q_{it} \\ s.t. q_{it} \leq \overline{K}_i + K_{i1}. \tag{14}$$

3.2.2 Model analysis

The model can be solved using backward induction, starting from Stage 2. If the capacity constraint is binding for both ports, the equilibrium traffic volume at port i is given by:

$$q_{it} = \overline{K}_i + K_{i1}. \tag{15}$$

Substituting this equilibrium traffic volume into the inverse demand function in Eq. (3) and Eq. (4), the equilibrium port charge is derived as:

$$\tau_{it} = a - b(\overline{K}_i + K_{i1}) + r(\overline{K}_{-i} + K_{-i1}). \tag{16}$$

If the capacity constraint is not binding for either port, the demand function is substituted into the TOC's profit function: $\pi_{it} = \tau_{it} q_{it} = \tau_{it}(\frac{a}{(b+r)} - \frac{b}{(b-r)(b+r)}\tau_{it} + \frac{r}{(b-r)(b+r)}\tau_{-it})$. The equilibrium port charges are obtained by solving the system of FOCs for profit maximization: $\frac{\partial \pi_{At}}{\partial \tau_{At}} = 0$ and $\frac{\partial \pi_{Bt}}{\partial \tau_{Bt}} = 0$. Solving these equations yields the equilibrium port charges:

$$\tau_{\mathrm{At}} = \frac{a(b-r)}{2b-r}, \tau_{\mathrm{Bt}} = \frac{a(b-r)}{2b-r}. \tag{17}$$

The equilibrium traffic can be obtained by substituting the equilibrium port charges into the demand function:

$$q_{\mathrm{At}} = \frac{ab}{(2b-r)(b+r)}, q_{\mathrm{Bt}} = \frac{ab}{(2b-r)(b+r)}. \tag{18}$$

Based on the assumption that both the PAs and TOCs fully know the demand quantities, and that the PAs make investment decisions considering the responses of the TOCs, equations (17) and (18) use to discuss that a rational PA would choose the investment level exactly required by the TOCs. For example, if the capacity investment by the PA exceeds the level required by the TOC (i.e., $\overline{K}_i + K_{i1} > \frac{ab}{(2b-r)(b+r)}$), it would result in overinvestment, as the PA could achieve the same outcome with the investment level exactly needed by the TOC (i.e., $\overline{K}_i + K_{i1} = \frac{ab}{(2b-r)(b+r)}$). Therefore, at the optimal investment level, the capacity constraint must be binding to avoid costs of excess or shortage. Equations (17) and (18) also provide the parameter functions for the port A non-binding scenario discussed later in Section 3.4.2.2.

Substituting the equilibrium port charge from Eq. (15), along with the equilibrium port traffic volume from Eq. (16), into the PA's objective function in Eq. (13), the PA's objective function is reformulated as:

$$\begin{aligned}\max_{\{K_{i1},I_{i1}\}} SW_i = &\Big(\frac{1}{2}(\bar{K}_i + K_{i1})(a + (a - b(\bar{K}_i + K_{i1}) + r(\bar{K}_{-i} + K_{-i1})))\\ &- E_{x_1}[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_i)]^+ - c_k K_{i1} - I_{i1}\Big)\\ &+ \beta\Big(\frac{1}{2}(\bar{K}_i + K_{i1})(a + (a - b(\bar{K}_i + K_{i1}) + r(\bar{K}_{-i} + K_{-i1})))\\ &- E_{x_2}[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})]^+\Big)\end{aligned} \tag{19}$$

We first examine the adaptation investment decision. In the PA's objective function, adaptation investment affects only the cost components, including: the disaster damage cost in period 1 (i.e., $- E_{x_1}[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_i)]^+$), the adaptation investment cost in period 1 (i.e., $-I_{i1}$), and the disaster damage cost in period 2 (i.e., $-\beta E_{x_2}[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})]^+$). Thus, the optimal adaptation investment I_{i1} should minimize these cost terms. We first derive the optimal I_{i1} as a function of K_{i1}, and then determine the optimal K_{i1}. The optimal I_{i1} must satisfy:

$$\min_{\{I_{i1}\}} E_{x_1}[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1})]^+ + I_{i1} + \beta E_{x_2}[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})]^+. \tag{20}$$

To solve for optimal I_{i1}, the derivative of the objective function is taken with respect to I_{i1}, and the first-order condition (FOC) is as follows:

$$\frac{\partial E_{x_1}[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1})]^+}{\partial I_{i1}} + 1 + \beta \cdot \frac{\partial E_{x_2}[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})]^+}{\partial I_{i1}} = 0. \tag{21}$$

The FOC is equivalent to:

$$\begin{aligned}&\frac{\partial E_{x_1}[I((\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1}))\cdot((\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1}))]}{\partial I_{i1}} + 1\\ &\quad + \beta\frac{\partial E_{x_2}\big[I\big((\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})\big)\cdot\big((\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})\big)\big]}{\partial I_{i1}} = 0,\end{aligned}$$

where $I(\cdot)$ represents the indicator function, defined as:

$$I(x) = \begin{cases} 1, if\ x > 0 \\ 0, if\ x \le 0 \end{cases}$$

Since $\frac{\partial E(I(f(x))f(x))}{\partial x} = E(I(f(x))\frac{\partial f(x)}{\partial x})$, where $f(x)$ is any function of variable x, the FOC can be rewritten as:

$$E_{x_1}[I((\overline{K}_i + K_{i1})x_1 - \theta(\overline{I}_i + I_{i1})) \cdot (-\theta)] + 1 + \beta \cdot E_{x_2}[I\left((\overline{K}_i + K_{i1})x_2 - \theta(\overline{I}_i + I_{i1})\right) \cdot (-\theta)] = 0.$$

Since $E\left(I\big(f(x)\big)\right) = P(f(x) > 0)$, the FOC can be reformulated as:

$$\begin{aligned}(-\theta) \cdot P\big((\overline{K}_i + K_{i1})x_1 - \theta(\overline{I}_i + I_{i1}) \ge 0\big) + 1 + \beta \cdot (-\theta) \cdot P\big((\overline{K}_i + K_{i1})x_2 - \theta(\overline{I}_i + I_{i1}) \ge 0\big) \\ = (-\theta) \cdot \Big(1 - P\big((\overline{K}_i + K_{i1})x_1 - \theta(\overline{I}_i + I_{i1}) \le 0\big)\Big) + 1 + \beta \cdot (-\theta) \\ \cdot \Big(1 - P\big((\overline{K}_i + K_{i1})x_2 - \theta(\overline{I}_i + I_{i1}) \le 0\big)\Big) \\ = (-\theta) \cdot \left(1 - P\left(x_1 \le \frac{\theta(\overline{I}_i + I_{i1})}{(\overline{K}_i + K_{i1})}\right)\right) + 1 + \beta \cdot (-\theta) \\ \cdot \left(1 - P\left(x_2 \le \frac{\theta(\overline{I}_i + I_{i1})}{(\overline{K}_i + K_{i1})}\right)\right) = 0,\end{aligned}$$

which is equivalent to:

$$(-\theta) \cdot \left(1 - F_{x_1}\left(\frac{\theta(\overline{I}_i + I_{i1})}{(\overline{K}_i + K_{i1})}\right)\right) + 1 + \beta \cdot (-\theta) \cdot \left(1 - F_{x_2}\left(\frac{\theta(\overline{I}_i + I_{i1})}{(\overline{K}_i + K_{i1})}\right)\right) = 0, \quad (22)$$

where $F_{x_t}(\cdot)$ is the CDF (cumulative distribution function) of x_t.

To obtain a closed-form solution, we must assume a probability distribution for x_t. For tractability, we assume that $x_1 \sim U[0,1]$, meaning x_1 follows a uniform distribution between 0 and 1, and that $x_2 \sim [0, x]$, meaning x_2 follows a uniform distribution between 0 and x. The parameter x represents climate change trends. If $x > 1$, it indicates worsening climate conditions. If $x < 1$, it indicates improving climate conditions.

Given the distribution of x_t, four scenarios arise with respect to the values of $F_{x_t}\left(\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}\right)$.

If $0<\frac{\theta(\bar{I}_i+I_{i1})}{\bar{K}_i+K_{i1}}<x<1$ (scenario 1, illustrated in Figure 1(a)), $F_{x_1}\left(\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}\right)=\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}$ and $F_{x_2}\left(\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}\right)=\frac{1}{x}\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}$.

If $0<x<\frac{\theta(\bar{I}_i+I_{i1})}{\bar{K}_i+K_{i1}}<1$ (scenario 2, illustrated in Figure 1(a)), $F_{x_1}\left(\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}\right)=\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}$ and $F_{x_2}\left(\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}\right)=1$.

If $0<\frac{\theta(\bar{I}_i+I_{i1})}{\bar{K}_i+K_{i1}}<1<x$ (scenario 3, illustrated in Figure 1(b)), $F_{x_1}\left(\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}\right)=\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}$ and $F_{x_2}\left(\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}\right)=\frac{1}{x}\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}$.

If $0<1<\frac{\theta(\bar{I}_i+I_{i1})}{\bar{K}_i+K_{i1}}<x$ (scenario 4, illustrated in Figure 1(b)), $F_{x_1}\left(\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}\right)=1$ and $F_{x_2}\left(\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}\right)=\frac{1}{x}\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}$.

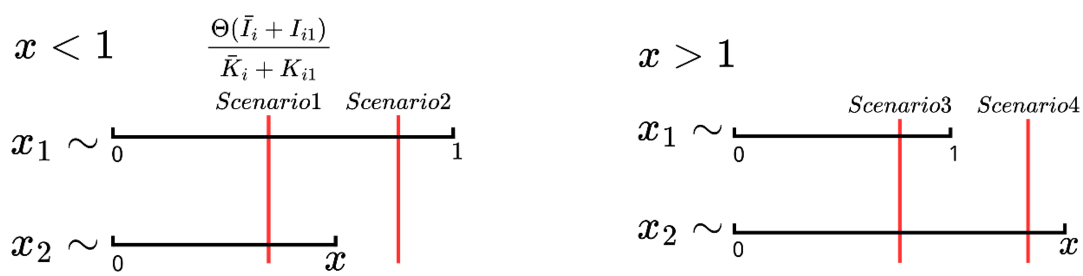


Figure 1(a) **Figure 1(b)**

Figure 1: Four scenarios with respect to the value of $F_{x_t}\left(\frac{\theta(\bar{I}_i+I_{i1})}{(\bar{K}_i+K_{i1})}\right)$

The closed-form solutions of the four scenarios are derived in the following Subsection 3.2.2.1 to 3.2.2.4. The comparative results for the following scenarios are summarized in Table 2.

3.2.2.1 Scenario 1: $0 < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < x < 1$

The FOC in Eq. (22) can be rewritten as:

$$(-\theta) \cdot \left(1 - \left(\frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}}\right)\right) + 1 + \beta \cdot (-\theta) \cdot \left(1 - \left(\frac{\frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}}}{x}\right)\right) = 0$$

After rearranging the terms, the optimal adaptation investment in period 1 by port i (I_{i1}), expressed as a function of K_{j1}, can be obtained as:

$$I_{i1} = \frac{(\bar{K}_i + K_{i1})x(\theta + \beta\theta - 1)}{(x + \beta)\theta^2} - \bar{I}_i. \tag{23}$$

Substituting Eq. (23) into the threshold, $\frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}}$, the range $0 < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < x < 1$ simplifies to $0 < \frac{x(\theta + \beta\theta - 1)}{(x+\beta)\theta} < x < 1$. Further rearrangement simplifies the range to $0 < 1 - \frac{1}{\theta} < x < 1$.

Within this range, the expected disaster cost in both periods at optimal I_{i1} are calculated as follows, with details available in the Appendix A.3:

$$E_{x_1}\left[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1})\right]^+ = \frac{(\bar{K}_i + K_{i1}) \cdot (\beta\theta - x(\beta\theta - 1))^2}{2(x + \beta)^2\theta^2}. \tag{24}$$

$$E_{x_2}\left[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})\right]^+ = \frac{(\bar{K}_i + K_{i1})x(1 - (1 - x)\theta)^2}{2(x + \beta)^2\theta^2}. \tag{25}$$

To simplify the expressions of equilibrium outcomes, the total cost in the social welfare function of port i is denoted as TC_i, which includes the capacity and adaptation investments and disaster damage costs over two periods.

$$TC_i = E_{x_1}\left[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1})\right]^+ + c_k \cdot K_{i1} + I_{i1} + E_{x_2}\left[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})\right]^+.$$

Specifically, for scenario 1, by plugging in Eq. (23) to (25) into TC_i, the total cost becomes:

$$TC_i^{I,1} = \frac{(\bar{K}_i + K_{i1}) \cdot (\beta\theta - x(\beta\theta - 1))^2}{2(x+\beta)^2\theta^2} + c_k \cdot K_{i1} + \frac{(\bar{K}_i + K_{i1})x(\theta + \beta\theta - 1)}{(x+\beta)\theta^2} - \bar{I}_i + \beta \cdot \frac{(\bar{K}_i + K_{i1})x(1 - (1 - x)\theta)^2}{2(x+\beta)^2\theta^2},$$

where the superscript I indicates Case I and superscript 1 indicates Scenario 1.

For simplicity, the derivative of the total cost with respect to K_{i1} (i.e., $\frac{\partial TC_i^{I,1}}{\partial K_{i1}}$) is denoted as the marginal cost $C_i^{I,1}$:

$$C_i^{I,1} = \frac{\partial TC_i}{\partial K_{i1}} = \frac{(\beta\theta - x(\beta\theta - 1))^2}{2(x+\beta)^2\theta^2} + c_k + \frac{x(\theta + \beta\theta - 1)}{(x+\beta)\theta^2} + \beta\frac{x(1-(1-x)\theta)^2}{2(x+\beta)^2\theta^2}. \qquad (26)$$

Eq. (26) sums all marginal-cost-related terms in social welfare into $C_i^{I,1}$. The equilibrium values of τ_{it}, q_{it}, and I_{i1} are expressed as functions of K_{i1} in Eq. (15), (16) and (23). We substitute these expressions into the social welfare function in Eq. (19) and obtain the specific social welfare function for scenario 1:

$$SW_i^{I,1} = \left(\frac{1}{2}(\overline{K}_i + K_{i1})\left(a + \left(a - b(\overline{K}_i + K_{i1}) + r(\overline{K}_{-i} + K_{-i1})\right)\right)\right)(1+\beta) - TC_i^{I,1}. \qquad (27)$$

The complete scenario-specific social welfare functions with calculated expressions for all three cases are provided in Appendix B.1.

The FOC with respect to K_{i1} can be obtained by solving two simultaneous FOCs (i.e., $\frac{\partial SW_A}{\partial K_{A1}} = 0 \; and \; \frac{\partial SW_B}{\partial K_{B1}} = 0$):

$$\frac{\partial SW_i^{I,1}}{\partial K_{i1}} = \frac{1}{2}(2a - 2b(\overline{K}_i + K_{i1}) - (\overline{K}_{-i} + K_{-i1})r)(1+\beta) - C_i^{I,1}. \qquad (28)$$

By solving the first-order conditions in Eq. (28), the equilibrium capacity investment is calculated as follows:

$$K_{i1}^{I,1,*} = \frac{2((\beta+1)a - C_i^{I,1})}{(2b+r)(1+\beta)} - \overline{K}_i, \qquad (29)$$

where * indicates the equilibrium and $C_i^{I,1}$ is expressed in Eq. (26).

The equilibrium capacity investment in Eq. (29) is subsequently substituted into Eq. (15) to (16) and (23) to derive the equilibrium adaptation investment, as well as the TOC-determined equilibrium prices and quantities across two periods:

$$I_{i1}^{I,1,*} = \frac{2x(a(1+\beta) - C_i^{I,1})(-1+\theta+\beta\theta)}{(2b+r)(1+\beta)(x+\beta)\theta^2} - \bar{I}_i, \tag{30}$$

$$\tau_{i1}^{I,1,*} = \tau_{i2}^{I,1,*} = \frac{2(b+r)C_i^{I,1} - ar(1+\beta)}{(2b+r)(1+\beta)}, \tag{31}$$

$$q_{i1}^{I,1,*} = q_{i2}^{I,1,*} = \frac{2(a(1+\beta) - C_i^{I,1})}{(2b+r)(1+\beta)}. \tag{32}$$

3.2.2.2 Scenario 2: $0 < x < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < 1$

The FOC in Eq. (22) can be rewritten as:

$$(-\theta) \cdot \left(1 - \left(\frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}}\right)\right) + 1 + \beta \cdot (-\theta) \cdot (1 - 1) = 0.$$

By rearranging the equation, the optimal adaptation investment of port i in period 1 (I_{i1}) is formulated as a function of K_{i1}:

$$I_{i1} = \frac{(\bar{K}_i + K_{i1})(-1+\theta)}{\theta^2} - \bar{I}_i. \tag{33}$$

By substituting Eq. (33) into the threshold expression, $\frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}}$, the original range $0 < x < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < 1$ simplifies to $0 < x < \frac{-1+\theta}{\theta} < 1$.

Within this range, the expected disaster costs over both periods based on the optimal I_{i1} are determined as follows and the complete explanation is available in Appendix A.3:

$$E_{x_1}\left[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1})\right]^+ = \frac{\bar{K}_i + K_{i1}}{2\theta^2}, \tag{34}$$

$$E_{x_2}\left[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})\right]^+ = 0. \tag{35}$$

By following the same calculations in Scenario 1, the total cost in the social welfare function for port i and Scenario 2 is presented as follows:

$$TC_i^{I,2} = \frac{\bar{K}_i + K_{i1}}{2\theta^2} + c_k \cdot K_{i1} + \frac{(\bar{K}_i + K_{i1})(-1+\theta)}{\theta^2} - \bar{I}_i + \beta \cdot 0,$$

where the superscript I represents Case I and superscript 2 indicates Scenario 2.

