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Government persuasion strategies for transport infrastructure adaptation: Spillover effects and social welfare impacts

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ABSTRACT

This paper explores the government's strategies to persuade multiple transport facility operators to undertake adaptation projects, particularly within the Asian doctrine governance regime, where the government exerts significant influence over facility operations. We develop a Bayesian persuasion model to analyze these strategies, focusing on the spillover effects among operators' projects and their externalities (both positive and negative) on social welfare. Our findings suggest that a straightforward signaling strategy, which directly advises operators on whether to invest, can effectively convey disaster information. When there are no spillover effects and the adaptation projects positively impact social welfare, the government should fully disclose disaster information and persuade operators based on their willingness to invest. However, higher adaptation costs or larger spillover effects complicate the government's persuasion efforts. To demonstrate the practical value of our theoretical framework, we apply our Bayesian persuasion model to the case of port adaptation in the Greater Bay Area in China. The model calibration results indicate that when operators act independently, larger spillover effects can lead to either lower or higher social welfare, depending on whether the adaptation projects have positive or negative impacts, respectively. When adaptation projects positively affect social welfare, operators' alliance strategies of joint adaptation investment or resource sharing enhance social welfare. If spillover effects exist among operators, a benefit distribution scheme based on the Shapley value can maintain stability within the grand coalition of all operators. Finally, increasing adaptation costs have uneven impacts on different operators, with those facing the highest costs being more likely to be excluded from the government's persuasion efforts.

1. Introduction

Adapting transport infrastructure, such as navigational lanes, seaports, and airports, to climate change is crucial due to the increasing frequency and severity of extreme weather events, rising sea levels, and temperature fluctuations. These changes pose significant risks to the integrity and functionality of critical transport systems. For instance, rising sea levels threaten coastal infrastructure, while more intense precipitation and heat waves can damage roads and bridges, leading to costly repairs and disruptions. Investing in climate-resilient infrastructure not only mitigates these risks but also ensures the continuity of essential services, supports economic stability, and enhances social welfare. By proactively adapting transport infrastructure, we can safeguard against future

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climate impacts, promote sustainable development, and protect the livelihoods of communities dependent on reliable transportation networks.

Given the substantial financial commitments required for such infrastructure projects, it is crucial to attract multiple stakeholders to participate in these investments. Joint investments among ports within a specific region, for example, can distribute the financial burden and enhance regional connectivity. Encouraging operators to engage in adaptation investments not only benefits the operators themselves but also has significant positive impacts on social welfare. One effective strategy to influence operators' investment behavior is through the use of propaganda as a "soft incentive strategy." This approach has several advantages, including lower costs and the ability to spread demonstrative effects among operators. The content of propaganda or media can be carefully controlled to convey disaster information. For example, if the disaster information is favorable to the government, it tends to be fully disclosed. Conversely, when the information is unfavorable, the government may obscure or present inaccuracies. While the government can control the content of propaganda, it does not directly influence operators' decisions. Instead, it indirectly affects their decisions by altering their beliefs about disaster information.

Due to its extensive scientific resources, the government holds a significant advantage in accessing general disaster information, which it aims to share with transport facility operators to encourage adaptation investments. This information encompasses potential severe impacts on transport facilities, such as extreme weather events, flooding, and earthquakes. For instance, the National Disaster Reduction Center of China (NDRCC) publishes various disaster information on its website, allowing users to search through its online system.[1]Similarly, the Ministry of Emergency Management of China releases monthly data and analyses on national disasters,[2] while the National Earthquake Prevention and Disaster Reduction Public Service Platform of China provides real-time global earthquake information.[3] Despite the government's superior resources and understanding of potential future disasters, it cannot predict the exact occurrence and intensity of these events with certainty. This uncertainty means that the information provided may not always be entirely accurate and could potentially mislead operators.[4] Consequently, the government exercises caution in disseminating this information.

In practice, governments and non-profit organizations frequently organize forums, conferences, and workshops to share expert opinions on the potential damage and resilience of various types of transport infrastructure. For instance, the Chinese government designates May 12 each year as the "National Day for Disaster Reduction," during which nationwide activities are held to promote disaster prevention knowledge to the public, enterprises, and social organizations. A joint report by the World Economic Forum and PwC (2023) indicates that the business sectors, including the transport industry, are continually updating their understanding of climate change-related disaster risks and adjusting their adaptation measures accordingly. Transport facility operators can leverage government-provided disaster information to inform their adaptation-related decisions. For example, the Singapore government has collaborated with Changi Airport to jointly develop a climate change adaptation strategy (ACI, 2018). The UNCTAD has established databases and knowledge transfer platforms for seaports worldwide to share disaster risk information and adaptation strategies. Similarly, the European Commission and the European Environment Agency (EEA) have created the Climate ADAPT platform to provide guidelines for seaport adaptation. In our paper, we explore whether the government should use this information to persuade operators to invest in adaptation measures. If so, we examine the extent to which information should be disclosed—whether fully or partially.

When managing multiple operators, the government must account for the interactions between them. To effectively encourage operators to participate in adaptation projects, several key issues need to be addressed. Firstly, the spillover effects among different operators' projects can create economies of scale, where the adaptation efforts of one operator benefit neighboring operators. For instance, the Delta Programme in The Netherlands is one of the world's largest adaptation projects addressing sea level rise (SLR). Meyer (2009, Page 443) noted that "A number of smaller ports in the delta-area (Vlissingen, Terneuzen, Gent, Dordrecht), are operating as one large port-cluster. Port-companies settled in Rotterdam have also terminals in Antwerp, and vice versa. Both ports and the smaller ports are connected which each other by navigation canals, pipelines, roads and railroads. Together they are the largest and most important port-cluster of Europe. Considering the common economic interest, and considering the common interest of The Netherlands and Belgium regarding flood-defence and improving environmental qualities, a common, cross-national approach for the South-west delta is inevitable." The Delta projects in a port's area can contribute to other ports in terms of flood defense, which can be considered a spillover effect in our study.