The marginal cost $C_i^{I,2}$ is defined as $\frac{\partial TC_i^{I,2}}{\partial K_{i1}}$ for simplicity:

$$C_i^{I,2} = \frac{\partial TC_i}{\partial K_{i1}} = \frac{1}{2\theta^2} + c_k + \frac{(-1+\theta)}{\theta^2}. \quad (36)$$

In Eq. (15), (16) and (33), the equilibrium values of τ_{it}, q_{it}, and I_{i1} are expressed in terms of K_{i1}. These equations are then substituted into the social welfare function in Eq. (19) and the scenario-specific social welfare function becomes:

$$SW_i^{I,2} = \left(\frac{1}{2}(\bar{K}_i + K_{i1})\left(a + \left(a - b(\bar{K}_i + K_{i1}) + r(\bar{K}_{-i} + K_{-i1})\right)\right)\right)(1+\beta) - TC_i^{I,2}. \quad (37)$$

By taking Eq. (37) with respect to K_{i1} (i.e., $\frac{\partial SW_A}{\partial K_{A1}} = 0$ and $\frac{\partial SW_B}{\partial K_{B1}} = 0$), the first order condition is derived:

$$\frac{\partial SW_i^{I,2}}{\partial K_{i1}} = \frac{1}{2}(2a - 2b(\bar{K}_i + K_{i1}) - (\bar{K}_{-i} + K_{-i1})r)(1+\beta) - C_i^{I,2}. \quad (38)$$

By solving the first-order conditions for ports A and B, the equilibrium capacity investments are obtained:

$$K_{i1}^{I,2,*} = \frac{2\left((\beta+1)a - C_i^{I,2}\right)}{(2b+r)(1+\beta)} - \bar{K}_i. \quad (39)$$

Eq. (39) is then substituted in equations (15) to (16) and (33) to calculate equilibrium values for adaptation investment, traffic volume and port charge across two periods:

$$I_{i1}^{I,2,*} = \frac{2(a(1+\beta) - C_i^{I,2})(\theta - 1)}{(2b+r)(1+\beta)\theta^2} - \bar{I}_i, \quad (40)$$

$$q_{i1}^{I,2,*} = q_{i2}^{I,2,*} = \frac{2(a(1+\beta) - C_i^{I,2})}{(2b+r)(1+\beta)}, \tag{41}$$

$$\tau_{i1}^{I,2,*} = \tau_{i2}^{I,2,*} = \frac{2(b+r)C_i^{I,2} - ar(1+\beta)}{(2b+r)(1+\beta)}. \tag{42}$$

3.2.2.3 Scenario 3: $0 < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < 1 < x$

Eq. (22) can be reformulated as follows:

$$(-\theta)\cdot\left(1-\left(\frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}}\right)\right) + 1 + \beta\cdot(-\theta)\cdot\left(1-\left(\frac{\frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}}}{x}\right)\right) = 0.$$

By rearranging the equation, the optimal adaptation investment is expressed as a function of K_{i1}:

$$I_{i1} = \frac{(\bar{K}_i + K_{i1})x(-1+\theta+\beta\theta)}{(x+\beta)\theta^2} - \bar{I}_i. \tag{43}$$

The equation (43) is then substituted into the threshold, $\frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}}$, and the simplified range is calculated as: $0 < \frac{x(-1+\theta+\beta\theta)}{(x+\beta)\theta} < 1 < x$.

Appendix A.3 shows calculation of disaster costs which match the results from Eq. (24) and (25) in Scenario 1:

$$E_{x_1}\,[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1})]^+ = \frac{(\bar{K}_i + K_{i1})\cdot(\beta\theta - x(\beta\theta-1))^2}{2(x+\beta)^2\theta^2}$$

$$E_{x_2}\,[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})]^+ = \frac{(\bar{K}_i + K_{i1})x(1-(1-x)\theta)^2}{2(x+\beta)^2\theta^2}$$

With only differences in the ranges of disaster intensity ($x < 1$ in Scenario 1 and $x > 1$ in Scenario 3), Scenario 3 and Scenario 1 share identical calculations and results. Consequently, the marginal cost function for Scenario 3 is the same as in Scenario 1 with only changes in superscript from Eq. (26) and is given by ($C_i^{I,1} = C_i^{I,3}$):

$$C_i^{I,3} = \frac{\partial TC_i}{\partial K_{i1}} = \frac{(\beta\theta - x(\beta\theta - 1))^2}{2(x+\beta)^2\theta^2} + c_k + \frac{x(\theta + \beta\theta - 1)}{(x+\beta)\theta^2} + \beta\frac{x(1-(1-x)\theta)^2}{2(x+\beta)^2\theta^2}.$$

All other parameter calculations including equilibrium capacity investments, TOC-selected equilibrium prices and quantities across both periods remain the same as in Scenario 1 which is shown in Eq. (29), (31) and (32).

3.2.2.4 Scenario 4: $1 < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < x$

Eq. (22) can be rearranged in the following form:

$$(-\theta)\cdot(1-1) + 1 + \beta\cdot(-\theta)\cdot\left(1 - \left(\frac{\frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}}}{x}\right)\right) = 0.$$

After rearranging, the optimal adaptation investment equation in period 1 becomes:

$$I_{i1} = \frac{(\bar{K}_i + K_{i1})x(-1+\beta\theta)}{\beta\theta^2} - \bar{I}_i. \tag{44}$$

The range $1 < \frac{\theta(\bar{I}_j + I_{j1})}{\bar{K}_j + K_{j1}} < x$ is simplified by incorporating equation (44) in the threshold, $\frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}}$ and the range is expressed as: $0 < 1 < x - \frac{x}{\beta\theta} < x$.

The expected disaster costs follow similar calculations as in the above scenarios with details provided in the Appendix A.3:

$$E_{x_1}\,[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1})]^+ = 0, \tag{45}$$

$$E_{x_2}\,[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})]^+ = \frac{(\bar{K}_i + K_{i1})x}{2\beta^2\theta^2}. \tag{46}$$

Applying the same calculation procedure in early scenarios, the total cost in the social welfare function for port i in Scenario 4 is expressed as:

$$TC_i^{I,4} = 0 + c_k \cdot K_{i1} + \frac{(\overline{K}_i + K_{i1})x(-1+\beta\theta)}{\beta\theta^2} - \overline{I}_i + \beta \cdot \frac{(\overline{K}_i + K_{i1})x}{2\beta^2\theta^2}.$$

By taking derivative with respect to K_{i1}, the result is represented as $C_{I,4}$:

$$C_i^{I,4} = \frac{\partial TC_i}{\partial K_{i1}} = c_k + \frac{x(-1+\beta\theta)}{\beta\theta^2} + \beta \cdot \frac{x}{2\beta^2\theta^2}.$$

The equilibrium values of τ_{it}, q_{it}, and I_{i1} are expressed as functions of K_{i1} in Eq. (15), (16) and (44). These expressions are substituted into the social welfare function in Eq. (19) and reorganized as:

$$SW_i^{I,4} = \left(\frac{1}{2}(\overline{K}_i + K_{i1})\left(a + \left(a - b(\overline{K}_i + K_{i1}) + r(\overline{K}_{-i} + K_{-i1})\right)\right)\right)(1+\beta) - TC_i^{I,4}. \quad (47)$$

The FOC with respect to K_{i1} can be obtained by differentiating SW_A and SW_B with respect to K_{A1} and K_{B1} simultaneously and the result is as follows:

$$\frac{\partial SW_i^{I,4}}{\partial K_{i1}} = \frac{1}{2}(2a - 2b(\overline{K}_i + K_{i1}) - (\overline{K}_{-i} + K_{-i1})r)(1+\beta) - C_i^{I,4}.$$

The equilibrium capacity investment of port i are derived by solving the above first-order conditions for ports A and B:

$$K_{i1}{}^* = \frac{2(a(\beta+1) - C_i^{I,4})}{(2b+r)(1+\beta)} - \overline{K}_i, \quad (48)$$

The remaining equilibrium values are determined by substituting $K_{i1}{}^*$ into equations (15) to (16) and (44):

$$I_{i1}{}^* = \frac{2x(-1+\beta\theta)(a(1+\beta) - C_i^{I,4})}{(2b+r)\beta(1+\beta)\theta^2} - \overline{I}_i, \quad (49)$$

$$\tau_{i1}^{I,4,*} = \tau_{i2}^{I,4,*} = \frac{2(b+r)C_i^{I,4} - ar(1+\beta)}{(2b+r)(1+\beta)}, \quad (50)$$

$$q_{i1}^{I,4,*} = q_{i2}^{I,4,*} = \frac{2(a(1+\beta) - C_i^{I,4})}{(2b+r)(1+\beta)}. \tag{51}$$

3.3 Case II: Both ports invest in period 2

3.3.1 Problem formulation

Stage 1: PAs' social welfare maximization problem

In Case II, the Port Authorities (PAs) of both ports A and B defer capacity (K_{i2}) and adaptation investment decisions (I_{i2}) to period 2. Since no investments are made in period 1, the capacity and adaptation investments remain at their initial endowment levels, $\overline{K}_i$ and $\overline{I}_i$ respectively. Once investments are made in period 2, the available capacity and adaptation levels become $\overline{K}_i + K_{i2}$ and $\overline{I}_i + I_{i2}$ respectively.

As shown in Case I, the objective of the PAs for both ports are to maximize social welfare. The total consumer surplus remains unchanged from Eq. (9) because investment timing influences only the disaster costs and the PA decisions without changing consumer behavior.

Since ports do not make investment in period 1, the expected disaster cost in period 1, D_{i1}, only relates to initial adaptation and capacity levels:

$$D_{i1} = E_{x_1}\,[\overline{K}_i \cdot x_1 - \theta \cdot \overline{I}_i]^+. \tag{52}$$

With the investments in period 2, the expected disaster cost in period 2, D_{i2}, is expressed as:

$$D_{i2} = E_{x_2}\,[(\overline{K}_i + K_{i2})x_2 - \theta(\overline{I}_i + I_{i2})]^+. \tag{53}$$

The objective function of the PAs in Case II can be formulated as:

$$\max_{\{K_{i2},I_{i2}\}} SW_i = \left(\frac{1}{2}q_{i1}(a+\tau_{i1}) - \ E_{x_1}\,[\overline{K}_i \cdot x_1 - \theta \cdot \overline{I}_i]^+\right) \\ + \beta\left(\frac{1}{2}q_{i2}(a+\tau_{i2}) - \ E_{x_2}\,[(\overline{K}_i + K_{i2})x_2 - \theta(\overline{I}_i + I_{i2})]^+ - c_k K_{i2} - I_{i2}\right). \tag{54}$$

Stage 2: TOCs' profit maximization problem

The TOC of port i maximizes its profits in both periods and is constrained by available capacity levels:

$$\max_{\{\tau_{i1}\}} \pi_{i1} = \tau_{i1} q_{i1} \qquad s.t.\, q_{i1} \leq \bar{K}_i \tag{55}$$

$$\max_{\{\tau_{i2}\}} \pi_{i2} = \tau_{i2} q_{i2} \qquad s.t.\, q_{i2} \leq \bar{K}_i + K_{i2} \tag{56}$$

3.3.2 Model analysis

In period 1, if the capacity constraint is binding for both ports, the equilibrium traffic volume at port i simply equals to the initial capacity endowment:

$$q_{i1} = \bar{K}_i. \tag{57}$$

The Eq. (57) is then incorporated into Eq. (3) and (4) to obtain the equilibrium port prices:

$$\tau_{i1} = a - b\bar{K}_i + r\bar{K}_{-i}. \tag{58}$$

If the capacity constraint is non-binding, equilibrium port charges, τ_{i1} and equilibrium traffic volume, q_{i1}, are calculated exactly as in Case I with the identical results in Eq. (17) and (18).

In period 2, when the capacity constraint is binding for both ports i, the equilibrium traffic volume at port i can be formulated as:

$$q_{i2} = \bar{K}_i + K_{i2}. \tag{59}$$

The Eq. (59) is then incorporated into the inverse demand functions in Eq. (3) and (4) and the equilibrium port charge is obtained:

$$\tau_{i2} = a - b(\bar{K}_i + K_{i2}) + r(\bar{K}_{-i} + K_{-i2}). \tag{60}$$

For non-binding capacity constraint, the equilibrium port charges, τ_{i2} traffic volume, q_{i2}, follow the same calculation in Case I as presented in Eq. (17) and (18).

The PAs determine their investment decisions by anticipating the TOCs' equilibrium choices. In period 1, the initial capacity endowment naturally governs the TOCs' equilibrium capacity choices.

In period 2, if the PAs invest in a capacity that exceeds the equilibrium needs of the TOCs (i.e., $\overline{K}_i + K_{i2} > \frac{ab}{(2b-r)(b+r)}$), it results in overinvestment, because the same results will be achieved by investing exactly the amount required by the TOCs (i.e., $\overline{K}_i + K_{i2} = \frac{ab}{(2b-r)(b+r)}$). Therefore, at equilibrium, the capacity constraint is always binding.

By substituting Eq. (57) to (60) into Eq. (54), the PAs' objective function is rewritten as:

$$\begin{aligned} \max_{\{K_{i2}, I_{i2}\}} SW_i = & \left(\frac{1}{2}\overline{K}_i(a + (a - b\overline{K}_i + r\overline{K}_{-i})) - \ E_{x_1}\left[\overline{K}_i \cdot x_1 - \theta \cdot \bar{I}_i\right]^+\right) \\ & + \beta\left(\frac{1}{2}(\overline{K}_i + K_{i2})(a + (a - b(\overline{K}_i + K_{i2}) + r(\overline{K}_{-i} + K_{-i2}))) \right. \\ & \left. - \ E_{x_2}\left[(\overline{K}_i + K_{i2})x_2 - \theta(\bar{I}_i + I_{i2})\right]^+ - c_k K_{i2} - I_{i2}\right). \end{aligned} \tag{61}$$

In Eq. (61), the adaptation investment, I_{i2}, only influences the disaster cost in period 2 (i.e., $E_{x_2}\left[(\overline{K}_i + K_{i2})x_2 - \theta(\bar{I}_i + I_{i2})\right]^+$) and adaptation investment cost in period 2 (i.e., $-I_{i2}$). Thus, the optimal adaptation investment I_{i2} is calculated by minimizing these total costs and is expressed as:

$$\min_{\{I_{i2}\}} E_{x_2}\left[(\overline{K}_i + K_{i2})x_2 - \theta(\bar{I}_i + I_{i2})\right]^+ \ + I_{i2}. \tag{62}$$

Following the same process as in Case I, the function is minimized by taking the partial derivative with respect to I_{i2}, with the details in the Appendix B.2, the function simplifies to:

$$F_{x_2}\left(\frac{\theta(\bar{I}_i + I_{i2})}{\overline{K}_i + K_{i2}}\right) = 1 - \frac{1}{\theta}.$$

Since $x_2 \sim U[0, x]$, the above equation can be rewritten as:

$$\left(\frac{\theta(\bar{I}_i + I_{i2})}{\overline{K}_i + K_{i2}}\right) \cdot \frac{1}{x} = 1 - \frac{1}{\theta}.$$

By rearranging this equation, the adaptation investment of the PAs as a function of capacity is given by:

$$I_{i2} = -\bar{I}_i + \frac{(\overline{K}_i + K_{i2})(-1 + \theta)}{\theta^2}. \tag{63}$$

Case II has only one valid range:

$$0 < \frac{\theta(\bar{I}_i + I_{i2})}{\bar{K}_i + K_{i2}} < x.$$

If the scenario for the threshold that exceeds the upper range (i.e., $x < \frac{\theta(\bar{I}_i+I_{i2})}{\bar{K}_i+K_{i2}}$), the cumulative distribution function $F_{x_2}\left(\frac{\theta(\bar{I}_i+I_{i2})}{\bar{K}_i+K_{i2}}\right)$ would equal to 1, which is higher than the right-hand side of $1-\frac{1}{\theta}$, making the equation not equal. The optimal condition of adaptation investment, I_{i2}, in Eq. (63) will not hold. The range can be further simplified as: $0 < x(1-\frac{1}{\theta}) < x$.

To calculate disaster costs in period 1, we assume the endowment capacity and adaptation are at their optimal levels. Following a similar process, with the details in Appendix B.2, the optimal $\bar{I}_i$ can be determined as follows:

$$\bar{I}_i = \frac{1}{\theta} \cdot \bar{K}_i \cdot (1-\theta).$$

The expected disaster costs at the optimal investment, I_{i2}, across both periods are shown in Appendix A.3:

$$E_{x_1}\,[\bar{K}_i \cdot x_1 - \theta \cdot \bar{I}_i]^+ = \frac{\bar{K}_i}{2\theta^2}, \tag{64}$$

$$E_{x_2}\,[(\bar{K}_i + K_{i2})x_2 - \theta(\bar{I}_i + I_{i2})]^+ = \frac{(\bar{K}_i + K_{i2})x}{2\theta^2}. \tag{65}$$

For port i, the total cost in the social welfare function becomes:

$$TC_i = E_{x_1}\,[\bar{K}_i \cdot x_1 - \theta \cdot \bar{I}_i]^+ + c_k \cdot K_{i2} + I_{i2} + E_{x_2}\,[(\bar{K}_i + K_{i2})x_2 - \theta(\bar{I}_i + I_{i2})]^+.$$

By substituting Eq. (63) to (65), the function is presented as:

$$TC_i^{II} = \frac{\bar{K}_i}{2\theta^2} + c_k \cdot K_{i2} + \frac{(\bar{K}_i + K_{i2})(-1+\theta)}{\theta^2} - \bar{I}_i + \beta \cdot \frac{(\bar{K}_i + K_{i2})x}{2\theta^2},$$

where the superscript I indicates Case II.

The marginal cost function, C_i^{II} is calculated by taking the derivative of total cost with respect to K_{i2} (i.e., $\frac{\partial TC_i^{II}}{\partial K_{i2}}$) and the resulting expression is given by:

$$C_i^{II} = \frac{\partial TC_i^{II}}{\partial K_{i2}} = \frac{1}{2\theta^2} + c_k + \frac{(-1+\theta)}{\theta^2} + \beta \cdot \frac{x}{2\theta^2}. \tag{66}$$

The expressions in Eq. (57) to (60) and (63) are substituted in the social welfare equation in Eq. (68). The social welfare function in Eq. (61) can be reorganized as:

$$\begin{aligned} SW_i^{II} = &\left(\frac{1}{2}\bar{K}_i\left(a + (a - b\bar{K}_i + r\bar{K}_{-i})\right)\right) \\ &+ \frac{\beta}{2}(\bar{K}_i + K_{i2})\left(a + \left(a - b(\bar{K}_i + K_{i2}) + r(\bar{K}_{-i} + K_{-i2})\right)\right) - TC_i^{II}. \end{aligned} \tag{67}$$

By taking the partial derivatives of the social welfare function with respect to capacity investment simultaneously (i.e., $\frac{\partial SW_A}{\partial K_{A2}} = 0$ and $\frac{\partial SW_B}{\partial K_{B2}} = 0$), the FOC is obtained:

$$\frac{\partial SW_i^{II}}{\partial K_{i2}} = \frac{\beta}{2}(2a - 2b(\bar{K}_i + K_{i2}) - (\bar{K}_{-i} + K_{-i2})r) - C_i^{II}, \tag{68}$$

where C_i^{II} is from Eq. (66).

The equilibrium capacity investment of port i can be calculated by solving Eq. (68):

$$K_{i2}^{II,*} = \frac{2((\beta+1)a - C_i^{II})}{(2b+r)(1+\beta)} - \bar{K}_i, \tag{69}$$

where C_i^{II} is from Eq. (66).

The Eq. (69) is then incorporated into Eq. (57) to (60) and (63) to calculate the equilibrium adaptation investment and the TOCs decisions on port prices and throughput quantities across two periods:

$$I_{i2}{}^* = \frac{2(a\beta - C_i^{II})x(-1+\theta)}{(2b+r)\beta\theta^2} - \bar{I}_i, \tag{70}$$

$$q_{i1}{}^* = \bar{K}_i, \tag{71}$$

$$\tau_{i1}{}^* = a - b\bar{K}_i - r\bar{K}_{-i}, \tag{72}$$

$$q_{i2}{}^{*} = \frac{2(a\beta - C_i^{II})}{(2b + r)\beta}, \tag{73}$$

$$\tau_{i2}{}^{*} = -\frac{ar\beta - 2bC_i^{II} - 2rC_i^{II}}{(2b + r)\beta}. \tag{74}$$

The comparative analysis is summarized in Table 2.

3.4 Case III: Port A invests in period 1 and Port B invests in period 2

3.4.1 Problem formulation

Stage 1: PAs' social welfare maximization problem

Under Case III assumptions, two situations are possible: port A invests early, while port B invests late, or port A invests late, while port B invests early. Due to the symmetrical results between these two situations, the study only focuses on the first situation in which port A invests in the first period and port B in the second period. In this case, the PA of port A makes capacity (K_{A1}) and adaptation investments (I_{A1}) in period 1 and the PA of port B decides on capacity (K_{B2}) and adaptation investments (I_{B2}) choices in period 2.

As shown in Case I, the PAs' objective is to maximize social welfare and the consumer surplus in Eq. (9) and the TOCs' function for both ports i in Eq. (10) remain unchanged.

Due to the differences in investment timing, ports A and B each follow the disaster damage cost function separately as in Case I and II. Thus, for port A, the disaster cost function is exactly the same as in Case I in Eq. (11) and (12), and for port B, the disaster cost function is given by Eq. (52) and (53). Thus, every term in the social welfare function for port A and port B respectively are the same as in Eq. (19) and Eq. (61).

Stage 2: TOCs' profit maximization problem

The TOCs of port A and B maximize its profit in each period and are constrained by its capacity which remains the same as in Eq. (14) and (55) to (56):

$$\max_{\{\tau_{At}\}} \pi_{At} = \tau_{At} q_{At}$$

$$s.t.\, q_{At} \leq \overline{K}_A + K_{A1}$$

$$\max_{\{\tau_{B1}\}} \pi_{B1} = \tau_{B1} q_{B1}$$

$$s.t. q_{B1} \leq \overline{K}_B$$

$$\max_{\{\tau_{B2}\}} \pi_{B2} = \tau_{B2} q_{B2}$$

$$s.t. q_{B2} \leq \overline{K}_B + K_{B2}$$

3.4.2 Model analysis

3.4.2.1 Ports A and B operate under capacity binding constraints across both periods

In this situation, both ports A and B operate under capacity binding constraints across both periods. For port A, the PAs in period 1 invest the capacity investment that exactly match the TOCs' optimal throughput quantities because the PAs have full knowledge of TOCs' throughput decisions which avoid over- or under- investments. In period 2, port A naturally takes on capacity binding constraints because the capacity investment of the PAs in the first period are optimal and by continuing operating under binding constraints, port A maintains optimal results and avoids waste in throughput quantities. For port B, in period 1, the capacity constraint is binding because no additional capacity and adaptation investments are incurred in this period. The throughput quantities chosen by TOCs are exactly met by initial capacity endowment to ensure efficiency and optimality. In period 2, the capacity investment of the PA of port B will invest the amount that exactly matches the throughput need of port B to avoid inefficiencies and ensure the social welfare is maximized. Thus, port B in period 2 also remains capacity binding.

Similar to Case I and II, the results below are derived using backward inductions which ensure that TOCs' decisions are integrated into the PAs' optimal investment choices. The equilibrium traffic volume at port A and B for period 1 is given by:

$$q_{A1} = \overline{K}_A + K_{A1}, \tag{75}$$

$$q_{B1} = \overline{K}_B. \tag{76}$$

The Eq. (75) and (76) are substituted in the inverse demand function in Eq. (3) and (4) to calculate equilibrium port charges for port i in period 1:

$$\tau_{i1} = a - b\overline{K}_i - bK_{i1} - \overline{K}_{-i} r. \tag{77}$$

Similarly, in period 2, the equilibrium throughput quantities at port A and B are derived as:

$$q_{A2} = \overline{K}_A + K_{A1}, \tag{78}$$

$$q_{B2} = \overline{K}_B + K_{B2}. \tag{79}$$

By substituting Eq. (78) and (79) into Eq. (3) and (4), the equilibrium traffic volume for port i in period 2 is given by:

$$\tau_{i2} = a - bK_{i1} - rK_{-i2} - b\overline{K}_i - r\overline{K}_{-i}. \tag{80}$$

As mentioned above, port A's disaster costs and adaptation investment, I_{A1}, for early investments match the calculations in Case I and port B's disaster costs and adaptation investment function, I_{B2}, for late investments follow the calculations in Case II. Therefore, the results of optimal I_{A1} for four different ranges and optimal I_{B2} remain unchanged as shown in Eq. (23), (33), (43), (44) and (63).

The full comparative analysis for Case III is excluded from Table 2 because only port A's sensitivity results demonstrate a clear directional effect of the parameters, and port B's results remain unclear.

3.4.2.1.1 Scenario 1: $0 < \frac{\theta(\bar{I}_i + I_{i1})}{\overline{K}_i + K_{i1}} < x < 1$

By following the calculations in Case I and II, the adaptation investment function I_{A1} and I_{B2} are directly from equations (23) and (63) respectively. The disaster costs remain the same as Eq. (24) and (25) in Case I for port A and Eq. (64) and (65) in Case II for port B. Thus, the total cost in the social welfare function for port A and B can be derived as:

$$TC_A^{III,1} = \frac{(\overline{K}_A + K_{A1}) \cdot (\beta\theta - x(\beta\theta - 1))^2}{2(x+\beta)^2\theta^2} + c_k \cdot K_{A1} + \frac{(\overline{K}_A + K_{A1})x(\theta + \beta\theta - 1)}{(x+\beta)\theta^2} - \bar{I}_A + \beta \cdot \frac{(\overline{K}_A + K_{A1})x(1-(1-x)\theta)^2}{2(x+\beta)^2\theta^2},$$

$$TC_B^{III,1} = \frac{\bar{K}_B}{2\theta^2} + c_k \cdot K_{B2} + \frac{(\bar{K}_B + K_{B2})(-1+\theta)}{\theta^2} - \bar{I}_B + \beta \cdot \frac{(\bar{K}_B + K_{B2})x}{2\theta^2},$$

where the superscript III indicates Case III and superscript 1 indicates Scenario 1.

The marginal cost $C_A^{III,1}$ and $C_B^{III,1}$ are calculated by taking derivative of the total cost with respect to K_{A1} and K_{B2} respectively:

$$C_A^{III,1} = \frac{\partial TC_A^{III,1}}{\partial K_{A1}} = \frac{(\beta\theta - x(\beta\theta - 1))^2}{2(x+\beta)^2\theta^2} + c_k + \frac{x(\theta + \beta\theta - 1)}{(x+\beta)\theta^2} + \beta\frac{x(1-(1-x)\theta)^2}{2(x+\beta)^2\theta^2},$$

$$C_B^{III,1} = \frac{\partial TC_B^{III,1}}{\partial K_{B2}} = \frac{1}{2\theta^2} + c_k + \frac{(-1+\theta)}{\theta^2} + \beta \cdot \frac{x}{2\theta^2}.$$

The equilibrium values of port A and B in Eq. (75) to (80) and adaptation investments, I_{A1} and I_{B2}, in Eq. (23) and (63) with the above two marginal cost functions are substituted into the social welfare functions in Eq. (19) and (61) for port A and B respectively. Then, these two social welfare functions are taking derivative with respect to K_{A1} and K_{B2} to solve for the equilibrium capacity investment for port A and B (i.e., $\frac{\partial SW_A}{\partial K_{A1}} = 0$ and $\frac{\partial SW_B}{\partial K_{B2}} = 0$):

$$K_{A1}^{III,1,*} = \frac{4b(a(1+\beta) - C_A^{III,1}) + 2r(C_B^{III,1} - b\bar{K}_B - a\beta)}{4b^2 + 4b^2\beta - r^2\beta} - \bar{K}_A, \quad (81)$$

$$K_{B2}^{III,1,*} = \frac{4b(\beta+1)(a\beta - C_B^{III,1}) - 2\beta r(a(\beta+1) - C_A^{III,1}) + \bar{K}_B r^2\beta}{\beta(4b^2 + 4b^2\beta - r^2\beta)} - \bar{K}_B. \quad (82)$$

The equilibrium capacity investments for both ports in Eq. (81) and (82) are then substituted to Eq. (23), (63) and (75) to (80) to calculate the equilibrium adaptation investments as well as the equilibrium throughput quantities and prices determined by TOCs.

$$I_{A1}{}^* = 2(-1+\theta+\beta\theta)x\frac{\left(2b\left(a - C_A^{III,1}\right) + r\left(C_B^{III,1} - b\bar{K}_B\right) + a\beta(2b-r)\right)}{(x+\beta)\left(-r^2\beta + 4b^2(1+\beta)\right)\theta^2} - \bar{I}_A,$$

$$I_{B2}{}^* = (\theta-1)x\frac{\left(4b(1+\beta)\left(a\beta - C_B^{III,1}\right) - 2\left(a(1+\beta) - C_A^{III,1}\right)r\beta + \bar{K}_B r^2\beta\right)}{\beta\left(-r^2\beta + 4b^2(1+\beta)\right)\theta^2} - \bar{I}_B,$$

$$q_{A1}{}^{*} = \frac{2(-2ab - 2ab\beta + ar\beta + br\overline{K}_B - rC_B^{III,1} + 2bC_A^{III,1})}{r^2\beta - 4b^2(1+\beta)},$$

$$q_{B1}{}^{*} = \overline{K}_B$$

$$\tau_{A1}{}^{*} = \frac{-2abr\beta + ar^2\beta + (-r^3\beta + b^2r(2+4\beta))\overline{K}_B + 2brC_B^{III,1} - 4b^2C_A^{III,1}}{r^2\beta - 4b^2(1+\beta)},$$

$$\tau_{B1}{}^{*} = \frac{1}{r^2\beta - 4b^2(1+\beta)}\big(-4ab^2 + 4abr - 4ab^2\beta + 4abr\beta - ar^2\beta + \left(4b^3(1+\beta) - br^2(2+\beta)\right)\overline{K}_B + 2r^2C_B^{III,1} - 4brC_A^{III,1}\big),$$

$$q_{A2}{}^{*} = \frac{2(-2ab - 2ab\beta + ar\beta + br\overline{K}_B - rC_B^{III,1} + 2bC_A^{III,1})}{r^2\beta - 4b^2(1+\beta)},$$

$$q_{B2}{}^{*} = \frac{r^2\beta\overline{K}_B - 4b(1+\beta)C_B^{III,1} + 2\beta(a(2b-r)(1+\beta) + rC_A^{III,1})}{\beta(-r^2\beta + 4b^2(1+\beta))},$$

$$\tau_{A2}{}^{*} = \frac{-a(2b-r)r\beta(2+\beta) - r(-2b^2+r^2)\beta\overline{K}_B + 2br(2+\beta)C_B^{III,1} + (4b^2 - 2r^2)\beta C_A^{III,1}}{\beta(-r^2\beta + 4b^2(1+\beta))},$$

$$\tau_{B2}{}^{*} = \frac{br^2\beta\overline{K}_B + (-2r^2\beta + 4b^2(1+\beta))C_B^{III,1} + r\beta(ar\beta - 2ab(1+\beta) + 2bC_A^{III,1})}{\beta(-r^2\beta + 4b^2(1+\beta))}.$$

3.4.2.1.2 Scenario 2: $0 < x < \frac{\theta(\bar{I}_i + I_{i1})}{\overline{K}_i + K_{i1}} < 1$

The adaptation investment functions, I_{A1} and I_{B2}, are directly from equations (33) and (63) respectively. The expected disaster costs for both periods are the same as in Eq. (34), (35) for port A and Eq. (64), (65) for port B. The total cost in the social welfare function can be calculated as:

$$TC_A^{III,2} = \frac{\overline{K}_A + K_{A1}}{2\theta^2} + c_k \cdot K_{A1} + \frac{(\overline{K}_A + K_{A1})(-1+\theta)}{\theta^2} - \bar{I}_A + \beta \cdot 0,$$

$$TC_B^{III,2} = \frac{\overline{K}_B}{2\theta^2} + c_k \cdot K_{B2} + \frac{(\overline{K}_B + K_{B2})(-1+\theta)}{\theta^2} - \bar{I}_B + \beta \cdot \frac{(\overline{K}_B + K_{B2})x}{2\theta^2},$$

where the superscript III indicates Case III and superscript 2 indicates Scenario 2.

By taking partial derivatives of $TC_A^{III,2}$ and $TC_B^{III,2}$ with respect to K_{A1} and K_{B2}, the resulting marginal cost functions are illustrated as $C_A^{III,2}$ and $C_B^{III,2}$:

$$C_A^{III,2} = \frac{\partial TC_A^{III,2}}{\partial K_{A1}} = \frac{1}{2\theta^2} + c_k + \frac{-1+\theta}{\theta^2},$$

$$C_B^{III,2} = \frac{\partial TC_B^{III,2}}{\partial K_{B2}} = \frac{1}{2\theta^2} + c_k + \frac{-1+\theta}{\theta^2} + \beta \cdot \frac{x}{2\theta^2}.$$

By incorporating $C_A^{III,2}$ and $C_B^{III,2}$ with Eq. (75) to (80) and adaptation investments in Eq. (33) and (63) into the social welfare functions in Eq. (19) and (61), the equilibrium capacity investment for port A and B is solved by taking derivatives of the rewritten social welfare functions with respect to K_{A1} and K_{B2}:

$$K_{A1}^{III,2,*} = \frac{4b(a(1+\beta) - C_A^{III,2}) + 2r(C_B^{III,2} - b\bar{K}_B - a\beta)}{4b^2 + 4b^2\beta - r^2\beta} - \bar{K}_A, \tag{83}$$

$$K_{B2}^{III,2,*} = \frac{4b(\beta+1)(a\beta - C_B^{III,2}) - 2\beta r(a(\beta+1) - C_A^{III,2}) + \bar{K}_B r^2\beta}{\beta(4b^2 + 4b^2\beta - r^2\beta)} - \bar{K}_B. \tag{84}$$

The Eq. (83) and (84) are then substituted into Eq. (33), (63), (75) to (80) to obtain equilibrium adaptation investments and equilibrium port throughput quantities and prices decided by the TOCs.

$$I_{A1}{}^* = 2(\theta-1)\frac{\left(2b\left(a(1+\beta) - C_A^{III,2}\right) - r\left(a\beta + b\bar{K}_B - C_B^{III,2}\right)\right)}{\left(-r^2\beta + 4b^2(1+\beta)\right)\theta^2} - \bar{I}_A,$$

$$I_{B2}{}^* = (\theta-1)x\frac{(4b(1+\beta)(a\beta - C_B^{III,2}) - r\beta(2a(1+\beta) - 2C_A^{III,2} - \bar{K}_B r))}{\beta(-r^2\beta + 4b^2(1+\beta))\theta^2} - \bar{I}_B,$$

$$q_{A1}{}^* = \frac{2(-2ab - 2ab\beta + ar\beta + br\bar{K}_B - rC_B^{III,2} + 2bC_A^{III,2})}{r^2\beta - 4b^2(1+\beta)},$$

$$q_{B1}{}^* = \bar{K}_B$$

$$\tau_{A1}{}^* = \frac{-2abr\beta + ar^2\beta + (-r^3\beta + b^2r(2+4\beta))\bar{K}_B + 2brC_B^{III,2} - 4b^2C_A^{III,2}}{r^2\beta - 4b^2(1+\beta)},$$

$$\tau_{B1}{}^* = \frac{1}{r^2\beta - 4b^2(1+\beta)}(-4ab^2 + 4abr - 4ab^2\beta + 4abr\beta - ar^2\beta + \left(4b^3(1+\beta) - br^2(2+\beta)\right)\bar{K}_B + 2r^2C_B^{III,2} - 4brC_A^{III,2}),$$

$$q_{A2}{}^* = \frac{2(-2ab - 2ab\beta + ar\beta + br\bar{K}_B - rC_B^{III,2} + 2bC_A^{III,2})}{r^2\beta - 4b^2(1+\beta)},$$

$$q_{B2}{}^* = \frac{r^2\beta\bar{K}_B - 4b(1+\beta)C_B^{III,2} + 2\beta(a(2b-r)(1+\beta) + rC_A^{III,2})}{\beta(-r^2\beta + 4b^2(1+\beta))},$$

$$\tau_{A2}{}^* = \frac{-a(2b-r)r\beta(2+\beta) - r(-2b^2 + r^2)\beta\bar{K}_B + 2br(2+\beta)C_B^{III,2} + (4b^2 - 2r^2)\beta C_A^{III,2}}{\beta(-r^2\beta + 4b^2(1+\beta))},$$

$$\tau_{B2}{}^* = \frac{br^2\beta\bar{K}_B + (-2r^2\beta + 4b^2(1+\beta))C_B^{III,2} + r\beta(ar\beta - 2ab(1+\beta) + 2bC_A^{III,2})}{\beta(-r^2\beta + 4b^2(1+\beta))}.$$

3.4.2.1.3 Scenario 3: $0 < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < 1 < x$

In Scenario 3, all parameter values are the same as in Scenario 1 under Case III with only differences in the range of disaster intensities. This means that the adaptation investments, disaster costs and social welfare functions remain the same with only changes in the superscripts in the cost functions to reflect the range difference. The scenario-specific cost functions with its corresponding superscripts are as follows:

$$C_A^{III,3} = \frac{\partial TC_A^{III,3}}{\partial K_{A1}} = \frac{(\beta\theta - x(\beta\theta - 1))^2}{2(x+\beta)^2\theta^2} + c_k + \frac{x(\theta + \beta\theta - 1)}{(x+\beta)\theta^2} + \beta\frac{x(1-(1-x)\theta)^2}{2(x+\beta)^2\theta^2},$$

$$C_B^{III,3} = \frac{\partial TC_B^{III,3}}{\partial K_{B2}} = \frac{1}{2\theta^2} + c_k + \frac{(-1+\theta)}{\theta^2} + \beta \cdot \frac{x}{2\theta^2}.$$

The equilibrium capacity investments, $K_{A1}^{III,3,*}$ and $K_{B2}^{III,3,*}$, are the same as shown in Eq. (81) and (82). With the exact same calculation processes, the equilibrium parameter results including adaptation investments and TOC-chosen port throughput quantities and prices remain the same as in Scenario 1 except for the superscripts.