Secondly, operators' investments in transport infrastructure can generate positive externalities for social welfare by enhancing regional logistics and stimulating economic growth. However, these improvements can also lead to negative externalities, such as increased congestion, which may adversely affect social welfare. Numerous studies have highlighted the positive externalities of transport adaptation projects on social welfare, particularly their role in disaster prevention for cities and coastal areas. For instance, the Port of Rotterdam and the Port of Amsterdam in The Netherlands have developed extensive adaptation projects under the Delta Programme to mitigate potential damage from SLR. This initiative not only benefits these ports but also protects the coastal cities and

[1] https://www.ndrcc.org.cn/sjcx/index.jhtml

[2] https://www.119.gov.cn/qmxfgk/sjtj/index.shtml

[3] http://www.earthquake.ac.cn/shikuang/shikuangSh

[4] Operators possess certain advantages over the government when it comes to specific disaster information, such as the precise damages to their own facilities. However, the government holds a clear advantage in general disaster information due to its extensive scientific resources and investigative capabilities. In our paper, we focus on the government's sharing of this general disaster information with operators, rather than the specific damages to individual facilities.

regions of The Netherlands from potential flooding. As Meyer (2009) noted, the Delta Works closed all estuary sea gates with dikes, except those providing access to the ports of Amsterdam and Antwerp. This example illustrates the dual function of port adaptation projects in enhancing port operations and preventing city disasters, with the latter being a significant positive externality. Conversely, studies on the negative externalities of transport adaptation projects are limited. However, if such a project leads to increased traffic in a region, the resulting congestion near the transport facility can be considered a negative externality. Additionally, the substantial investments required for transport adaptation projects can place a heavy burden on the government's fiscal budget. Many governments provide significant subsidies for these projects, which may divert funds from other social services.

Lastly, the potential for operators to form alliances can significantly impact the effectiveness of the government's persuasion strategies. Here, "alliance" refers to groups of operators who cooperate on adaptation projects, engage in joint investments, or share adaptation resources. Such collaboration benefits all members of the operator group. For example, nearby transport facilities, such as ports or airports, can jointly invest in costly adaptation projects. They can also share resources during disasters. If one port (or airport) is less affected or has more resources, it can assist those that are more impacted. For instance, before a hurricane, less adapted ports might transfer ships to better-adapted ports with reserve capacity. The more adapted ports can also share evacuation, drainage, and maintenance equipment and personnel to help the more damaged ports recover and resume operations quickly. This resource sharing enhances inter-port cooperation, leading to operator alliances. In the aviation sector, airport-to-airport mutual aid programs have been established in the US, where several airports have agreements to provide expert assistance and material support to those affected by natural disasters. The Southeast Airports Disaster Operations Group (SADOG), founded in 2004 under the leadership of Savannah-Hilton Head International Airport and Orlando International Airport, aims to organize member airports to provide mutual aid for hurricane recovery. More than 20 airports have joined SADOG, offering mutual aid for hurricane relief (Seddighi and Baharmand, 2020; Alam and Ray-Bennett, 2021). These considerations highlight the complexity of designing effective strategies to encourage adaptation investments in transport infrastructure. The government's role in managing these investments and influencing operators' decisions is critical for maximizing both economic and social benefits.

In our paper, a transport facility refers to a transport terminal that serves as a transit center, providing services between one or multiple transportation modes. This includes port terminals (seaports or river ports), airport terminals, railway stations, and road transport stations. A transport facility operator is an entity responsible for managing the operations of these facilities. This can be a terminal operator or a station operator (for railway or road transport stations). Competing transport facility operators are those whose services overlap in their hinterlands, leading them to vie for customers within a given region. For example, two terminal operators located in nearby ports may compete with each other in providing cargo handling services.

This study seeks to address several critical questions concerning the government's role in encouraging multiple operators to invest in the adaptation of transport infrastructure. Firstly, how can the government effectively motivate multiple operators to participate in these adaptation investments? Additionally, what are the impacts of spillover effects among operators' adaptation projects on the design of the government's persuasion strategies? Secondly, we examine the effects of both positive and negative externalities of operators' adaptation projects on the performance of these government strategies. Lastly, we investigate how operators' alliance strategies influence the effectiveness of the government's persuasion efforts.

It is important to note that governments in different regions exert varying degrees of influence on transport facility construction. Lee and Flynn (2011) and Lee and Lam (2017) identify three principles that guide government port policies: the Anglo-Saxon Doctrine, the Continental (European) Doctrine, and the Asian Doctrine. The Anglo-Saxon Doctrine emphasizes that ports should be financially self-sufficient and profitable. In contrast, the Continental Doctrine views ports as part of social infrastructure, not necessarily focused on profitability. The Asian Doctrine, similar to the Continental Doctrine, involves significant central government participation in port planning, investment, pricing, and governance. In our paper, we explore how the government aims to influence operators' investment decisions indirectly by persuading them with disaster information. Our model is particularly suited to ports operating under the Asian Doctrine governance regime, and we will apply our theoretical framework to a Chinese case in Section 4.