$$I_{A1}{}^* = 2(-1+\theta+\beta\theta)x\frac{\left(2b\left(a - C_A^{III,3}\right) + r\left(C_B^{III,3} - b\bar{K}_B\right) + a\beta(2b-r)\right)}{(x+\beta)\left(-r^2\beta + 4b^2(1+\beta)\right)\theta^2} - \bar{I}_A,$$

$$I_{B2}{}^* = (\theta-1)x\frac{\left(4b(1+\beta)\left(a\beta - C_B^{III,3}\right) - 2\left(a(1+\beta) - C_A^{III,3}\right)r\beta + \bar{K}_B r^2\beta\right)}{\beta\left(-r^2\beta + 4b^2(1+\beta)\right)\theta^2} - \bar{I}_B,$$

$$q_{A1}{}^* = \frac{2(-2ab - 2ab\beta + ar\beta + br\bar{K}_B - rC_B^{III,3} + 2bC_A^{III,3})}{r^2\beta - 4b^2(1+\beta)},$$

$$q_{B1}{}^* = \bar{K}_B$$

$$\tau_{A1}{}^* = \frac{-2abr\beta + ar^2\beta + (-r^3\beta + b^2r(2+4\beta))\bar{K}_B + 2brC_B^{III,3} - 4b^2C_A^{III,3}}{r^2\beta - 4b^2(1+\beta)},$$

$$\tau_{B1}{}^* = \frac{1}{r^2\beta - 4b^2(1+\beta)}\left(-4ab^2 + 4abr - 4ab^2\beta + 4abr\beta - ar^2\beta + \left(4b^3(1+\beta) - br^2(2+\beta)\right)\bar{K}_B + 2r^2C_B^{III,3} - 4brC_A^{III,3}\right),$$

$$q_{A2}{}^* = \frac{2(-2ab - 2ab\beta + ar\beta + br\bar{K}_B - rC_B^{III,3} + 2bC_A^{III,3})}{r^2\beta - 4b^2(1+\beta)},$$

$$q_{B2}{}^* = \frac{r^2\beta\bar{K}_B - 4b(1+\beta)C_B^{III,3} + 2\beta(a(2b-r)(1+\beta) + rC_A^{III,3})}{\beta(-r^2\beta + 4b^2(1+\beta))},$$

$$\tau_{A2}{}^{*} = \frac{-a(2b-r)r\beta(2+\beta) - r(-2b^2+r^2)\beta\overline{K}_B + 2br(2+\beta)C_B^{III,3} + (4b^2-2r^2)\beta C_A^{III,3}}{\beta(-r^2\beta+4b^2(1+\beta))},$$

$$\tau_{B2}{}^{*} = \frac{br^2\beta\overline{K}_B + (-2r^2\beta+4b^2(1+\beta))C_B^{III,3} + r\beta(ar\beta - 2ab(1+\beta) + 2bC_A^{III,3})}{\beta(-r^2\beta+4b^2(1+\beta))}.$$

3.4.2.1.4 Scenario 4: $1 < \frac{\theta(\bar{I}_i + I_{i1})}{\overline{K}_i + K_{i1}} < x$

The adaptation investment functions for ports A and B are obtained from Eq. (44) and (63) as well as the disaster damage cost functions are from Eq. (45) and (46) for port A and Eq. (64) and (65) for port B. Thus, the total cost in the social welfare function can be expressed as:

$$TC_A^{III,4} = 0 + c_k \cdot K_{A1} + \frac{(\overline{K}_A + K_{A1})x(-1+\beta\theta)}{\beta\theta^2} - \bar{I}_A + \beta \cdot \frac{(\overline{K}_A + K_{A1})x}{2\beta^2\theta^2},$$

$$TC_B^{III,4} = \frac{\overline{K}_B}{2\theta^2} + c_k \cdot K_{B2} + \frac{(\overline{K}_B + K_{B2})(-1+\theta)}{\theta^2} - \bar{I}_B + \beta \cdot \frac{(\overline{K}_B + K_{B2})x}{2\theta^2}.$$

The marginal total cost functions are calculated by taking derivative of the total cost functions with respect to K_{A1} and K_{B2}:

$$C_A^{III,4} = \frac{\partial TC_A^{III,4}}{\partial K_{A1}} = c_k + \frac{x(-1+\beta\theta)}{\beta\theta^2} + \beta \cdot \frac{x}{2\beta^2\theta^2},$$

$$C_B^{III,4} = \frac{\partial TC_B^{III,4}}{\partial K_{B2}} = \frac{1}{2\theta^2} + c_k + \frac{(-1+\theta)}{\theta^2} + \beta \cdot \frac{x}{2\theta^2}.$$

The cost functions $C_{\text{III},4,A}$ and $C_{\text{III},4,B}$ with adaptation investments in Eq. (44), (63) and equilibrium prices and throughput quantities in Eq. (75) to (80) are substituted into the social welfare functions in Eq. (19) and (61). By taking partial derivatives of these reorganized social welfare functions with respect to K_{A1} and K_{B2}, the equilibrium capacity investments are calculated as:

$$K_{A1}^{III,4,*} = \frac{4b(a(1+\beta) - C_A^{III,4}) + 2r(C_B^{III,4} - b\overline{K}_B - a\beta)}{4b^2+4b^2\beta - r^2\beta} - \overline{K}_A, \tag{85}$$

$$K_{B2}^{III,4,*} = \frac{4b(\beta+1)(a\beta - C_B^{III,4}) - 2\beta r(a(\beta+1) - C_A^{III,4}) + \overline{K}_B r^2\beta}{\beta(4b^2+4b^2\beta - r^2\beta)} - \overline{K}_B. \tag{86}$$

The Eq. (85) and (86) are then substituted into Eq. (44), (63) and (75) to (80) to determine the remaining parameters.

$$I_{A1}{}^{*} = 2x(\beta\theta - 1)\frac{(2b(a(1+\beta) - C_A^{III,4}) - r(a\beta + b\overline{K}_B - C_B^{III,4}))}{\beta(-r^2\beta + 4b^2(1+\beta))\theta^2} - \bar{I}_A,$$

$$I_{B2}{}^{*} = x(\theta - 1)\frac{(4b(1+\beta)(a\beta - C_B^{III,4}) - r\beta(2a(1+\beta) - 2C_A^{III,4} - \overline{K}_B r))}{\beta(-r^2\beta + 4b^2(1+\beta))\theta^2} - \bar{I}_B,$$

$$q_{A1}{}^{*} = \frac{2(-2ab - 2ab\beta + ar\beta + br\overline{K}_B + 2bC_A^{III,4} - rC_B^{III,4})}{r^2\beta - 4b^2(1+\beta)},$$

$$q_{B1}{}^{*} = \overline{K}_B$$

$$\tau_{A1}{}^{*} = \frac{ar(-2b+r)\beta + (-r^3\beta + b^2 r(2+4\beta))\overline{K}_B - 4b^2 C_A^{III,4} + 2brC_B^{III,4}}{r^2\beta - 4b^2(1+\beta)},$$

$$\tau_{B1}{}^{*} = \frac{1}{r^2\beta - 4b^2(1+\beta)}(-4ab^2 + 4abr - 4ab^2\beta + 4abr\beta - ar^2\beta + (4b^3(1+\beta) - br^2(2+\beta))\overline{K}_B - 4brC_A^{III,4} + 2r^2 C_B^{III,4}),$$

$$q_{A2}{}^{*} = \frac{2(-2ab - 2ab\beta + ar\beta + br\overline{K}_B + 2bC_A^{III,4} - rC_B^{III,4})}{r^2\beta - 4b^2(1+\beta)},$$

$$q_{B2}{}^{*} = \frac{r^2\beta\overline{K}_B - 4bC_B^{III,4} + 2\beta(a(2b-r)(1+\beta) + rC_A^{III,4} - 2bC_B^{III,4})}{\beta(-r^2\beta + 4b^2(1+\beta))},$$

$$\tau_{A2}{}^{*} = \frac{-r(-2b^2 + r^2)\beta\overline{K}_B + 4brC_B^{III,4} + \beta(-a(2b-r)r(2+\beta) + (4b^2 - 2r^2)C_A^{III,4} + 2brC_B^{III,4}}{\beta(-r^2\beta + 4b^2(1+\beta))}$$

$$\tau_{B2}{}^{*} = \frac{br^2\beta\overline{K}_B + 4b^2 C_B^{III,4} + \beta(ar(r\beta - 2b(1+\beta)) + 2brC_A^{III,4} + (4b^2 - 2r^2)C_B^{III,4})}{\beta(-r^2\beta + 4b^2(1+\beta))}.$$

3.4.2.2 Port A has non-binding capacity in period 2 while Port B faces binding capacity in both periods

In this situation, port B operates under capacity binding constraints across both periods. In the first period, there is no capacity or adaptation investments by the PA of port B, so the capacity constraints are naturally binding for port B, indicating the throughput quantities of TOCs can not exceed the initial capacity endowment. In the second period, the PA of port B have anticipated the TOCs' throughput decisions and invest the exact amount of additional capacity investment to meet the throughput quantities required by TOCs which ensures the optimal results. For port A, in the first period, given enough knowledge of TOCs by the PA, the additional capacity investment by the PAs match with the throughput quantities of TOCs without any additional or waste amount in period 1, so the capacity constraint is binding. However, in period 2, since the PA of port B invest in additional capacity and adaptation investments, and this leads to increased market competition as port B gains more market shares. Under competition, port A suffers from reduced market shares which potentially lead to a situation that its available capacity may exceed the throughput quantities that is needed by TOCs. Thus, port A would operate under non-binding capacity constraint in period 2 due to port competition.

The TOCs profit maximization for port B remains the same as shown in Section 3.4.1:

$$\max_{\{\tau_{A1}\}} \pi_{A2} = \tau_{A1} q_{A1}$$
$$s.t.\, q_{A1} \leq \overline{K}_A + K_{A1}$$
$$\max_{\{\tau_{A2}\}} \pi_{A2} = \tau_{A2} q_{A2}$$
$$s.t.\, q_{A2} \leq \overline{K}_A + K_{A1}$$

$$\max_{\{\tau_{B1}\}} \pi_{B1} = \tau_{B1} q_{B1}$$
$$s.t.\, q_{B1} \leq \overline{K}_B$$
$$\max_{\{\tau_{B2}\}} \pi_{B2} = \tau_{B2} q_{B2}$$
$$s.t.\, q_{B2} \leq \overline{K}_B + K_{B2}$$

Similar to previous calculations, the functions are solved by using backward induction. In period 1, both ports A and B operate under capacity binding constraint, so the TOCs' decisions on throughput quantities and prices remain the same as in Eq. (75) to (77). In period 2, the equilibrium throughput volume is given by:

$$q_{A2} = -\frac{b(-a + rK_{\mathrm{B}2} + r\overline{K}_B)}{2b^2 - r^2}, \tag{87}$$

$$q_{B2} = \overline{K}_B + K_{B2}. \tag{88}$$

By incorporating Eq. (87) and (88) into Eq. (3) and (4), the equilibrium price is calculated as:

$$\tau_{A2} = -\frac{(b-r)(b+r)(-a + rK_{B2} + r\overline{K}_B)}{2b^2 - r^2}, \tag{89}$$

$$\tau_{B2} = -\frac{(b-r)(-2ab - ar + 2b^2K_{B2} + 2brK_{B2} + 2b^2\overline{K}_B + 2br\overline{K}_B)}{2b^2 - r^2}. \tag{90}$$

Similar to Section 3.4.2.1, the disaster damage costs and adaptation investments, I_{A1} and I_{B2}, remain the same as Case I for port A and Case II for port B. Thus, the adaptation investments in

Eq. (23), (33), (43), (44) for optimal I_{A1} and Eq. (63) for optimal I_{B2} remain unchanged. The total cost function in social welfare functions and the marginal total cost function are the same as in Section 3.4.2.1 for each respective range for ports A and B. The only difference between Section 3.4.2.1 and Section 3.4.2.2 is the TOCs' throughput decisions and prices in period 2 as shown in Eq. (87) to (90). The port A's non-binding capacity constraint in period 2 influence the TOCs' decisions and subsequently influence the social welfare calculations. For simplicity, in the following four ranges, only the parts changes compared to Section 3.4.2.1 are illustrated.

3.4.2.2.1 Scenario 1: $0 < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < x < 1$

The equilibrium values of τ_{it}, q_{it}, I_{A1} and I_{B2} as expressed in function of K_{A1} and K_{B2} from Eq. (75) to (77), (87) to (90), (23) and (63) with $C_A^{III,1}$ and $C_B^{III,1}$ are substituted into the social welfare function in Eq. (19) and (61) which the reorganized social welfare function is then taking partial derivative with respect to K_{A1} and K_{B2} to obtain equilibrium capacity investment of port A and B:

$$K_{A1}^{III,1,*} = \frac{2a - 2b\bar{K}_A - r\bar{K}_B - 2C_A^{III,1}}{2b}, \tag{91}$$

$$K_{B2}^{III,1,*} = \frac{4ab^2\beta - abr\beta - 2ar^2\beta - 4b^3\beta\bar{K}_B + 4br^2\beta\bar{K}_B - 4b^2C_B^{III,1} + 2r^2C_B^{III,1}}{4b(b^2 - r^2)\beta}. \tag{92}$$

The Eq. (91) and (92) is substituted to the adaptation investments in Eq. (23) and (63) and the equilibrium TOC-chosen prices and throughput quantities across two periods in Eq. (75) to (77) and (87) to (90) and these parameter values are calculated:

$$\begin{aligned} I_{A1}^* = \frac{1}{2b(x+\beta)\theta^2}(&-2ax + 2ax\theta + 2ax\beta\theta - 2bx\theta^2\bar{I}_A - 2b\beta\theta^2\bar{I}_A + rx\bar{K}_B - rx\theta\bar{K}_B \\ &- rx\beta\theta\bar{K}_B + 2xC_A^{III,1} - 2x\theta C_A^{III,1} - 2x\beta\theta C_A^{III,1}), \\ I_{B2}^* = -\frac{1}{4b(b-r)(b+r)\beta\theta^2}(&4ab^2x\beta - abrx\beta - 2ar^2x\beta - 4ab^2x\beta\theta + abrx\beta\theta \\ &+ 2ar^2x\beta\theta + 4b^3\beta\theta^2\bar{I}_B - 4br^2\beta\theta^2\bar{I}_B - 4b^2xC_B^{III,1} + 2r^2xC_B^{III,1} \\ &+ 4b^2x\theta C_B^{III,1} - 2r^2x\theta C_B^{III,1}), \end{aligned}$$

$$q_{A1}^* = \frac{2a - r\bar{K}_B - 2C_A^{III,1}}{2b},$$

$$q_{B1}^* = \bar{K}_B,$$

$$\tau_{A1}{}^* = \frac{1}{2}(-r\bar{K}_B + 2C_A^{III,1}),$$
$$\tau_{B1}{}^* = -\frac{-2ab + 2ar + 2b^2\bar{K}_B - r^2\bar{K}_B - 2rC_A^{III,1}}{2b},$$
$$q_{A2}{}^* = \frac{4ab^3\beta - 4ab^2r\beta - 3abr^2\beta + 2ar^3\beta + 4b^2rC_B^{III,1} - 2r^3C_B^{III,1}}{4(b-r)(b+r)(2b^2-r^2)\beta},$$
$$q_{B2}{}^* = \frac{4ab^2\beta - abr\beta - 2ar^2\beta - 4b^2C_B^{III,1} + 2r^2C_B^{III,1}}{4b(b-r)(b+r)\beta},$$
$$\tau_{A2}{}^* = \frac{4ab^3\beta - 4ab^2r\beta - 3abr^2\beta + 2ar^3\beta + 4b^2rC_B^{III,1} - 2r^3C_B^{III,1}}{4b(2b^2-r^2)\beta},$$
$$\tau_{B2}{}^* = \frac{-abr\beta + 4b^2C_B^{III,1} - 2r^2C_B^{III,1}}{2(2b^2-r^2)\beta}.$$

3.4.2.2.2 Scenario 2: $\mathbf{0 < x < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < 1}$

The equilibrium prices and traffic volume determined by TOCs in Eq. (75) to (77) and (87) to (90) as well as the adaptation investments in Eq. (33) to (63) with $C_A^{III,2}$ and $C_B^{III,2}$ are substituted into the social welfare function in Eq. (19) and (61) and the rewritten social welfare function is then taking simultaneous partial derivatives with port-respective capacity investments, K_{A1} and K_{B2}:

$$K_{A1}^{III,2,*} = \frac{2a - 2b\bar{K}_A - r\bar{K}_B - 2C_A^{III,2}}{2b}, \tag{93}$$
$$K_{B2}^{III,2,*} = \frac{4ab^2\beta - abr\beta - 2ar^2\beta - 4b^3\beta\bar{K}_B + 4br^2\beta\bar{K}_B - 4b^2C_B^{III,2} + 2r^2C_B^{III,2}}{4b(b^2-r^2)\beta}. \tag{94}$$

The Eq. (93) and (94) are then incorporated into the adaptation investments for ports A and B in Eq. (33) and (63) and equilibrium port charges and throughput quantities decided by the TOCs in Eq. (75) to (77) and (87) to (90).

$$I_{A1}{}^* = \frac{(-1+\theta)(2a - r\bar{K}_B - 2C_A^{III,2})}{2b\theta^2} - \bar{I}_A,$$
$$I_{B2}{}^* = \frac{4b(-b^2+r^2)\beta\theta^2\bar{I}_B + x(-1+\theta)(a(4b^2 - br - 2r^2)\beta + (-4b^2+2r^2)C_B^{III,2})}{4b(b^2-r^2)\beta\theta^2},$$
$$q_{A1}{}^* = -\frac{-2a + r\bar{K}_B + 2C_A^{III,2}}{2b},$$
$$q_{B1}{}^* = \bar{K}_B,$$
$$\tau_{A1}{}^* = -\frac{1}{2}r\bar{K}_B + C_A^{III,2},$$
$$\tau_{B1}{}^* = \frac{2a(b-r) + (-2b^2+r^2)\bar{K}_B + 2rC_A^{III,2}}{2b},$$

$$q_{A2}{}^{*} = \frac{a(4b^3 - 4b^2r - 3br^2 + 2r^3)\beta + (4b^2r - 2r^3)C_B^{III,2}}{4(2b^4 - 3b^2r^2 + r^4)\beta},$$

$$q_{B2}{}^{*} = \frac{4ab^2\beta - abr\beta - 2ar^2\beta - 4b^2C_B^{III,2} + 2r^2C_B^{III,2}}{4b^3\beta - 4br^2\beta},$$

$$\tau_{A2}{}^{*} = \frac{a(4b^3 - 4b^2r - 3br^2 + 2r^3)\beta + (4b^2r - 2r^3)C_B^{III,2}}{8b^3\beta - 4br^2\beta},$$

$$\tau_{B2}{}^{*} = \frac{-abr\beta + (4b^2 - 2r^2)C_B^{III,2}}{4b^2\beta - 2r^2\beta}.$$

3.4.2.2.3 Scenario 3: $\mathbf{0 < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < 1 < x}$

Everything in Scenario 3 is the exact same as Scenario 1 with the only exception in superscripts indicating different scenarios ($C_A^{III,3} = C_A^{III,1}$, $C_B^{III,3} = C_B^{III,1}$). The results are shown again with updated superscripts:

$$I_{A1}{}^{*} = \frac{1}{2b(x + \beta)\theta^2}(-2ax + 2ax\theta + 2ax\beta\theta - 2bx\theta^2\bar{I}_A - 2b\beta\theta^2\bar{I}_A + rx\bar{K}_B - rx\theta\bar{K}_B - rx\beta\theta\bar{K}_B + 2xC_A^{III,3} - 2x\theta C_A^{III,3} - 2x\beta\theta C_A^{III,3}),$$

$$I_{B2}{}^{*} = -\frac{1}{4b(b - r)(b + r)\beta\theta^2}(4ab^2x\beta - abrx\beta - 2ar^2x\beta - 4ab^2x\beta\theta + abrx\beta\theta + 2ar^2x\beta\theta + 4b^3\beta\theta^2\bar{I}_B - 4br^2\beta\theta^2\bar{I}_B - 4b^2xC_B^{III,1} + 2r^2xC_B^{III,3} + 4b^2x\theta C_B^{III,3} - 2r^2x\theta C_B^{III,3}),$$

$$q_{A1}{}^{*} = \frac{2a - r\bar{K}_B - 2C_A^{III,3}}{2b},$$

$$q_{B1}{}^{*} = \bar{K}_B,$$

$$\tau_{A1}{}^{*} = \frac{1}{2}(-r\bar{K}_B + 2C_A^{III,3}),$$

$$\tau_{B1}{}^{*} = -\frac{-2ab + 2ar + 2b^2\bar{K}_B - r^2\bar{K}_B - 2rC_A^{III,3}}{2b},$$

$$q_{A2}{}^{*} = \frac{4ab^3\beta - 4ab^2r\beta - 3abr^2\beta + 2ar^3\beta + 4b^2rC_B^{III,3} - 2r^3C_B^{III,3}}{4(b - r)(b + r)(2b^2 - r^2)\beta},$$

$$q_{B2}{}^{*} = \frac{4ab^2\beta - abr\beta - 2ar^2\beta - 4b^2C_B^{III,3} + 2r^2C_B^{III,3}}{4b(b - r)(b + r)\beta},$$

$$\tau_{A2}{}^{*} = \frac{4ab^3\beta - 4ab^2r\beta - 3abr^2\beta + 2ar^3\beta + 4b^2rC_B^{III,3} - 2r^3C_B^{III,3}}{4b(2b^2 - r^2)\beta},$$

$$\tau_{B2}{}^{*} = \frac{-abr\beta + 4b^2C_B^{III,3} - 2r^2C_B^{III,3}}{2(2b^2 - r^2)\beta}.$$

3.4.2.2.4 Scenario 4: $\mathbf{1 < \frac{\theta(\bar{I}_i + I_{i1})}{\bar{K}_i + K_{i1}} < x}$

The adaptation investment functions for port A and B in Eq. (44), (63) and the TOCs' equilibrium port charges and throughput quantities in Eq. (75) to (77) for period 1 and Eq. (87) to (90) for period 2 with $C_A^{III,4}$ and $C_B^{III,4}$ are substituted into the social welfare function in Eq. (19) and (61) which the two social welfare functions are then taking partial derivative with respect to K_{A1} and K_{B2} simultaneously:

$$K_{A1}^{III,4,*} = \frac{2a - 2b\bar{K}_A - r\bar{K}_B - 2C_A^{III,4}}{2b}, \tag{95}$$

$$K_{B2}^{III,4,*} = \frac{4ab^2\beta - abr\beta - 2ar^2\beta - 4b^3\beta\bar{K}_B + 4br^2\beta\bar{K}_B - 4b^2C_B^{III,4} + 2r^2C_B^{III,4}}{4b(b^2 - r^2)\beta}. \tag{96}$$

The equilibrium prices and traffic volume decided by TOCs and adaptation investments are obtained by substituting Eq. (95) and (96) to Eq. (75) to (77), (87) to (90), (44) and (63).

$$I_{A1}{}^* = -\frac{2ax - 2ax\beta\theta + 2b\beta\theta^2\bar{I}_A - rx\bar{K}_B + rx\beta\theta\bar{K}_B - 2xC_A^{III,4} + 2x\beta\theta C_A^{III,4}}{2b\beta\theta^2},$$

$$I_{B2}{}^* = -\frac{1}{4b(b-r)(b+r)\beta\theta^2}(4ab^2x\beta - abrx\beta - 2ar^2x\beta - 4ab^2x\beta\theta + abrx\beta\theta + 2ar^2x\beta\theta + 4b^3\beta\theta^2\bar{I}_B - 4br^2\beta\theta^2\bar{I}_B - 4b^2xC_B^{III,4} + 2r^2xC_B^{III,4} + 4b^2x\theta C_B^{III,4} - 2r^2x\theta C_B^{III,4}),$$

$$q_{A1}{}^* = \frac{2a - r\bar{K}_B - 2C_A^{III,4}}{2b},$$

$$q_{B1}{}^* = \bar{K}_B,$$

$$\tau_{A1}{}^* = \frac{1}{2}(-r\bar{K}_B + 2C_A^{III,4}),$$

$$\tau_{B1}{}^* = -\frac{-2ab + 2ar + 2b^2\bar{K}_B - r^2\bar{K}_B - 2rC_A^{III,4}}{2b},$$

$$q_{A2}{}^* = \frac{4ab^3\beta - 4ab^2r\beta - 3abr^2\beta + 2ar^3\beta + 4b^2rC_B^{III,4} - 2r^3C_B^{III,4}}{4(b-r)(b+r)(2b^2 - r^2)\beta},$$

$$q_{B2}{}^* = \frac{4ab^2\beta - abr\beta - 2ar^2\beta - 4b^2C_B^{III,4} + 2r^2C_B^{III,4}}{4b(b-r)(b+r)\beta},$$

$$\tau_{A2}{}^* = \frac{4ab^3\beta - 4ab^2r\beta - 3abr^2\beta + 2ar^3\beta + 4b^2rC_B^{III,4} - 2r^3C_B^{III,4}}{4b(2b^2 - r^2)\beta},$$

$$\tau_{B2}{}^* = \frac{-abr\beta + 4b^2C_B^{III,4} - 2r^2C_B^{III,4}}{2(2b^2 - r^2)\beta}.$$

3.5 Comparative analysis of equilibrium results

After deriving the closed-form equilibrium, I conduct comparative analysis to examine how different parameters would affect the equilibrium decisions. The analysis focuses on how changes in parameters influence equilibrium outcomes of capacity investments (K_{it}), adaptation investments (I_{it}), throughput quantities (q_{it}) and port charges (τ_{it}). Case III is removed due to unclear analytical results with only port A's comparative statistics available. All parameters with ambiguous results are also excluded to keep clarity. Under Case I, the parameter results of Scenarios 1 and 3 are identical, so the direction of parameters are illustrated together.

Explanation of symbols: "↑" indicates an increase in the parameter results in an increase in the corresponding variable, "↓" indicates an increase in the parameter results in a decrease in the corresponding variable, "∼" denotes unclear results.

Table 2: Sensitivity analysis under Case I and Case II

	Case I	**Case I**	**Case I**	**Case II**
Parameter	Scenario 1 and 3	Scenario 2	Scenario 4	
Customer willingness to pay (a)	K_{i1}↑ I_{i1}↑ q_{i1}, q_{i2}↑ τ_{i1}, τ_{i2}↓	K_{i1}↑ I_{i1}↑ q_{i1}, q_{i2}↑ τ_{i1}, τ_{i2}↓	K_{i1}↑ I_{i1}↑ q_{i1}, q_{i2}↑ τ_{i1}, τ_{i2}↓	K_{i2}↑ I_{i2}↑ q_{i2}↑ τ_{i2}↓
Unit capacity investment cost (c_k)	K_{i1}↓ I_{i1}↓ q_{i1}, q_{i2}↓ τ_{i1}, τ_{i2}↑	K_{i1}↓ I_{i1}↓ q_{i1}, q_{i2}↓ τ_{i1}, τ_{i2}↑	K_{i1}↓ I_{i1}↓ q_{i1}, q_{i2}↓ τ_{i1}, τ_{i2}↑	K_{i2}↓ I_{i2}↓ q_{i2}↓ τ_{i2}↑
Adaptation investment efficiency (θ)	K_{i1}↑ q_{i1}, q_{i2}↑ τ_{i1}, τ_{i2}↓	K_{i1}↑ q_{i1}, q_{i2}↑ τ_{i1}, τ_{i2}↓	K_{i1}↑ q_{i1}, q_{i2}↑ τ_{i1}, τ_{i2}↓	K_{i2}↑ q_{i2}↑ τ_{i2}↓
Disaster intensity (x)	q_{i1}, q_{i2}↓ τ_{i1}, τ_{i2}↑	∼	K_{i1}↓ q_{i1}, q_{i2}↓ τ_{i1}, τ_{i2}↑	K_{i2}↓ q_{i2}↓ τ_{i2}↑
Initial capacity endowment ($\bar{K}_i$)	K_{i1}↓	K_{i1}↓	K_{i1}↓	K_{i2}↓
Initial adaptation endowment ($\bar{I}_i$)	I_{i1}↓	I_{i1}↓	I_{i1}↓	I_{i2}↓

Discount factor (β)	~	$K_{i1}\uparrow$ $I_{i1}\uparrow$ $q_{i1}, q_{i2}\uparrow$ $\tau_{i1}, \tau_{i2}\downarrow$	~	~

The increase in customer willingness to pay (a) and adaptation investment efficiency (θ) boosts investment decisions and demonstrates a consistent pattern in both Case I and Case II. As customer demand increases, the PAs of both ports choose to invest more in capacity and adaptation ($K_{it}\uparrow$, $I_{it}\uparrow$), encouraging the TOCs to increase throughput quantities ($q_{it}\uparrow$) to sustain the growing demand. To capture more market share in a competitive environment, the TOCs set lower port charges ($\tau_{it}\downarrow$). Similarly, as adaptation investment becomes more efficient, the PAs invest more in adaptation ($I_{it}\uparrow$). With higher protection and a safer operational environment, the PAs invest more in capacity ($K_{it}\uparrow$). These improved capacity and resilience protection levels encourage the TOCs to handle more throughputs ($q_{it}\uparrow$) and decrease prices to capture more market shares ($\tau_{it}\downarrow$). Conversely, an increase in the unit capacity investment cost (c_k) reduces the incentives of investment decisions. Higher unit costs increase the expense of maintaining current capacity investment levels, so the PAs choose to reduce capacity investment ($K_{it}\downarrow$) to alleviate financial pressure. With the halt of capacity expansion projects, the PAs decrease adaptation investment ($I_{it}\downarrow$) because same or lower operational capacity no longer need for additional resilience protection measures. Without further capacity expansion, the TOCs decrease throughput quantities ($q_{it}\downarrow$) and charge higher prices ($\tau_{it}\uparrow$) to maintain operational efficiency.

Disaster intensity (x) mainly influences throughput and port charge decisions. Under higher disaster intensity, the TOCs reduce throughput quantities ($q_{it}\downarrow$) to buffer against expected disruptions and raise prices ($\tau_{it}\uparrow$) to compensate for operational risks and maintain current profitability. Specifically, in Scenario 4 under both Case I and Case II, increasing disaster intensity leads to decreasing capacity investments ($K_{it}\downarrow$) due to higher chances of operational disruption. The relationship between initial capacity endowment ($\bar{K}_i$) and added capacity investment, and between initial adaptation investment ($\bar{I}_i$) and added adaptation investment, remains consistent across both Case I and Case II. Higher levels of initial endowment reduce the incentive for new investments (K_{it}, $I_{it}\downarrow$) because the endowment already provides sufficient capacity and resilience. The discount factor (β) only appears in Scenario 2 under Case I and brings positive effect on capacity and adaptation investments (K_{i1}, $I_{i1}\uparrow$). This shows that future investment returns are more valuable than the current ones, which the PAs will invest more today for higher future profits. When the PAs invest more, capacity expands and resilience improves, enabling the TOCs to increase throughput quantities ($q_{i1,2}\uparrow$) and lower prices ($\tau_{i1,2}\downarrow$) to gain more market shares.

4. Numerical analysis

To better understand the relationships between key parameters and support rational investment decisions, several baseline parameters are chosen, as outlined in Table 3. All parameters are in normalized form to satisfy the model's feasibility requirements (positive demand, non-negative profits and investments) and to produce realistic equilibrium outcomes. These values serve as a benchmark scenario rather than representing any specific port data and remain consistent across all three cases to ensure that the analysis isolates the effects of disaster intensity on social welfare and investment decisions. For simplicity, "both binding" refers to the situation where both ports A and B face binding capacity constraints across the two periods, and "port A non-binding" indicates that port A have non-binding capacity constraints.

Table 3: Baseline parameter values for all three cases

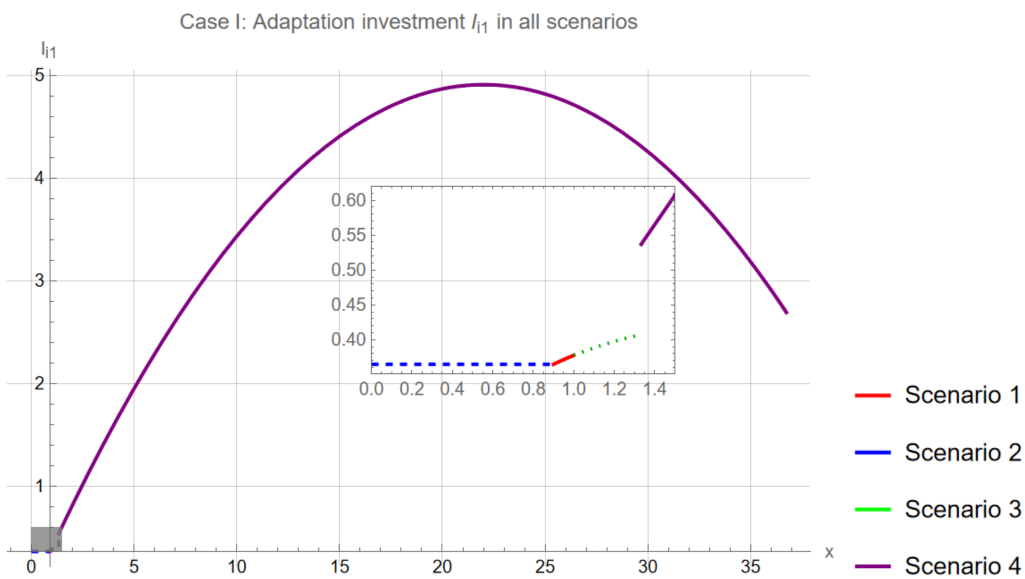
Competition level	$r = 0.3$
Unit capacity costs	$c_k = 2$
Efficiency of adaptation investment	$\theta = 10$
Discount factor	$\beta = 0.4$
Maximum prices customer willing to pay without quantities	$a = 4$
The slope	$b = 0.4$
Initial capacity endowment of port A and B	$\overline{K}_A = \overline{K}_B = 0.5$
Initial adaptation endowment of port A and B	$\bar{I}_A = \bar{I}_B = 0.045$

The disaster intensity parameters, x_1 and x_2, follow uniform distributions, with $x_1 \sim [0,1]$ and $x_2 \sim [0, x]$, respectively. The upper boundary x varies across cases and does not have a fixed baseline value. Based on the equilibrium equations and the baseline parameters in Table 3, figures are generated by varying x within their respective range for each case. These figures illustrate the impact of disaster intensity on adaptation investments, capacity investments, and social welfare.

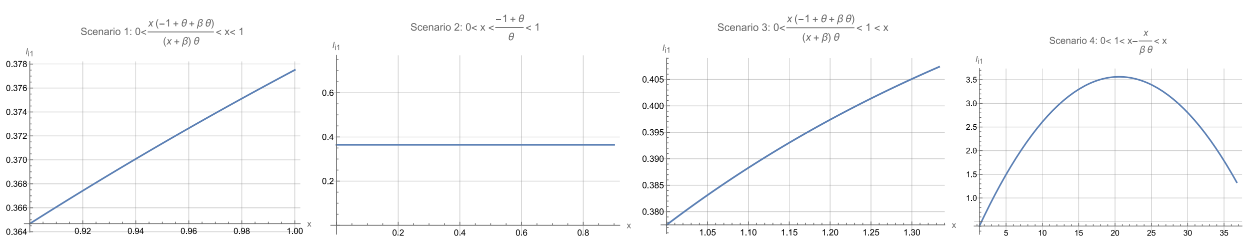
4.1 Impact of disaster intensity on investment decisions

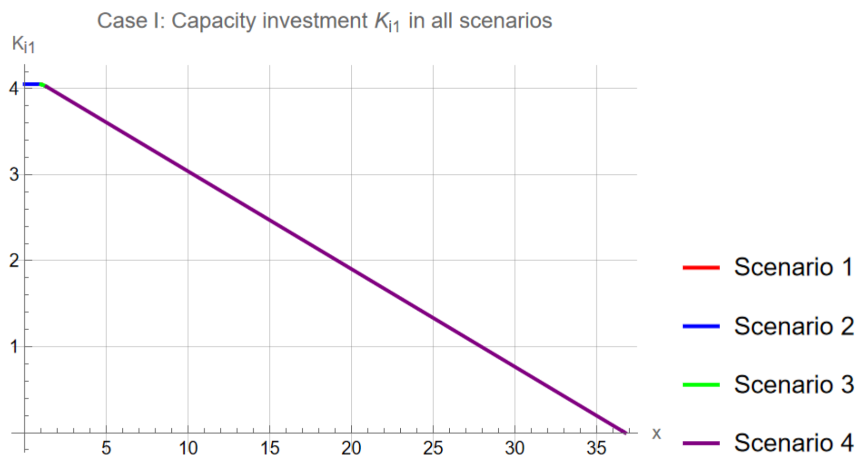
Figure 2: Case I – Adaptation Investment (I_{i1}) and capacity investment (K_{i1}) with varying disaster intensity (x)

The zoomed plot for adaptation investment is shown below.

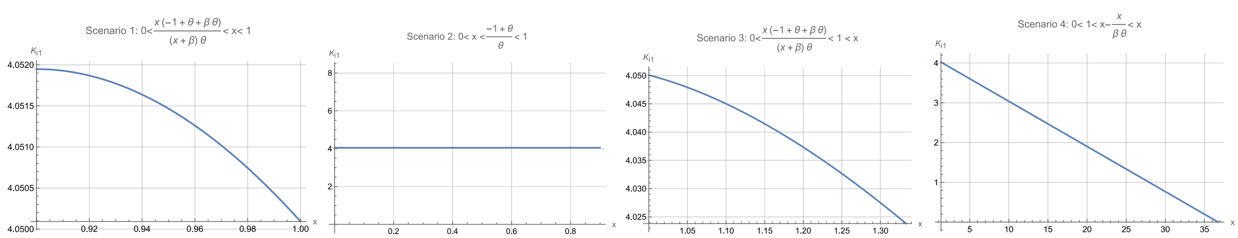


Scenario-specific adaptation investment plots for port i (zoomed-in views of the above graph)





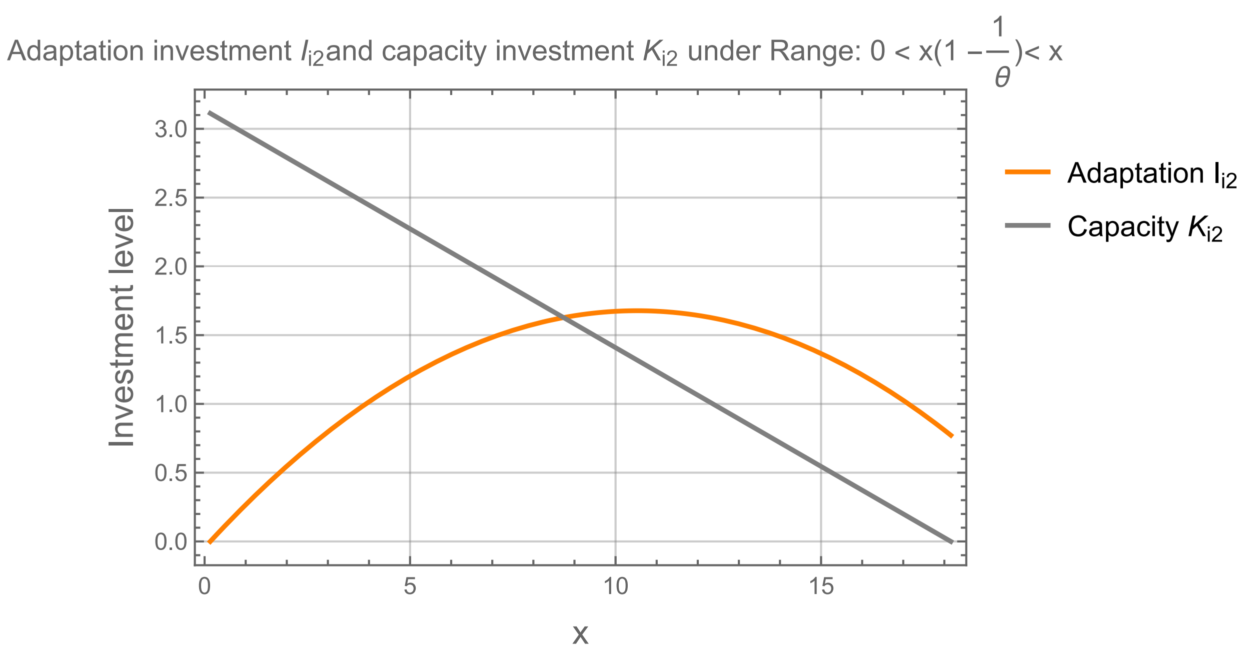
Scenario-specific capacity investment plots for port i



As shown in the combined graphs, capacity investment (K_{i1}) consistently declines as disaster intensity increases, and adaptation investment (I_{i1}) continually increases, but suddenly decreases after reaching a certain disaster intensity threshold. This suggests that ports prioritize adaptation investment under small to moderate disaster intensity but face diminishing returns in high disaster intensity.