Our research makes significant contributions in both theoretical modeling and practical applications. In terms of modeling, we develop a framework for designing government persuasion strategies to encourage multiple operators to engage in transport adaptation. Our model specifically examines the spillover effects among adaptation projects and their externalities (both positive and negative) on social welfare. Additionally, we analyze the impacts of operators' alliance strategies on the government's adaptation persuasion efforts, addressing issues not previously considered in the transport adaptation literature. In terms of applications and policy implications, we apply our theoretical model to the case of port adaptation in the Greater Bay Area (GBA) of China. The outcomes of our model calibration provide novel and valuable policy insights. For instance, we find that in the absence of spillover effects and when adaptation projects have positive externalities on social welfare, the government should fully disclose disaster information to operators and persuade them based on their willingness to invest. However, higher adaptation costs or larger spillover effects complicate the government's persuasion efforts. When operators act independently, larger spillover effects can lead to either lower or higher social welfare, depending on whether the adaptation projects have positive or negative impacts, respectively. Moreover, when adaptation projects have positive externalities on social welfare, operators' alliance strategies not only benefit themselves but also enhance social welfare. If spillover effects exist among operators, a benefit distribution scheme based on the Shapley value can maintain stability within the grand coalition of all operators. Finally, increasing adaptation costs have uneven impacts on different operators, with those facing the highest costs being more likely to be excluded from the government's persuasion efforts.

The rest of this paper is organized as follows. Section 2 reviews the related literature. Section 3 describes the economic model under different cases. Section 4 makes the model calibrations using the data from a real case. Section 5 concludes this study.

2. Literature review

Our study relates two streams of literature: transport adaptation and Byesian persuasion.

Research on transport adaptation can be categorized based on methodology. Some studies employ empirical methods, including case studies, surveys, and comparative analyses, to examine facility adaptation across various transport sectors. These sectors include seaports (e.g., Becker et al., 2012, 2013; Yang et al., 2018; Wang and Ng, 2022; Lin et al., 2020; Ng et al., 2013; Panahi et al., 2020; Wang et al., 2024), urban transport (e.g., Herrera and MacAskill, 2021; Vajjarapu and Verma, 2021), and general transportation or logistics (e.g., Griese et al., 2021; Melkonyan et al., 2024). Other studies develop economic models to investigate various aspects of transport adaptation, as summarized in Table 1. For a comprehensive overview, readers can refer to the review paper by Randrianarisoa et al. (2020).

The second stream of literature relevant to our work is the theory and application of Bayesian persuasion. Kamenica and Gentzkow (2011) first introduced the Bayesian persuasion concept and analysis framework. Over the following decades, the theory has evolved to address various orientations, including the Bayesian persuasion problem between a sender and multiple receivers (e.g., Bergemann and Morris, 2019; Arieli and Babichenko, 2019), persuading a privately informed receiver (Candogan, 2022), persuasion in networks (Candogan, 2022), Bayesian persuasion with cheap talk (Jain, 2018), and scenarios where the receiver's payoff depends on the posterior mean of the sender's signal (Candogan, 2020). For further reading, review papers by Kamenica (2019) and Gentzkow (2019) are recommended. In terms of applications, Bayesian persuasion has been extended to various fields, including operations management (Candogan, 2020), marketing (Drakopoulos et al., 2021; Shi et al., 2022), disaster management (Alizamir et al., 2020), crowdsourcing (Papanastasiou et al., 2018), spatial resource management (Yang et al., 2019), social services (Anunrojwong et al., 2023), and finance (Szydlowski, 2021). Dughmi (2017) provides a comprehensive review of these applications.

Compared to existing transport adaptation studies, our paper models the government's persuasion of multiple operators who experience positive spillover effects from each other. We also consider the potential positive or negative externalities of transport adaptation projects on social welfare. Furthermore, our model calibration not only demonstrates the applicability of our model but also offers valuable insights into transport adaptation that have not been previously explored in the literature.

3. Models

3.1. Settings

In a given region, there are N transport facility operators (hereinafter referred to as operators) who are encouraged to invest in adaptation projects. Each operator's adaptation decision is represented by a binary variable, i.e., $a_i = \{0, 1\}$, where 1 indicates that the operator invests in adaptation, and 0 indicates that it does not. Let the adaptation cost for operator i be r_i, with $r_1 < r_2 < \cdots < r_n$. Both the

Table 1
Comparisons on the literature of transport adaptation using economic models.

Literature	Government's strategies	Single/multiple operators and their relationship	Period	Externality of the adaptation on social welfare	Information
Gong et al. (2020)	/	Single	One	/	Full
Jiang et al. (2020)	/	Multiple competing seaports	One	Positive	Full
Randrianarisoa and Zhang (2019)	/	Two competing seaports	Two	/	Information update
Wang and Zhang (2018), Wang et al. (2020)	/	Two competing seaports	One	/	Ambiguity
Xia and Lindsey (2021)	/	Single	Two	/	Full
Xiao et al. (2015)	/	Single	Two	/	Information update
Yang et al. (2022)	/	Single	One	/	Asymmetric
Zheng et al. (2021a)	Minimum requirement and subsidy	Multiple competing seaports with adaptation spillover effect	One	/	Ambiguity
Zheng et al. (2021b)	Minimum requirement and subsidy	Two competing seaports sharing adaptation resources	One	/	Full
Zheng et al. (2022a)	Subsidy	Two competing transport terminals	One	/	Incomplete and ambiguity
Zheng et al. (2022b)	Subsidy and information publicity	Two competing seaports	One	/	Asymmetric
Zheng et al. (2023)	Subsidy and persuasion	Multiple competing seaports with adaptation spillover effect	One	/	Incomplete
Wu et al. (2024)	Subsidy	A seaport and a dry port with competition	One	/	Full
Zheng et al., 2024	Subsidy	Two competing transport terminals	Infinite	/	Full
This paper	Persuasion	Multiple transport terminals with adaptation spillover effect	One	Positive or negative	Incomplete