In the individual plot for Scenario 1, when the disaster intensities are small, adaptation investment steadily increases. The positive slope shows the effectiveness of early adaptation investment against small climate intensity. In contrast, capacity investment in Scenario 1 exhibits an opposite trend, which decreases as the disaster intensity increases. This reflects that ports focus more on adaptation investments over capacity expansion under small ranges of climate intensities. In Scenario 2, both I_{i1} and K_{i1} remain constant regardless of changes in disaster intensity. This is due to no disaster costs incurred within the range of x_2, so ports choose to maintain their current investment levels. In Scenario 3, as x becomes larger, adaptation investment increases more sharply than in Scenario 1, showing enhanced resilience under moderate disaster intensity. The slope of capacity investment is steeper than Scenario 1. This suggests that ports are reallocating their resources more rapidly from capacity expansion to other areas including adaptation investments. The gap between Scenarios 3 and 4 reflects that as disaster intensity moves from moderate to high level, building resilience against more severe disruptions is urgent and required. In Scenario 4, as x becomes extremely large, ports initially invest more in adaptation. However, after a certain disaster intensity level, adaptation investment shows diminishing returns, which additional investment either fails to provide sufficient protection or is no longer cost-effective. For K_{i1}, capacity investment steadily decreases as x becomes really large, which indicates that ports consistently reduce the priority of capacity expansion investments.

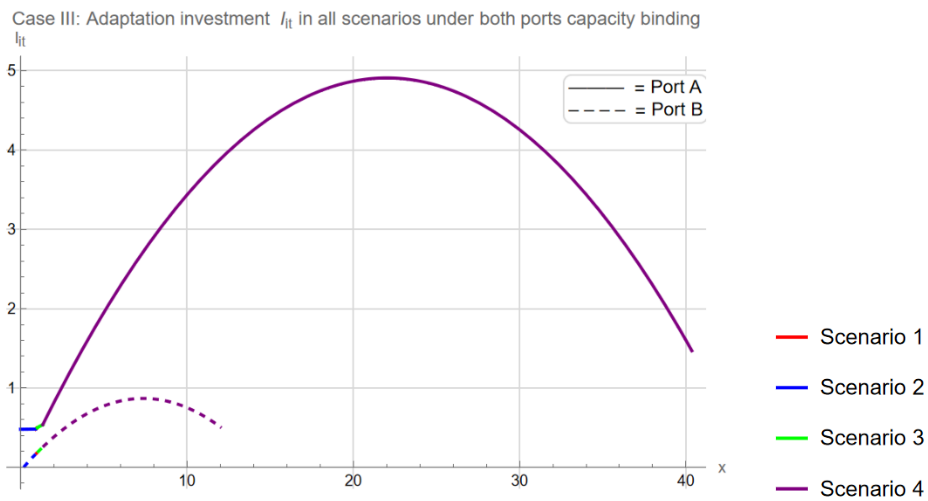
Figure 3: Case II – Adaptation Investment (I_{i2}) and capacity investment (K_{i2}) with varying disaster intensity (x)



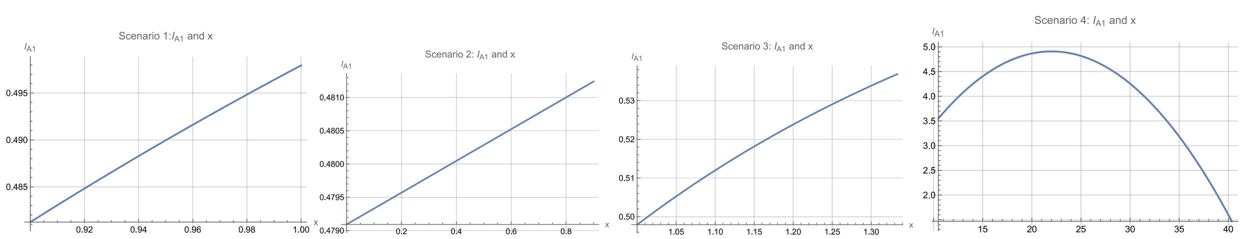
In Case II, as x increases, ports A and B invest more in adaptation to improve resilience. However, after reaching a disaster intensity level, adaptation investment begins to decrease. This suggests that investing in resilience initially has a greater marginal benefit than its marginal costs, but the benefit decreases, suggesting that the current adaptation investment is inefficient for dealing with extreme disaster intensity. Capacity investment decreases as x increases, which indicates a shift in the ports' investment budgets toward other areas including adaptation investments. Compared to

Figure 2, early investment under Case I results in higher adaptation and capacity investment levels, showing the benefits of proactive plans.

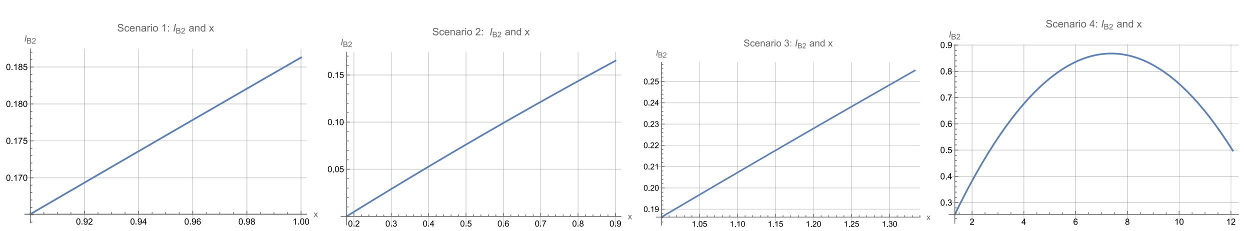
Figure 4: Case III – Adaptation Investment ($I_{i1,2}$) and capacity investment ($K_{i1,2}$) with varying disaster intensity (x) under both ports capacity binding

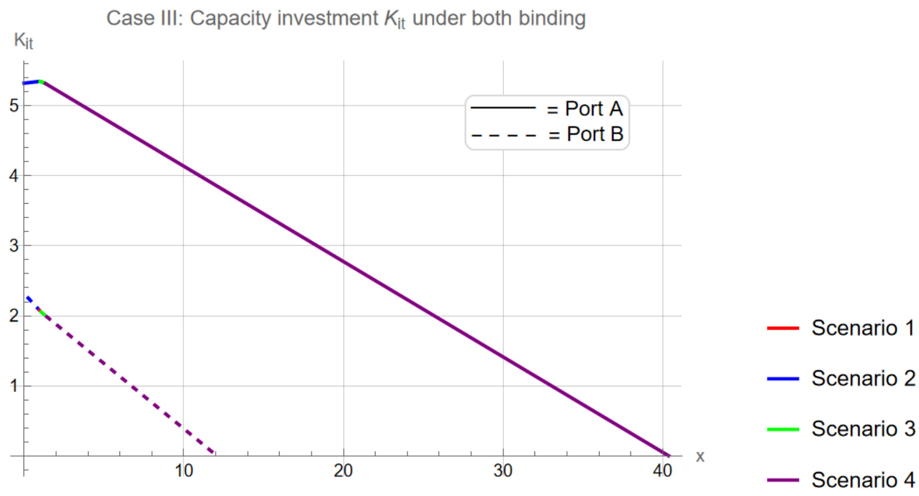


Scenario-specific adaptation investment plots for port A

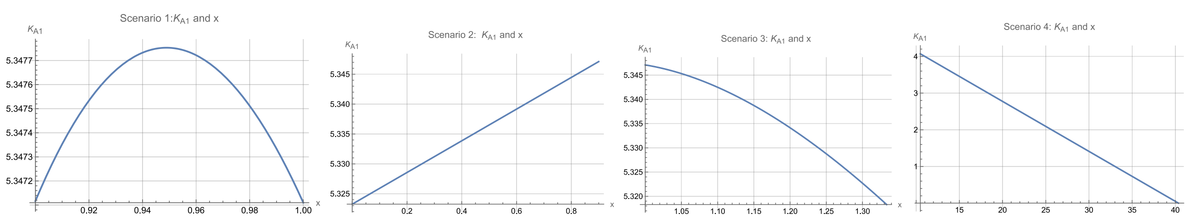


Scenario-specific adaptation investment plots for port B

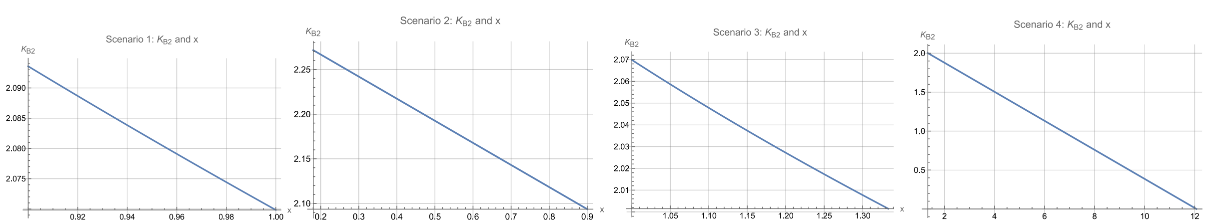




Scenario-specific capacity investment plots for port A



Scenario-specific capacity investment plots for port B

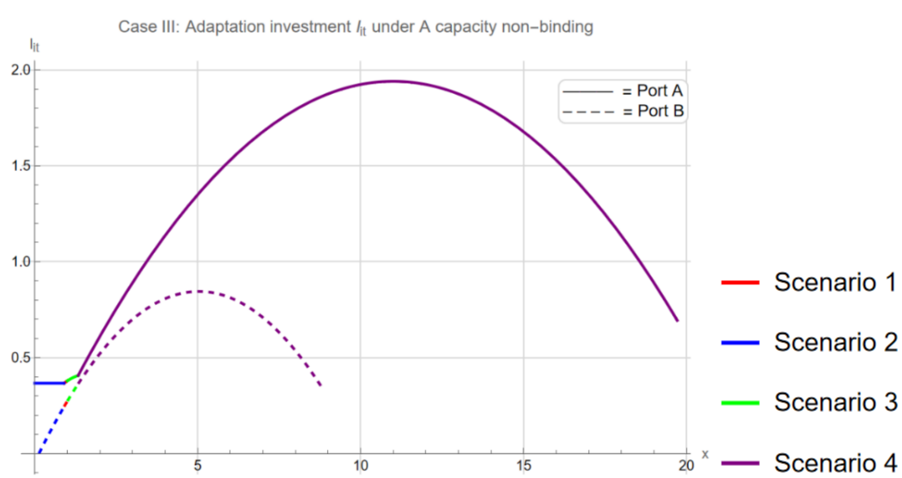


Both adaptation and capacity investments by port A in all four scenarios are higher than port B, suggesting early investments offer higher investment quantities and flexibility. In individual plot for Scenario 1, adaptation investments (I_{A1} and I_{B2}) demonstrate a linear increase with x. Both ports are trying to build some level of resilience in low disaster intensities for future disruptions. Capacity investment (K_{A1}) initially increases with x, but later decreases. This suggests that after certain disaster intensity, investing in capacity is no longer effective in coping with climate disruptions. K_{B2} decreases as disaster intensity increases. With consistently increasing adaptation investments, late investment of port B focuses more on adaptation. In Scenario 2, with higher disaster intensity, both ports continue to increase adaptation investments. K_{A1} shows a positive linear trend compared to the decline in port B. This shows that port A tries to balance adaptation and capacity investments to cope with higher chances of operational disruptions. With continuously increasing adaptation investment, port B, which invests late, improves its resilience quickly to urgently address future extreme disruptions.

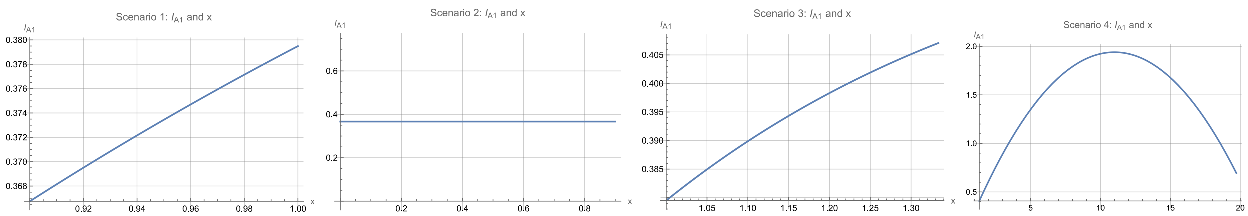
In Scenario 3, both I_{A1} and I_{B2} increase linearly with x, but capacity investments (K_{A1} and K_{B2}) decreases as x increases. With higher disaster intensity, both ports choose to invest in more resilience for risk mitigation instead of expanding capacity. Port A demonstrates a less steep slope in both adaptation and capacity investments, showing that early investments allow for more balanced considerations and flexibility to adjust investments. In Scenario 4, as x becomes very large, both ports initially increase adaptation investment, but decline after certain disaster intensity. Under high disaster intensity, the additional adaptation investments no longer provide resilience benefits. Capacity investments consistently decrease. At very high disaster intensities, both ports choose to halt capacity expansion and focus on building resilience.

Figure 5: Case III - Adaptation Investment ($I_{i1,2}$) and capacity investment ($K_{i1,2}$) with varying disaster intensity (x) under port A capacity non-binding in period 2

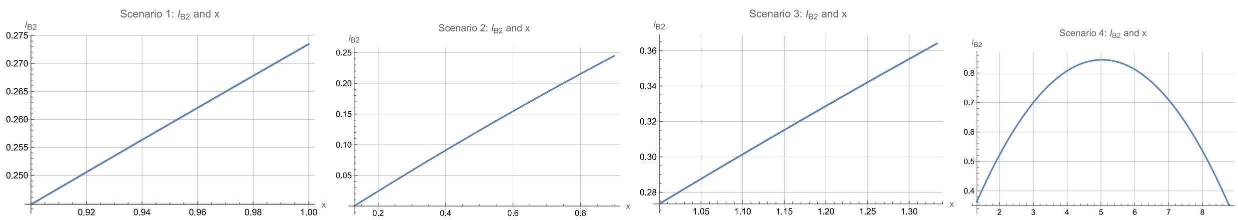
In period 2, port A invests more in capacity under competition, but with lower market shares, the equilibrium throughput is now lower than the available capacity ($q_{A2} \leq \bar{K}_A + K_{A1}$), which results in a non-binding capacity constraint.