government and the operators share a common prior belief about the probability of a disaster occurring, denoted as μ_0. The benefit for operator i from adaptation is defined as:

$$U_i = \omega F(a_i + \beta a_j) - a_i r_i \tag{1}$$

where $\omega = 1$ (or $\omega = 0$, respectively) indicates the occurrence of the disaster (or no disaster, respectively). $F(.)$ is the operator's utility after its adaptation investment, with $F' > 0$, $F'' < 0$ and $F(0) = 0$. The operator's utility from its adaptation projects is derived from the reduction in losses during a disaster. When no disaster occurs, the operator incurs no losses and, consequently, no need for rescue or loss reduction, regardless of whether it has undertaken adaptation projects. However, when a disaster does occur, an operator with adaptation projects in place can reduce its losses to a certain extent, thereby achieving some level of loss reduction. Conversely, an operator without adaptation projects will experience no loss reduction. In order to simplify the analysis, we assume that the government has precise knowledge of disaster occurrences, i.e., knowing whether $\omega = 1$ or $\omega = 0$ exactly, while the operators are only aware of the probability of such events, i.e., $prob(\omega = 1)$. The key point here is the information asymmetry between the government and the operators, which significantly influences the actions of both parties. $\beta \in [0, 1)$ is a parameter reflecting the spillover effect from operator j's adaptation investment. The government's objective is to maximize social welfare, which is influenced by the externalities of the operators' adaptation projects. The social welfare function is:

$$SW = \sum_{i=1}^{N} \left[\omega F\left(a_i + \sum_{i \neq i}^{N} \beta a_j \right) - a_i r_i \right] + \omega k G\left(\sum_{i=1}^{N} a_i \right) \tag{2}$$

where $G(.)$ is used to reflect the externality from the operators' adaptation and $k = \{-1, 1\}$ is used to present its negative or positive effect to the social welfare. As mentioned in the introduction, the operators' adaptation may lead to more social welfare improvement such as environmental protection and further economy development, but sometimes the negative impacts, i.e., more congestion from more traffic. Here $G' > 0$. If $k = 1$, it indicates that the total externality from the operators' adaptation investment is positive. If $k = -1$, it indicates that the total externality from the operators' adaptation investment is negative.

We assume that all facilities' adaptation projects have identical externalities on social welfare, with their asymmetry arising solely from differences in adaptation costs. This assumption is reasonable when these facilities are located nearby and their adaptation projects contribute similarly to a given region. For example, the adaptation projects of Hong Kong Port and Shenzhen Port both serve to prevent SLR flooding in their respective cities. However, due to varying labor costs, their adaptation expenses differ.

3.2. Signalling mechanism

In our setting, the government has more precise information about the disaster and knows the real value of ω. The challenge is to convey this information to the operators, who may not fully trust the government's signals due to differing objectives. The operators update their beliefs using Bayes' law based on the signals received from the government. This scenario presents a Bayesian persuasion problem, where the government designs a signalling strategy to share disaster information with the operators. Formally, a signalling strategy comprises n finite sets $\{\Theta_i\}_{i=1,\cdots n}$ where Θ_i is the signal set to operator i, and a mapping $\phi: \Omega \rightarrow \Delta(\Theta_1 \times \Theta_2 \times \cdots \times \Theta_n)$. Here $\Omega = \{0, 1\}$ is the state space which indicates the occurrence of the disaster. The government sends a signal profile $\theta = (\theta_1, \theta_2, \cdots \theta_n)$ to the operators. After receiving the signals (with the corresponding conditional probability $\varphi(\theta|\omega)$), operator i updates its belief on the disaster occurrence probability based on the following Bayesian law:

$$\rho(w = 1|\theta) = \frac{\mu_0 \varphi(\theta|w = 1)}{\mu_0 \varphi(\theta|w = 1) + (1 - \mu_0)\varphi(\theta|w = 0)} \tag{3}$$

We assume that the signals received by operators are not shared among them. Technically, the government's signals could be either private or public (Arieli and Babichenko, 2019). Private signals may differ for each operator, assuming that operators do not communicate or share their signals with each other. Public signals, on the other hand, mean that all operators receive the same information. Although in some cases the government's signals should be public, there are technical challenges that make the analysis of public signaling complex. This complexity arises from the failure of the revelation principle argument, which means it is no longer sufficient to optimize only over straightforward and public mechanisms (Kamenica and Gentzkow, 2011; Bergemann and Morris, 2019). Therefore, our paper primarily focuses on private signals. While the lack of discussion on public signals may lead to incomplete investigations of the government's possible persuasion strategies, our analysis still provides a useful benchmark on related issues.

The game structure between the government and the operators unfolds in three stages:

Stage 1: The government designs the persuasion strategy before the disaster occurs.
Stage 2: Based on the signals from the government, the operators update their beliefs and make adaptation investment decisions simultaneously.
Stage 3: The disaster occurs.

3.3. Government's strategy design

3.3.1. Straightforward persuasion strategy

Suppose operator i's best response strategy after receiving signal θ_i is $g_i(\theta_i)$. Given that the state ω is binary, the government's signals can be simplified to two forms: IN (invest) or NO (not invest). The government sends these recommendations based on the disaster information it possesses. Following Kamenica and Gentzkow (2011) and Arieli and Babichenko (2019), we define a straightforward signaling strategy as one where operator i's best response is to follow the government's signal.

Definition 1. *A signalling strategy is straightforward if operator i's best response strategy is $g_i(\theta_i) = \theta_i$ when the government's signal $\theta_i = \{Invest, Not\}$.*

A straightforward persuasion strategy involves the government directly advising operators on whether to invest in adaptation projects. This approach is grounded in the "revelation principle," which posits that the information designer (in this case, the government) issues only "action recommendations that are obeyed" (Bergemann and Morris, 2019). Bergemann and Morris (2019) argue that it is sufficient to focus on a set of signals that correspond to the actions to be taken by the agents (the operators, in this context). Consequently, the government's "direct recommendations" are followed because they meet the "obedience" conditions.

3.3.2. Government's problem

The optimal straightforward strategy must be persuasive, meaning it is in the operators' best interest to follow the government's recommendations. This requires that each operator finds it beneficial to follow the recommendation, given that the other operator does the same. In our case, a straightforward signalling strategy means that the government sends its signals to the operators (maybe differently) to directly recommend them to make the adaptation investment or not. Meanwhile, the operators follow the government's recommendation. Let $\mathbb{Z} = \{1, 2, \cdots N\}$ be the set of operators and $S \subseteq \mathbb{Z}$ be the set of the operators who receive the signals. φ_ω^S is the probability that all operators in the set S receive the same signal when the state is ω. In a single instance, the government's recommendation can only take a binary form, i.e., 0 or 1 (investing or not investing). However, in a multi-instance scenario, we use probability to express the intensity of the government's recommendation or the frequency of its investment recommendations. Based on this definition, the government's strategy design can be formulated as an optimization problem[5]:

$$\begin{aligned} &\max \mu_0 \sum_{S \subseteq N} \varphi_0^S \left(-\sum_{i \in S} r_i \right) + (1-\mu_0) \sum_{S \subseteq N} \varphi_1^S [|S|(F(1 + (|S|-1)\beta) \\ &+ (|N| - |S|)F(|S|\beta) - \sum_{i \in S} r_i + kG(|S|)] \end{aligned} \tag{4a}$$

s.t.

$$\begin{aligned} &\mu_0 \sum_{S \subseteq N, i \in S} \varphi_0^S(-r_i) + (1-\mu_0)[\sum_{S \subseteq N, i \in S} \varphi_1^S (F(1 + (|S|-1)\beta) - r_i) + \\ &\sum_{S \subseteq N, i \notin S} \varphi_1^S F(|S|\beta)] \geq (1-\mu_0)[\sum_{S \subseteq N, i \in S} \varphi_1^S F((|S|-1)\beta) + \sum_{S \subseteq N, i \notin S} \varphi_1^S F(|S|\beta)], \forall i \end{aligned} \tag{4b}$$

$$\begin{aligned} &\mu_0 \sum_{S \subseteq N, i \notin S} \varphi_0^S(-r_i) + (1-\mu_0)[\sum_{S \subseteq N, i \in S} \varphi_1^S F((|S|-1)\beta) + \sum_{S \subseteq N, i \notin S} \varphi_1^S F(1 + |S|\beta) - r_i] \\ &\leq (1-\mu_0)[\sum_{S \subseteq N, i \in S} \varphi_1^S F((|S|-1)\beta) + \sum_{S \subseteq N, i \notin S} \varphi_1^S F(|S|\beta)], \forall i \end{aligned} \tag{4c}$$

$$\sum_{S \subseteq N} \varphi_i^S = 1, \forall i = 0, 1 \tag{4d}$$

$$\varphi_i^S \geq 0, \forall i = 0, 1, \forall S \subseteq N \tag{4e}$$

The objective function (4a) represents the government's goal of maximizing expected social welfare by selecting appropriate signals, denoted as φ_ω^S, to send to the operators. Constraints (4b) and (4c) are operator i's incentive compatibility (IC) constraints. In (4b), when the government recommends the operator group S to make the adaptation investment, and operator i belongs to this group, i.e., $S \subseteq N$, $i \in S$, its utility is $F(1 + (|S| - 1)\beta) - r_i$, if it follows the recommendation. Note that operator i not only benefits from its own adaptation, but also enjoys the spillover effects from the other $|S| - 1$ operators in the group. When operator i does not belong to this group, i.e., $i \notin S$, its utility only comes from the spillover effect of the adaptation investors, i.e., $F(|S|\beta)$. If operator i does not take actions, it may still enjoy the spillover effect of other adaptation investors, i.e., $F((|S| - 1)\beta)$ when i belongs to the recommended group, and $F(|S|\beta)$ when i does not belong to the recommended group. Thus, constraint (4b) indicates that operator i can be better off following the government's recommendation. Similar explanations apply to (5c), which indicates that operator i's utility is less than if

[5] To enhance understanding of the government's persuasion problem, we provide an example involving two operators in the appendix.

it takes no action, when it does not follow the government's recommendations. Constraints (4d) and (4e) describe the characteristics of the probabilities under different scenarios.

Since adaptation projects require time to construct, facility adaptation is typically a long-term plan made in advance, with investments based on the facility operators' expected utility. Therefore, we assume that adaptation projects can be completed before a disaster occurs. However, it is possible for some disasters to happen before the completion of the adaptation investment. In such cases, the uncertainty of the disaster and the adaptation investment does not affect transport operations and market equilibrium, and thus, it is beyond the scope of our modeling. This point has also been elaborated in other studies, such as Wang and Zhang (2018). To keep the problem manageable, we do not develop a multi-period model. In a multi-period setting, if the decision-makers' (both the government and facility operators) posterior beliefs are not influenced by the adaptation investments and their performance, the model outcome will not change qualitatively (note that in our model, the facility operators' posterior belief is only affected by the government's signals). However, a multi-period adaptation investment model could be considered in future studies.

Before solving Problem (4a) – (4e), we find some properties on the government's optimal persuasion strategies, which are presented in the following proposition. All proofs are provided in the appendix.