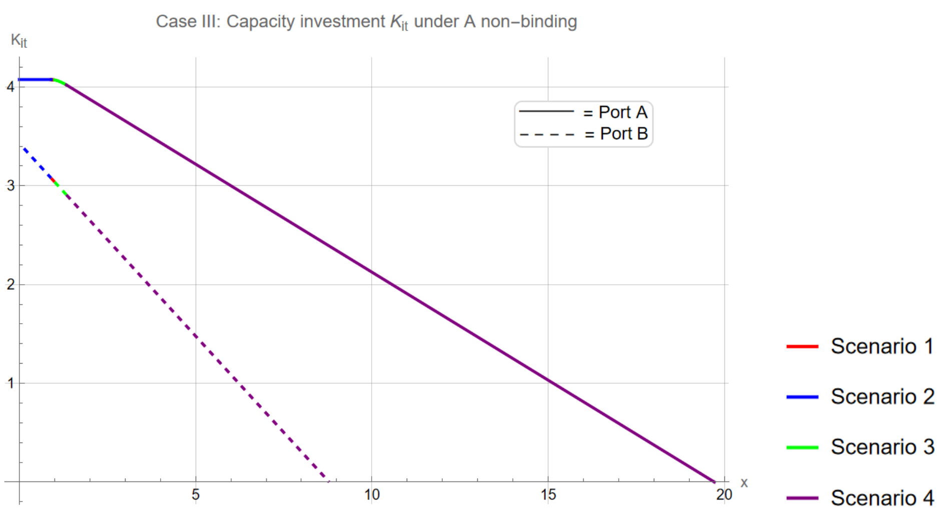


Scenario-specific adaptation investment plots for port A

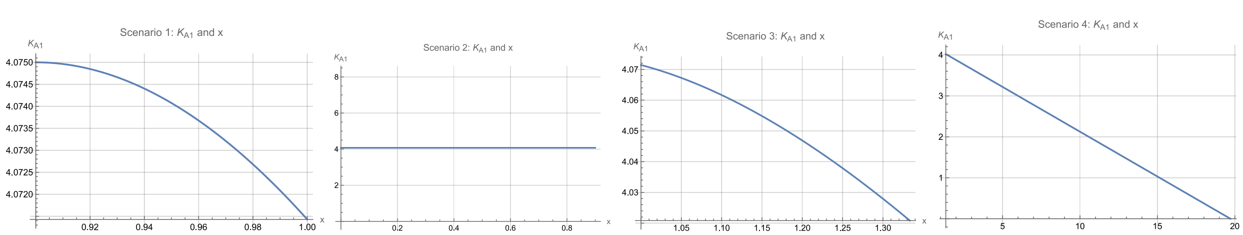


Scenario-specific adaptation investment plots for port B

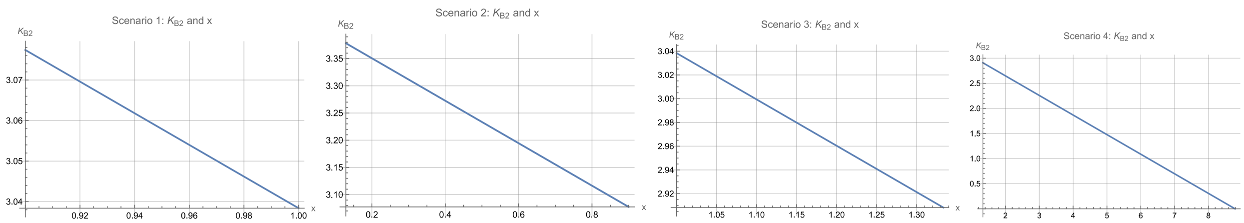




Scenario-specific capacity investment plots for port A



Scenario-specific capacity investment plots for port B

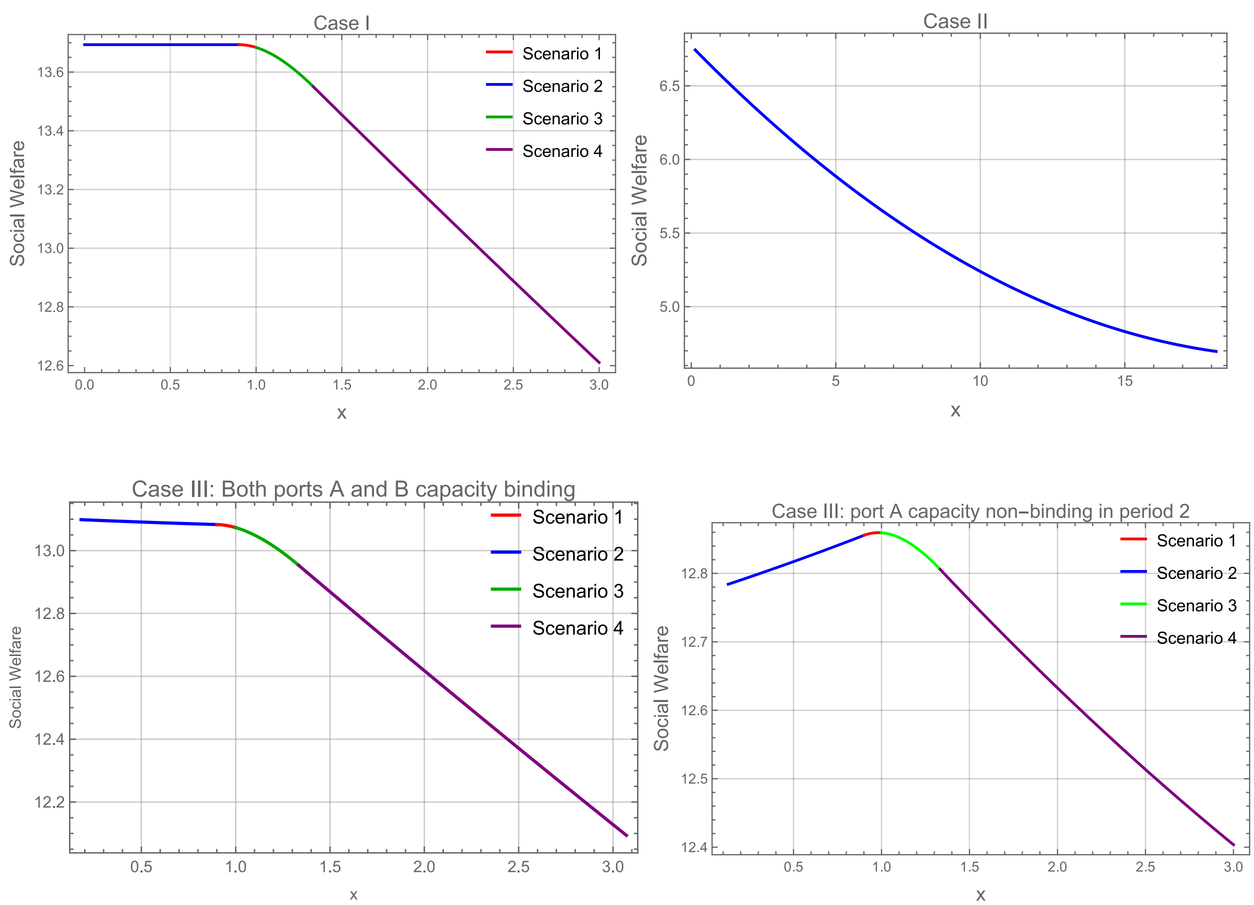


Across all four scenarios, port A has higher investment values due to early investment benefits. In the individual plots for Scenario 1, the adaptation investments (I_{A1} and I_{B2}) illustrate an increasing trend as x increases. Capacity investments (K_{A1} and K_{B2}) decrease with increasing x, but the slope of K_{A1} is less steep compared to K_{B2}. This indicates that port A's non-binding constraint in period 2 helps maintain capacity levels more effectively. Both ports A and B choose to invest more in resilience and less in capacity expansion under small disaster intensity. Compared to Figure 4, port A's adaptation investments demonstrate a similar pattern, but capacity investment decreases more smoothly instead of an inverted U-shape trend with a sudden increase and decrease. With non-binding capacity constraints, port A obtains more flexibility in investment choices and can gradually decrease capacity investment based on demand and operational needs. In Scenario 2, port A chooses constant adaptation and capacity investments because no disaster costs are incurred within the range of x_2. Compared to Figure 4, both capacity and adaptation investments no longer need to maintain an increasing trend to satisfy binding constraints and can be flexible to invest a steady amount without considering changes in x. Meanwhile, port B increases adaptation investment and decreases capacity investment with increasing x, shifting its focus towards resilience to gain immediate protection.

In Scenario 3, both I_{A1} and I_{B2} increase as x rises. K_{A1} and K_{B2} decline as x becomes larger. Compared to the fully binding case in Figure 4, both investments resemble similar patterns. This demonstrates that the non-binding capacity constraint in period 2 has mere influence under moderate disaster intensity. In Scenario 4, both I_{A1} and I_{B2} initially rise with increasing x, but later decline. This is because of the diminishing returns of adaptation investment which make both ports challenging to maintain effective risk mitigation. Port A's optimal point is higher and later than port B's, which suggests early investments bring more sustained resilience. K_{A1} and K_{B2} both show a decreasing trend as x increases and indicates both ports choose to decrease capacity expansion in extreme disaster intensity. Compared to Figure 4, port A’s capacity investment follows a similar pattern, but adaptation investment shows a more gradual increase and decline. This shows that non-binding capacity constraints provide greater stability and flexibility in regulating investments under extreme disaster intensity.

4.2 Impact of disaster intensity on social welfare

Figure 6: Social welfare comparison across scenarios under Case I, II, III



Across all three cases, as disaster intensity increases, the social welfare function decreases. This aligns with theoretical expectations, which higher intensity disaster intensity increases the disaster-related costs, decreases port profits, reduces consumer surplus and ultimately lowers social welfare. The analysis does not include individual social welfare plots for each scenario across the three cases because the combined graphs already show the trends clearly.

In Case I, the social welfare is the highest compared to other cases, showing the importance of early adaptation and capacity investments. The flat line in Scenario 2 occurs because no disaster costs are incurred within the range of x_2. As a result, changes in x have no impact on the social welfare function. In Scenario 3, the social welfare function demonstrates a similar trend as in Scenario 1 but with a slightly smoother slope. In Scenario 4, social welfare declines more rapidly compared to the other scenarios. This indicates that early investments are not generating enough resilience to address high disaster intensity. Overall, when x is larger than 1, the social welfare function begins decreasing fast which demonstrate the early investments is uncapable of keeping high returns under high disaster intensity. In Case II, the social welfare function begins at its highest value but decreases sharply as disaster intensity x increases. This rapid decline indicates the vulnerability and unpreparedness of ports that delay capacity and adaptation investments. The decline becomes slower when x is around 10. This suggests that the loss of social welfare is mainly due to the failure of building resilience proactively. Compared to Case I, it is shown that for smaller disaster intensities, early investments offer better and smoother social welfare levels.

In Case III, when both ports face capacity binding constraints, in Scenarios 1 and 2, the range of x is relatively small and social welfare gradually decreases. This shows early investments at port A demonstrate some resilience to small disaster intensities. The social welfare impact from disaster disruptions intensifies as x becomes larger in Scenarios 3 and 4. Both early and late investments fail to address climate impacts and maintain social welfare in high disaster levels. When port A operates under non-binding capacity constraints, Scenarios 1 and 2 show a positive correlation between social welfare and disaster intensity. The combination of early investments and non-binding capacity constraints at port A provides flexible investment options that help reduce disaster impacts on social welfare. As x becomes larger in Scenario 3 and 4, the influence of port A's non-binding constraints diminishes due to B's capacity binding constraints and late investment strategies. In Scenario 4, although the decline in social welfare is initially steeper compared to the same scenario in both ports under capacity binding constraints, the slope later decreases, benefiting from the flexible adaptation strategies under port A's non-binding capacity constraint. Compared to both ports binding case, for small to moderate ranges of x, the non-binding constraints provide an increasing trend and lower decline in social welfare. For higher disaster intensity ($x > 1$), port

A's non-binding constraint helps social welfare remain at higher levels and allows social welfare to decline more smoothly.

To better illustrate the results and make investment decisions, numerical social welfare is computed as the sum of the social welfare of port A and port B, reflecting the overall market social welfare rather than focusing on individual port. The current social welfare, $SW_{current}$, is calculated by averaging the range of x and incorporating it with the baseline parameters in Table 3 into the general social welfare equation. Similarly, the value of x for $SW_{maximum}$ and $SW_{minimum}$ are selected based on maximum and minimum social welfare points observed in the above figures of social welfare versus x. The results, along with the corresponding numerical ranges, are shown in Table 4.

Table 4: Social welfare calculations

Case I		$SW_{Current}$	$SW_{Maximum}$	$SW_{Minimum}$	Per-Case Min-Max
Scenario 1	$0.9 < x < 1$	13.691	13.693	13.684	
Scenario 2	$0 < x < 0.9$	13.69	13.69	13.69	
Scenario 3	$1 < x < 1.333$	13.63	13.68	13.55	
Scenario 4	$1.33 < x < 36.7429$	5.62	7.62	2.2	
Overall					2.2-13.693
Case II		$SW_{Current}$	$SW_{Maximum}$	$SW_{Minimum}$	
	$0.138 < x < 18.16$	5.33	6.73	4.7	
Overall					4.7-6.73
Case III - both binding		$SW_{Current}$	$SW_{Maximum}$	$SW_{Minimum}$	
Scenario 1	$0.9 < x < 1$	13.08	13.08	13.07	
Scenario 2	$0.18 < x < 0.9$	13.09	13.1	13.08	
Scenario 3	$1 < x < 1.333$	13.03	13.07	12.96	
Scenario 4	$10.48 < x < 12.07$	8.56	8.96	8.42	
Overall					8.42-13.08
Case III - A non-binding		$SW_{Current}$	$SW_{Maximum}$	$SW_{Minimum}$	
Scenario 1	$0.9 < x < 1$	12.86	12.8595	12.8593	

Scenario 2	$0.13 < x < 0.9$	12.82	12.85	12.78	
Scenario 3	$1 < x < 1.333$	12.84	12.86	12.80	
Scenario 4	$1.333 < x < 8.787$	12.05	12.80	11.8	
Overall					11.8-12.86

In Case I, where both ports A and B invest early, social welfare is the highest across all comparisons (current, maximum or minimum) when x is relatively small to moderate levels ($x < 1.333$). The outcome is preferred under both binding and non-binding scenarios as early investments yield the highest $SW_{current}$ under moderate disaster probabilities. However, when x becomes very large ($x > 1.333$), social welfare in both Case I and III drops significantly. In this larger range, the non-binding condition in Case III achieves the best performance by offering flexibility to manage severe climate disruptions. When x is small ($x < 1.333$), the binding constraints for both ports A and B in Case III result in higher social welfare compared to when port A adopts non-binding constraints. This is because binding constraints optimize adaptation and capacity investments without any waste or underuse of resources. As x increases significantly, Case I exhibits the largest gap between $SW_{maximum}$ and $SW_{minimum}$. This indicates the inefficiencies in resource allocation under extreme disaster intensities. While Case I perform well for smaller disaster intensities, it lacks robustness against severe climate disruptions. For small ranges ($x < 1.333$), the $SW_{current}$ in Case II is significantly lower than in other cases which demonstrate that late investments are not optimal decisions. However, when comparing Case II to Scenario 4 of Case I within the similar ranges, Case II achieves higher $SW_{minimum}$, but lower $SW_{current}$ and $SW_{maximum}$. This aligns with previous observations that Scenario 4 of Case I has a larger Min-Max gap which demonstrate higher variability, lower minimum social welfare values and increased vulnerability to rising x. In contrast, Case II demonstrates more stability in its Min-Max range under high disaster intensities, though its overall social welfare performs moderately.

5. Conclusion and future research directions

This study proposes a two-period model to analyze the capacity and adaptation investment timing decisions and its influences on the social welfare with the presence of competition, climate uncertainty. It brings two main contributions to the field of literature. The first is the model introduces a more comprehensive investment decision framework for two ports which analyzes both synchronous (early, late) and asynchronous (dynamic) investment timing strategies. Unlike existing literatures by Xiao et al. (2015), Randrianarisoa and Zhang (2019) and Wang et al. (2022), it extends the timing choices between immediate or later in only disaster prevention investing settings to more dynamic investing scenarios with interdependent capacity and adaptation investment choices. Secondly, the study examines the disaster intensity boundaries for each specific case and analyze the investment decisions between competitive ports across different ranges. This approach offers a more realistic and intuitive framework for policymakers and practitioners to better understand how disaster intensities influence the investment timing decisions, resource allocation decisions and social welfare.

Firstly, as disaster intensity x increases, social welfare decreases across all cases due to increasing disaster costs and reduced consumer surplus. Under low disaster intensity, ports tend to increase adaptation investments, while capacity investment patterns differ due to investment priorities between resilience and expansion. At higher disaster intensity levels, adaptation investments initially rise but then decrease once x surpasses a certain threshold, beyond which additional resilience measures become less effective in mitigating the impacts of extreme disasters. Secondly, early investments enable higher levels of capacity and adaptation investments through proactive planning, while late investments choose to shift resources toward adaptation to address immediate risks. Thirdly, investment timing decisions are closely related to the range of disaster intensity. When x is small to moderate ($x < 1.333$), early investments result in higher social welfare and slower rates of social welfare decline. However, under large disaster intensity ($x > 1.333$), early investments lose their advantages as they become less effective in sustaining resilience. When one port invests early under non-binding capacity constraints in period 2 and the other port invests late, social welfare is higher and illustrates a smoother decline under extreme disaster intensities. This highlights non-binding capacity constraints offer greater flexibility in allocating resources between adaptation and capacity which ports can be more effective in coping with severe disruptions.

Several future research directions can be considered. First, the baseline parameters in Case III can take on different values between ports A and B to illustrate the different characteristics of ports A and B for more realistic results. Second, future studies could source parameters from reality to enhance its practicality. Third, the current model focuses only on the competition between two ports and could be extended to competitions among multiple ports. Fourth, future research could incorporate information accumulation, allowing the realization of disaster uncertainties in period 1 to inform and update the uncertainty estimates for period 2. Fifth, instead of predetermined investment timings, future studies could allow each port to decide on when or whether to invest based on the decisions of its competitors. Sixth, multi-stage investment timing models could be used to analyze how the investment timings influence long-term social welfare. Seventh, future studies could investigate separate capacity and adaptation investment decisions rather than joint decision-making. Last, the social welfare function could include more factors such as environmental shocks, technical advancements, and governmental subsidies to make the model more realistic.

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Appendix

Appendix A

Appendix A.1 List of mathematical notations

Model notations

i	Port i, i = A or B
t	Period t, $t = 1$ or 2
τ_{it}	Port charges of port i in period t
q_{it}	Traffic volume of port i in period t
$\overline{K}_i$	Initial capacity endowment of port i
K_{it}	Capacity investment of port i in period t
β	Discount factor
$\bar{I}_i$	Initial adaptation endowment of port i
I_{it}	Adaptation investment of port i in period t
θ	Effectiveness of adaptation investment
x_1, x_2	Disaster intensity in period t
c_k	Cost of capacity investment per unit
a	Maximum price customers willing to pay without quantities
b	Slope of demand function
r	Degree of substitutability between ports A and B
SW_i	Social welfare of port i

Appendix A.2 Calculations of consumer surplus

Under linear demand function, the consumer surplus is defined as the difference between the maximum price the customer willing to pay and the actual price they pay (Xiao et al. 2012, Zhu et al. 2019, and Balliauw, 2019):

$$CS(q_i) = \frac{1}{2} \cdot q_i(a - \tau_i)$$

The full derivation of the consumer surplus of port A and B is as follows:

$$CS\,(q_A, q_B) = \int_0^{q_A} P_A(q_A, q_B)dq_A + \int_0^{q_B} P_B(q_A, q_B)dq_B - \tau_A q_A - \tau_B q_B$$

$$= \int_0^{q_A}(a - bq_A - rq_B)\,dq_A + \int_0^{q_B}(a - bq_B - rq_A)\,dq_B - \tau_A q_A - \tau_B q_B$$

$$= a(q_A + q_B) - \frac{1}{2}b({q_A}^2 + {q_B}^2) - rq_A q_B - \tau_A q_A - \tau_B q_B$$

This function is then separated into terms involving port A and B respectively:

$$CS_A = aq_A - \frac{1}{2}b{q_A}^2 - \frac{1}{2}rq_A q_B - \tau_A q_A$$

$$CS_B = aq_B - \frac{1}{2}b{q_B}^2 - \frac{1}{2}rq_A q_B - \tau_B q_B$$

By plugging $\tau_A = a - bq_A - rq_B$ and $\tau_B = a - bq_B - rq_A$ (equation (1) and (2) in the text) into the above equations:

$$CS_A = aq_A - \frac{1}{2}b{q_A}^2 - \frac{1}{2}rq_A q_B - (a - bq_A - rq_B) \cdot q_A$$

$$= aq_A - \frac{1}{2}b{q_A}^2 - \frac{1}{2}rq_A q_B - aq_A + b{q_A}^2 + rq_A q_B$$

$$= \frac{1}{2}b{q_A}^2 + \frac{1}{2}rq_A q_B$$

$$= q_A \cdot \frac{1}{2} \cdot (bq_A + rq_B)$$

$$CS_B = aq_B - \frac{1}{2}b{q_B}^2 - \frac{1}{2}rq_A q_B - (a - bq_B - rq_A) \cdot q_B$$

$$= aq_B - \frac{1}{2}bq_B{}^2 - \frac{1}{2}rq_Aq_B - aq_B + bq_B{}^2 + rq_Aq_B$$

$$= \frac{1}{2}bq_B{}^2 + \frac{1}{2}rq_Aq_B$$

$$= q_B \cdot \frac{1}{2} \cdot (bq_B + rq_A)$$

From equations $\tau_A = a - bq_A - rq_B$ and $\tau_B = a - bq_B - rq_A$, we can infer $a - \tau_A = bq_A + rq_B$ and $a - \tau_B = bq_B + rq_A$. Thus, the above equations can be substituted as:

$$CS_A = q_A \cdot \frac{1}{2} \cdot (bq_A + rq_B) = \frac{1}{2} \cdot q_A \cdot (a - \tau_A)$$

$$CS_B = q_B \cdot \frac{1}{2} \cdot (bq_B + rq_A) = \frac{1}{2} \cdot q_B \cdot (a - \tau_B)$$