Proposition 1. *The government's optimal persuasion strategy has the following properties:*

(i) When the government thinks that no disaster will occur, it never persuades any operators to invest;
(ii) Higher adaptation cost or larger spillover effect makes persuading the operators more difficult.

Proposition 1 provides us some useful insights on the government's persuasion strategies, which may be useful for us to understand some outcomes in our model calibrations in the next section. First, it indicates that the government should fully disclose its disaster information when it thinks that no disaster will occur. This is straightforward. Second, it tells us that higher adaptation cost or larger spillover effect are not good to the government's persuasion. Higher adaptation cost increases the operators' action cost, while larger spillover effect increases the operators' waiting value or their reserved utility (because of the free rider effect). All these lead to their reluctant adaptation actions and raise the difficulty of the government's persuasion strategies.

Deterministic recommendations (e.g., always recommend investment $\varphi(\theta|w = i) = 1$or never recommend investment $\varphi(\theta|w = i) = 0$) are merely edge cases of probabilistic signaling. By considering stochasticity, our framework subsumes deterministic strategies as special cases. The reason why probabilistic recommendation dominates the deterministic one is: the operators may not fully follow the government's recommendations, because they need to update their beliefs based on the Bayes law. If their utilities are completely consistent with the government, fully disclosing the information to the operators, or recommending the government's preferred plan to the operators definitely (or deterministic recommendation) is the best. In our case, when the government thinks that no disaster will occur, its objective (the social welfare) is completely consistent with all operators under no adaptation investment. Therefore, the government never persuades any operators to invest definitely. When government and operator utilities are perfectly aligned (e.g., no disaster expected), deterministic recommendations suffice because operators trust and follow the government's advice (here, do not invest). When utilities diverge (e.g., government prefers investment due to social welfare, but operators face different objectives with the government), deterministic recommendations (invest with probability of 1) may backfire. Operators, updating beliefs via Bayes' rule, may distrust "too-good-to-be-true" advice, leading to non-compliance. Probabilistic recommendations act as a *coarse* but credible signal. By not fully disclosing its information, the government avoids triggering skepticism. This mirrors mixed-strategy equilibria in games.

3.3.3. A special case with no spillover effect and the externality of the adaptation to the social welfare being positive

In order to obtain more insights, we first investigate a special case that there is no spillover effect among the operators' adaptation projects, i.e., $\beta = 0$, and their adaptation projects have the positive externality on the social welfare, i.e., $k = 1$. Solving Problem (4a) – (4e) when $\beta = 0$ and $k = 1$, we have the following proposition.

Proposition 2. *When there are no spillover effects among the operators' adaptation projects and these projects have a positive externality on social welfare, the government should fully disclose disaster information to the operators. In this scenario, the government's optimal persuasion strategies align entirely with the operators' willingness to invest. Specifically, if the government believes no disaster will occur, it does not persuade operators to invest. Conversely, if a disaster is anticipated, the government only needs to recommend investment to those operators who are already inclined to do so, i.e.,*

(i) if $F(1) \geq r_n$, the government recommends all operators to invest;
(ii) if $r_1 < \cdots < r_{i-1} \leq F(1) < r_i < \cdots < r_n$, the government only recommends to operator groups $\{1, 2, \cdots i-1\}$ to invest with probability 1;
(iii) if $F(1) < r_1$, the government never recommends any operators to invest.

Proposition 2 provides us a simple rule for the government to design its persuasion strategies when there is no spillover effect among the operators' adaptation projects and their adaptation projects have the positive externality on the social welfare. That is, fully disclosing its disaster information to the operators and persuading them according to their willingness. Note that when $k = 1$, there is no conflicts between the government's objective and the operators' benefit towards the adaptation projects. $\beta = 0$ prevents the operators' opportunity behaviour and coordinate their behaviour with the government's objective (because the government never wishes any operators to free ride the others, which reduces their enthusiasms to make the adaptation investments). These two factors significantly simplify the government's persuasion problem and make its strategy more “straightforward”.

It is difficult to solve problem (5a) – (5e) analytically in the general case. Therefore, we apply this model to a real case in the next section. Through the model calibrations, we can obtain the conclusions based on the real parameter values, which can provide us some practical management insights and policy implications.

4. Model calibrations: application to the greater bay area of China

Currently, there are very few quantitative empirical studies on transport facility adaptation, making it challenging to obtain the necessary parameter values for calibration purposes. Consequently, we must rely on data from various, albeit limited, sources that discuss different cases. Although these data may not be entirely consistent (i.e., they may not refer to the same region), they can serve as a basis for determining the parameter values in our model. In this section, we aim to gather data from related literature to calibrate our model, demonstrating its practicality and helping us derive relevant policy implications.

4.1. Parameter values

For the adaptation costs and benefits of transport facilities, we draw on data from Wang et al. (2024), who examined adaptation projects at the ports of Hong Kong (HK) and Shenzhen (SZ) in response to SLR. These ports are located in close proximity and may face similar threats from SLR. The adaptation projects at one port not only enhance its own flood defenses but also benefit nearby areas, as these port cities are interconnected. Several adaptation project options are discussed in their paper, and we use the "hybrid management" plan as an example. According to Wang et al. (2024), the net present values of the adaptation projects under the "hybrid management" plan for the ports of HK and SZ are \$2.39 billion and \$2.87 billion, respectively, with benefit-cost ratios of 1.63 and 2.48.[6] Thus, we can calculate their adaptation costs as \$3.79 billion and \$1.94 billion, and their adaptation revenues as \$9.97 billion and \$6.75 billion, respectively. Additionally, the total lengths of the coastal lines covered by these adaptation projects are 365 km for HK and 145 km for SZ. Using these data, we derive the following power function to represent the relationship between a port's revenues from its adaptation investment and the scale of its adaptation project, i.e., the function $F(.)$ in our model:

$$BF = 0.82 * CL^{0.42} \tag{5}$$

where BF is the port's revenues from its adaptation investment and CL is the length of the coastal lines covered by its adaptation.

To analyze the impacts of facility operators' coalition on the government's strategy design, it is beneficial to examine a case involving more than two operators. Therefore, we include another significant port, the port of Guangzhou (GZ), which is located in the same region (GBA) and has competitive and cooperative relationships with HK and SZ. Since there is no adaptation data available for the port of GZ, we infer it using the information from HK and SZ. Given the similar geographic and natural conditions of these ports, especially between SZ and GZ, it is reasonable to use SZ's data for inference. We assume that the ports' throughputs or capacities are proportional to their adaptation scales and costs. In 2023, the total throughputs of the ports of SZ and GZ were 287 million and 675 million tons, respectively. Based on this, we estimate that the adaptation scale of GZ is 341 km, with adaptation costs of \$4.56 billion. To obtain interesting results, we set the adaptation costs in the benchmark scenario to 1.5 times the costs reported by Wang et al. (2024). Thus, the adaptation costs for the ports of HK, SZ, and GZ in the benchmark scenario are \$5.69 billion, \$2.91 billion, and \$6.84 billion, respectively.

There is currently no data available on the spillover effects of adaptation projects between ports. Therefore, we assume that $\beta = 0.1$ in our base scenarios and use sensitivity analysis to address potential biases in this estimate.

Another crucial component of our model is the social impact of adaptation projects, represented by the function $G(.)$. For this, we refer to Halsnæs et al. (2023), who examined the damage costs and adaptation measures related to flood disasters in Danish urban areas. Their study uses insurance payment data to derive a depth-damage function for floods, incorporating damage costs from residential, commercial, and industrial areas, as well as infrastructure and roads in Denmark. Figure 5 in their paper illustrates the relationship between flooding damage per square meter and water depth. Using their data, we can estimate the social benefits of adaptation projects, specifically the savings in damage costs from floods, by applying a power function to represent the positive externality on social welfare.

$$FD = 292.85 * WD^{0.73}, R^2 = 0.995 \tag{6}$$

where FD is the flooding damage per m^2 (Euros) and WD is the water depth of the flood. Considering HK, SZ and GZ locate nearly in the same region, it is reasonable their social benefit functions of the adaptation project are the same and $G = FD*Area$, where Area is the area of the city. Moreover, according to Wang et al. (2024), the objective of the adaptation projects of HK and SZ is to confront the anticipated SLR in 2050, i.e., 0.3 m, which is taken as the value of WD in our case.

Table 2 summarizes the parameter values in our model calibration.

[6] The net present values derived from Wang et al. (2024) may not be directly applicable to the Chinese Greater Bay Area due to differing assumptions and conditions. However, finding alternative data sources is challenging. To address this issue, we employ sensitivity analysis to illustrate some qualitative properties of our model and provide valuable insights.

Table 2
Parameter values.

Parameter	Value	Unit
Port revenue function: $F(.)$	$BF = 0.82{*}CL^{0.42}$	Billion US$
Social benefit functions of the adaptation project: $G(.)$	$G = 1.1{*}Area{*}292.85{*}WD^{0.73}{*}10^{-3}$	Billion US$
City area: Area	HK: 1114; SZ: 1997; GZ: 7434	km^2
Water depth of the flood: WD	0.3 for all three cities	m
Scale of the adaptation projects: CL	HK: 365; SZ: 145; GZ: 341	km
Adaptation cost: r_i	HK: 5.69; SZ: 2.91; GZ: 6.84	Billion US$
Spillover effect of the adaptation projects: β	$\beta \in [0.05, 0.15]$	
Probability of the disaster: μ_0	$\mu_0 \in (0, 1)$	

Note: 1. The exchange rate between the US$ and the Euro is 1.1 US$/Euro.
2. The data of the city areas come from the *China Statistics Yearbook*. https://www.stats.gov.cn/sj/ndsj/.

4.2. Impacts of the spillover effect between the operators

We apply our model (4a) – (4e) to the case with the parameters in Table 2. In order to obtain more insights, here we investigate the impacts of the spillover effect among the operators, i.e., β. Especially, we consider the two situations, depending on whether the operators' adaptation projects have the positive or negative impacts on the social welfare. In order to simplify the expressions, we use 1, 2 and 3 to represent the port of HK, SZ and GZ, respectively, in the notations. The results are illustrated in Table 3. From Table 3, we have the following observation.

Observation 1. *A larger spillover effect among operators results in lower (or higher) social welfare if their adaptation projects have positive (or negative) impacts on social welfare.*