Appendix A.3 Derivations of disaster costs across three cases

Case I and III - Scenario 1 and Scenario 3 in Section 3.2.2.1, 3.2.2.3, 3.4.2.1.1 and 3.4.2.1.3

Substituting equation $I_{i1} = \frac{(\bar{K}_i + K_{i1})x(-1+\theta+\beta\theta)}{(x+\beta)\theta^2} - \bar{I}_i$ into the inside term of the disaster costs equations $E_{x_1}\,[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1})]^+$ and $E_{x_2}\,[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})]^+$, the results are shown as follows:

$$(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1}) = \frac{(\bar{K}_i + K_{i1})(x + x(-1+x_1-\beta)\theta + x_1\beta\theta)}{(x+\beta)\theta}$$

$$(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1}) = \frac{(\bar{K}_i + K_{i1})(\beta\theta - x(-1+\beta\theta))^2}{2(x+\beta)^2\theta^2}$$

Next, the expected value and indicator function in disaster costs functions are expressed as follows:

$$E_{x_1}\,\left[I \cdot \left(\frac{(\bar{K}_i + K_{i1})(x + x(-1+x_1-\beta)\theta + x_1\beta\theta)}{(x+\beta)\theta}\right) \cdot \left(\frac{(\bar{K}_i + K_{i1})(x + x(-1+x_1-\beta)\theta + x_1\beta\theta)}{(x+\beta)\theta}\right)\right]$$

$$E_{x_2}\,\left[I \cdot \left(\frac{(\bar{K}_i + K_{i1})(\beta\theta - x(-1+\beta\theta))^2}{2(x+\beta)^2\theta^2}\right) \cdot \left(\frac{(\bar{K}_i + K_{i1})(\beta\theta - x(-1+\beta\theta))^2}{2(x+\beta)^2\theta^2}\right)\right]$$

The indicator functions ensures that only positive terms included in calculation of expected disaster costs. The expectation is then computed as an integral over the ranges of $x_1 \sim [0,1]$ and $x_2 \sim [0, X]$. The results are as follows:

$$E_{x_1}\,[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1})]^+ = \frac{(\bar{K}_i + K_{i1})(x + x(-1 + x_2 - \beta)\theta + x_2\beta\theta)}{(x+\beta)\theta}$$

$$E_{x_2}\,[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})]^+ = \frac{(\bar{K}_i + K_{i1})x(1 + (-1 + x)\theta)^2}{2(x+\beta)^2\theta^2}$$

Case I and III - Scenario 2 in Section 3.2.2.2, 3.4.2.1.2 and 3.4.2.1.2

Following the same calculations above, the adaptation equation $I_{i1} = -\bar{I}_i + \frac{(\bar{K}_i + K_{i1})(-1+\theta)}{\theta^2}$ are substituted into the inside term of disaster cost functions and the results are given as:

$$(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1}) = \frac{(\bar{K}_i + K_{i1})(1 + (-1 + x_1)\theta)}{\theta}$$

$$(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1}) = \frac{(\bar{K}_i + K_{i1})(1 + (-1 + x_2)\theta)}{\theta}$$

The expected values with indicator functions are represented as:

$$E_{x_1}\,[I \cdot \left(\frac{(\bar{K}_i + K_{i1})(1 + (-1 + x_1)\theta)}{\theta}\right) \cdot \left(\frac{(\bar{K}_i + K_{i1})(1 + (-1 + x_1)\theta)}{\theta}\right)]$$

$$E_{x_2}\,[I \cdot \left(\frac{(\bar{K}_i + K_{i1})(1 + (-1 + x_2)\theta)}{\theta}\right) \cdot \left(\frac{(\bar{K}_i + K_{i1})(1 + (-1 + x_2)\theta)}{\theta}\right)]$$

By taking the integral with its respective ranges and the results are illustrated below:

$$E_{x_1}\,[(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1})]^+ = \frac{\bar{K}_i + K_{i1}}{2\theta^2}$$

$$E_{x_2}\,[(\bar{K}_i + K_{i1})x_2 - \theta(\bar{I}_i + I_{i1})]^+ = 0$$

Case I and III - Scenario 4 in Section 3.2.2.4, 3.4.2.1.4 and 3.4.2.1.4

By following the same processes with the above scenarios, the disaster cost functions are as follows:

$$(\bar{K}_i + K_{i1})x_1 - \theta(\bar{I}_i + I_{i1}) = \frac{(\bar{K}_i + K_{i1})(x - x\beta\theta + x_1\beta\theta)}{\beta\theta}$$

$$(\overline{K}_i + K_{i1})x_2 - \theta(\overline{I}_i + I_{i1}) = \frac{(\overline{K}_i+K_{i1})(x-x\beta\theta+x_2\beta\theta)}{\beta\theta}$$

The expected value and indicator functions are expressed as:

$$E_{x_1}\left[I \cdot \left(\frac{(\overline{K}_i+K_{i1})(x-x\beta\theta+x_1\beta\theta)}{\beta\theta}\right) \cdot \left(\frac{(\overline{K}_i+K_{i1})(x-x\beta\theta+x_1\beta\theta)}{\beta\theta}\right)\right]$$

$$E_{x_2}\left[I \cdot \left(\frac{(\overline{K}_i+K_{i1})(x-x\beta\theta+x_2\beta\theta)}{\beta\theta}\right) \cdot \left(\frac{(\overline{K}_i+K_{i1})(x-x\beta\theta+x_2\beta\theta)}{\beta\theta}\right)\right]$$

By taking integrals with respective ranges of x_1 and x_2, the results are shown as:

$$E_{x_1}\left[(\overline{K}_i + K_{i1})x_1 - \theta(\overline{I}_i + I_{i1})\right]^+ = 0$$

$$E_{x_2}\left[(\overline{K}_i + K_{i1})x_2 - \theta(\overline{I}_i + I_{i1})\right]^+ = \frac{(\overline{K}_i+K_{i1})x}{2\beta^2\theta^2}$$

Case II in Section 3.3.2

By following the similar calculations as above, the disaster cost functions are as follows:

$$\overline{K}_i \cdot x_1 - \theta \cdot \overline{I}_i = \frac{\overline{K}_i(1-\theta+x_1\theta)}{\theta}$$

$$(\overline{K}_i + K_{i1})x_2 - \theta(\overline{I}_i + I_{i1}) = \frac{(\overline{K}_i+K_{i2})(x-x\theta+x_2\theta)}{\theta}$$

The expected value with indicator functions are as follows:

$$E_{x_1}\left[I \cdot \left(\frac{\overline{K}_i(1-\theta+x_1\theta)}{\theta}\right) \cdot \left(\frac{\overline{K}_i(1-\theta+x_1\theta)}{\theta}\right)\right]$$

$$E_{x_2}\left[I \cdot \left(\frac{(\overline{K}_i+K_{i2})(x-x\theta+x_2\theta)}{\theta}\right) \cdot \left(\frac{(\overline{K}_i+K_{i2})(x-x\theta+x_2\theta)}{\theta}\right)\right]$$

Taking integrals with respect to x_1 and x_2, the results are given by:

$$E_{x_1}\left[\overline{K}_i \cdot x_1 - \theta \cdot \overline{I}_i\right]^+ = \frac{\overline{K}_i}{2\theta^2}$$

$$E_{x_2}\left[(\overline{K}_i + K_{i2})x_2 - \theta(\overline{I}_i + I_{i2})\right]^+ = \frac{(\overline{K}_i+K_{i2})x}{2\theta^2}$$

Appendix B

Appendix B.1 Port-specific social welfare equations

Case I-Scenario 1

$$SW_i = \frac{1}{2}q_{i1}(a-\tau_{i1}) + \tau_{i1}q_{i1} - \frac{(\overline{\mathrm{K}}_i + K_{i1})(\beta\theta - x(-1+\beta\theta))^2}{2(x+\beta)^2\theta^2} - c_k K_{i1} - (\frac{(\overline{\mathrm{K}}_{i1} + K_{i1})x(-1+\theta+\beta\theta)}{(x+\beta)\theta^2} - \overline{\mathrm{I}}_i)) + \beta \cdot (\frac{1}{2}q_{i2}(a-\tau_{i2}) + \tau_{i2}q_{i2} - \frac{(\overline{\mathrm{K}}_i + K_{i2})x(1+(-1+x)\theta)^2}{2(x+\beta)^2\theta^2}))$$

Case I-Scenario 2

$$SW_i = \frac{1}{2}q_{i1}(a-\tau_{i1}) + \tau_{i1}q_{i1} - \frac{\overline{\mathrm{K}}_i + K_{i1}}{2\theta^2} - c_k K_{i1} - (\frac{(\overline{\mathrm{K}}_{i1} + K_{i1})(-1+\theta)}{\theta^2} - \overline{\mathrm{I}}_i)) + \beta \cdot (\frac{1}{2}q_{i2}(a-\tau_{i2}) + \tau_{i2}q_{i2} - 0))$$

Case I-Scenario 3

$$SW_i = \frac{1}{2}q_{i1}(a-\tau_{i1}) + \tau_{i1}q_{i1} - \frac{(\overline{\mathrm{K}}_i + K_{i1})(\beta\theta - x(-1+\beta\theta))^2}{2(x+\beta)^2\theta^2} - c_k K_{i1} - (\frac{(\overline{\mathrm{K}}_{i1} + K_{i1})x(-1+\theta+\beta\theta)}{(x+\beta)\theta^2} - \overline{\mathrm{I}}_i)) + \beta \cdot (\frac{1}{2}q_{i2}(a-\tau_{i2}) + \tau_{i2}q_{i2} - \frac{(\overline{\mathrm{K}}_i + K_{i2})x(1+(-1+x)\theta)^2}{2(x+\beta)^2\theta^2}))$$

Case I-Scenario 4

$$SW_i = \frac{1}{2}q_{i1}(a-\tau_{i1}) + \tau_{i1}q_{i1} - 0 - c_k K_{i1} - (\frac{(\overline{\mathrm{K}}_i + K_{i1})x(-1+\beta\theta)}{\beta\theta^2} - \overline{\mathrm{I}}_i)) + \beta \cdot (\frac{1}{2}q_{i2}(a - \tau_{i2}) + \tau_{i2}q_{i2} - \frac{(\overline{\mathrm{K}}_i + K_{i1})x}{2\beta^2\theta^2}))$$

Case II

$$SW_i = \frac{1}{2}q_{i1}(a-\tau_{i1}) + \tau_{i1}q_{i1} - \frac{\overline{\mathrm{K}}_i}{2\theta^2} + \beta\cdot(\frac{1}{2}q_{i2}(a-\tau_{i2}) + \tau_{i2}q_{i2} - \frac{x(\overline{\mathrm{K}}_i + K_{i2})}{2\theta^2} - c_k K_{i2} - (\frac{(\overline{\mathrm{K}}_i + K_{i2})x(\theta-1)}{\theta^2} - \overline{\mathrm{I}}_i))$$

Case III-Scenario 1

The social welfare functions for both ports A and B choose capacity binding constraints and A chooses non-binding constraints under period 2 remain the same, so the functions are illustrated under different ranges only.

$$SW_A = \frac{1}{2}q_{A1}(a-\tau_{\mathrm{A1}}) + \tau_{\mathrm{A}}q_{\mathrm{A1}} - \frac{(\overline{\mathrm{K}}_A + K_{\mathrm{A1}})(\beta\theta - x(-1+\beta\theta))^2}{2(x+\beta)^2\theta^2} - c_k K_{\mathrm{A1}} - (\frac{(\overline{\mathrm{K}}_{\mathrm{A1}} + K_{\mathrm{A}})x(-1+\theta+\beta\theta)}{(x+\beta)\theta^2} - \overline{\mathrm{I}}_A)) + \beta\cdot(\frac{1}{2}q_{\mathrm{A2}}(a-\tau_{\mathrm{A2}}) + \tau_{\mathrm{A2}}q_{\mathrm{A2}} - \frac{(\overline{\mathrm{K}}_A + K_{\mathrm{A2}})x(1+(-1+x)\theta)^2}{2(x+\beta)^2\theta^2}))$$

$$SW_B = \frac{1}{2}q_{B1}(a-\tau_{\mathrm{B1}}) + \tau_{\mathrm{B1}}q_{\mathrm{B1}} - \frac{\overline{\mathrm{K}}_B}{2\theta^2} + \beta\cdot(\frac{1}{2}q_{\mathrm{B2}}(a-\tau_{\mathrm{B2}}) + \tau_{\mathrm{B2}}q_{\mathrm{B2}} - \frac{x(\overline{\mathrm{K}}_B + K_{\mathrm{B2}})}{2\theta^2} - c_k K_{\mathrm{B2}} - (\frac{(\overline{\mathrm{K}}_B + K_{\mathrm{B2}})x(\theta-1)}{\theta^2} - \overline{\mathrm{I}}_B))$$

Case III-Scenario 2

$$SW_A = \frac{1}{2}q_{A1}(a-\tau_{\mathrm{A1}}) + \tau_{\mathrm{A1}}q_{\mathrm{A1}} - \frac{\overline{\mathrm{K}}_A + K_{\mathrm{A1}}}{2\theta^2} - c_k K_{\mathrm{A1}} - (\frac{(\overline{\mathrm{K}}_{\mathrm{A1}} + K_{\mathrm{A1}})(-1+\theta)}{\theta^2} - \overline{\mathrm{I}}_A)) + \beta\cdot(\frac{1}{2}q_{\mathrm{A2}}(a-\tau_{\mathrm{A2}}) + \tau_{\mathrm{A2}}q_{\mathrm{A2}} - 0))$$

$$SW_B = \frac{1}{2}q_{B1}(a-\tau_{\mathrm{B1}}) + \tau_{\mathrm{B1}}q_{\mathrm{B1}} - \frac{\overline{\mathrm{K}}_B}{2\theta^2} + \beta\cdot(\frac{1}{2}q_{\mathrm{B2}}(a-\tau_{\mathrm{B2}}) + \tau_{\mathrm{B2}}q_{\mathrm{B2}} - \frac{x(\overline{\mathrm{K}}_B + K_{\mathrm{B2}})}{2\theta^2} - c_k K_{\mathrm{B2}} - (\frac{(\overline{\mathrm{K}}_B + K_{\mathrm{B2}})x(\theta-1)}{\theta^2} - \overline{\mathrm{I}}_B))$$

Case III-Scenario 3

$$SW_A = \frac{1}{2} q_{A1}(a - \tau_{A_1}) + \tau_A q_{A1} - \frac{(\overline{K}_A + K_{A1})(\beta\theta - x(-1 + \beta\theta))^2}{2(x + \beta)^2\theta^2} - c_k K_{A1} - (\frac{(\overline{K}_{A1} + K_A)x(-1 + \theta + \beta\theta)}{(x + \beta)\theta^2} - \overline{I}_A)) + \beta \cdot (\frac{1}{2} q_{A2}(a - \tau_{A2}) + \tau_{A2} q_{A2} - \frac{(\overline{K}_A + K_{A2})x(1 + (-1 + x)\theta)^2}{2(x + \beta)^2\theta^2}))$$

$$SW_B = \frac{1}{2} q_{B1}(a - \tau_{B1}) + \tau_{B1} q_{B1} - \frac{\overline{K}_B}{2\theta^2} + \beta \cdot (\frac{1}{2} q_{B2}(a - \tau_{B2}) + \tau_{B2} q_{B2} - \frac{x(\overline{K}_B + K_{B2})}{2\theta^2} - c_k K_{B2} - (\frac{(\overline{K}_B + K_{B2})x(\theta - 1)}{\theta^2} - \overline{I}_B))$$

Case III-Scenario 4

$$SW_A = \frac{1}{2} q_{A_1}(a - \tau_{A1}) + \tau_{A1} q_{A1} - 0 - c_k K_{A1} - (\frac{(\overline{K}_A + K_{A1})x(-1 + \beta\theta)}{\beta\theta^2} - \overline{I}_A)) + \beta \cdot (\frac{1}{2} q_{A2}(a - \tau_{A2}) + \tau_{A2} q_{A2} - \frac{(\overline{K}_A + K_{A1})x}{2\beta^2\theta^2}))$$

$$SW_B = \frac{1}{2} q_{B1}(a - \tau_{B1}) + \tau_{B1} q_{B1} - \frac{\overline{K}_B}{2\theta^2} + \beta \cdot (\frac{1}{2} q_{B2}(a - \tau_{B2}) + \tau_{B2} q_{B2} - \frac{x(\overline{K}_B + K_{B2})}{2\theta^2} - c_k K_{B2} - (\frac{(\overline{K}_B + K_{B2})x(\theta - 1)}{\theta^2} - \overline{I}_B))$$

Appendix B.2 Detailed calculations of optimal I_i and $\overline{I}_i$ in Section 3.3.2

The optimal adaptation function for Case II is defined as follows:

$$\min_{\{I_{i2}\}} E_{x_2}\ [(\overline{K}_i + K_{i2})x_2 - \theta(\overline{I}_i + I_{i2})]^+ + I_{i2}$$

By following the same processes as in Case I and incorporating the indicator function, the equation becomes:

$$\frac{\partial E_{x_2}\left[I\left((\overline{K}_i + K_{i2})x_2 - \theta(\overline{I}_i + I_{i2})\right) * \left((\overline{K}_i + K_{i2})x_2 - \theta(\overline{I}_i + I_{i2})\right)\right]}{\partial I_{i2}} + 1 = 0$$

$$E_{x_2}\left[I\left((\bar{K}_i + K_{i2})x_2 - \theta(\bar{I}_i + I_{i2})\right) \cdot (-\theta)\right] + 1 = 0$$

$$E_{x_2}\left[I\left((\bar{K}_i + K_{i2})x_2 - \theta(\bar{I}_i + I_{i2})\right)\right] = \frac{1}{\theta}$$

$$P_{x_2}\left(\frac{\theta(\bar{I}_i + I_{i2})}{\bar{K}_i + K_{i2}}\right) = 1 - \frac{1}{\theta}$$

To calculate the disaster costs for period 1, the initial adaptation endowment, $\bar{I}_i$, is first determined by minimizing the associated costs under assumption that $\bar{I}_i$ is optimal for the initial capacity endowment, $\bar{K}_i$. The corresponding objective function is expressed as:

$$\min_{\{\bar{I}_i\}} E_{x_0}\,[\bar{K}_i \cdot x_0 - \theta \cdot \bar{I}_i]^+ + \bar{I}_i$$

$$\frac{\partial E_{x_0}\,[\bar{K}_i \cdot x_0 - \theta \cdot \bar{I}_i]^+ + \bar{I}_i}{\partial \bar{I}_i} = 0$$

$$\frac{\partial E_{x_0}[I(\bar{K}_i \cdot x_0 - \theta \cdot \bar{I}_i) * (\bar{K}_i \cdot x_0 - \theta \cdot \bar{I}_i)] + \bar{I}_i}{\partial \bar{I}_i} = 0$$

$$-\theta \cdot P(\bar{K}_i \cdot x_0 - \theta \cdot \bar{I}_i \geq 0) + 1 = 0$$

$$F_{x_0}\left(\frac{\theta \cdot \bar{I}_i}{\bar{K}_i}\right) = 1 - \frac{1}{\theta}$$

$$\bar{I}_i = \tfrac{1}{\theta} \cdot \bar{K}_i \cdot (1 - \theta)$$