Observation 1 indicates that larger spillover effect among the operators may NOT always benefit the social welfare. When the operators' adaptation projects have the positive impacts ($k = 1$) on the social welfare, larger spillover effect is not good to the social welfare. This is counter intuitive. The reason is explained as follows. From Section 3.3.2 we know that increasing β raises the operators' reserved utility (when they do not take actions), which makes it harder promote their actions (because of the free rider effect). In terms of social welfare, if for certain reasons some operators cannot be recommended or incentivized, it is better for the government to exclude the operators in the following order: first HK, then SZ and finally GZ, because GZ has lower "cost benefit ratio" (in terms of social welfare) than SZ, and than HK. However, increasing β makes some operators' IC constraints not be satisfied and thereby they are removed from the government's persuasion plan (to be encouraged to make the adaptation investment). In other words, they never receive the government's recommendations or signals (to make the adaptation investment). This removing order may not be consistent with the government's preferring one. In our case, if $k > 0$, examining the government's persuasion strategy (Column 4 in Table 3), we find that the probability to promote Operator 2 (SZ) decreases as β increases. Note that when $\beta = 0$, SZ is recommended along with the other two operators (the three operators are recommended simultaneously). When $\beta = 0.05$, SZ can be recommended along with the other two operators in the probability of 0.776, and with Operator 3 (GZ) together in the probability of 0.224. However, when $\beta = 0.15$, SZ is only recommended along with the other two operators in the probability of 0.97. When $\beta = 0.2$, SZ's recommended probability is reduced to 0.873. We know that dropping HK in the government's persuasion plan is better than dropping SZ. However, their IC constraints prevent the government from its referenced plan and force it to drop SZ. This leads to the decreasing of social welfare. When $k = -1$, the government's preferred excluding order is: first GZ, then SZ and finally HK. Meanwhile, increasing β still raises their reserved utility and discourages their actions. From Column 4 in Table 3 we know that the dropping order forced by the operators' IC constraints is consistent with the government's preferred one, when $k = -1$. This leads to the outcome that larger spillover effect benefits social welfare when the operators' adaptation projects have the negative externality on the society.

Observation 1 provides us the following policy implications. First, the spillover effect among the different transport adaptation projects may not necessarily benefit the social welfare, depending on whether the externality of the adaptation projects is positive. This gives us some guides when choosing the transport adaptation projects in a given area. More adaptation projects not only lead to huge financial burden to the transport operators, but also have significant impacts on the whole social welfare (which may not be good). Therefore, the proper transport adaptation planning in the region is important. Second, promoting the transport adaptation needs to consider the transport operators' willingness. Larger spillover effect may make the operators reluctant to invest and add difficulties to the government's persuasion strategies. This means that governments may need to put more efforts on its persuasion activities.

4.3. Impacts of the increasing adaptation costs

It is well known that adaptation is costly. In addition, it may have increasing cost because the climate change and its impacts have the acceleration trend. Here we investigate the effects from the variation of adaptation cost. To restrict our discussions, we focus on the cases where the adaptation projects have the positive externality on the social welfare. We assume that all the adaptation costs of these three ports change and the related outcomes are shown in Table 4. Based on Table 4, we have the following observation.

Table 3
Impacts of the spillover effect on the expected social welfare.[7]

k	β	$E(SW)$	Persuasion strategy
$k = 1$	0	994.70	$\varphi_1^{123} = 1$
	0.05	971.92	$\varphi_1^{23} = 0.224$, $\varphi_1^{123} = 0.776$
	0.1	914.66	$\varphi_1^{23} = 0.775$, $\varphi_1^{123} = 0.225$
	0.15	886.14	$\varphi_1^{13} = 0.030$, $\varphi_1^{123} = 0.970$
	0.2	868.72	$\varphi_1^{3} = 0.127$, $\varphi_1^{123} = 0.873$
$k = -1$	0.05	−99.91	$\varphi_1^{1} = 0.972$, $\varphi_1^{12} = 0.028$
	0.1	−77.83	$\varphi_1^{1} = 0.809$, $\varphi_1^{\phi} = 0.191$
	0.15	−68.33	$\varphi_1^{1} = 0.717$, $\varphi_1^{\phi} = 0.283$
	0.2	−62.64	$\varphi_1^{1} = 0.663$, $\varphi_1^{\phi} = 0.337$

[7] As stated in Proposition 2, if the government believes that no disaster will occur, i.e., ω = 0, it does not persuade any operators to invest, i.e., $\varphi_0^S = 0$. Consequently, we exclude these trivial cases and do not include them in Table 5.

Observation 2. *When adaptation projects have a positive externality on social welfare, increasing adaptation costs harm social welfare. However, their impacts on the government's persuasion strategies towards different operators are imbalanced. The operator who has the highest adaptation cost is more likely to be excluded in the government's persuasion (the government does not promote it to take adaptation action).*

It is not surprising that higher adaptation costs reduce social welfare. However, what is interesting is how these costs differently impact the government's persuasion strategies toward various operators, even when they face the same scale of adaptation cost increase. As adaptation costs rise, the port with the highest costs is more likely to be excluded from the government's persuasion efforts. In our case, GZ, which has the highest adaptation cost, is removed from the government's persuasion strategy when the adaptation cost increment reaches 40 %. Fig. 1 illustrates the government's preferences for different coalitions. Recall the government's objective function (e.g., (4a) in the case of three operators). The government aims to allocate the probability distribution to different coalitions

Table 4
Impacts of the cost variation on the expected social welfare.

Cost variation	$E(SW)$	Signalling strategy
−20 %	998.47	$\varphi_1^{123} = 1$
−10 %	969.01	$\varphi_1^{23} = 0.269$, $\varphi_1^{123} = 0.731$
0 %	914.66	$\varphi_1^{23} = 0.775$, $\varphi_1^{123} = 0.225$
+10 %	859.93	$\varphi_1^{3} = 0.162$, $\varphi_1^{23} = 0.838$
+20 %	804.76	$\varphi_1^{3} = 0.452$, $\varphi_1^{23} = 0.548$
+30 %	742.40	$\varphi_1^{2} = 0.013$, $\varphi_1^{3} = 0.733$, $\varphi_1^{123} = 0.254$
+40 %	246.38	$\varphi_1^{1} = 0.202$, $\varphi_1^{2} = 0.131$, $\varphi_1^{12} = 0.667$
+50 %	206.33	$\varphi_1^{1} = 0.399$, $\varphi_1^{2} = 0.156$, $\varphi_1^{12} = 0.445$
+60 %	191.90	$\varphi_1^{12} = 1$

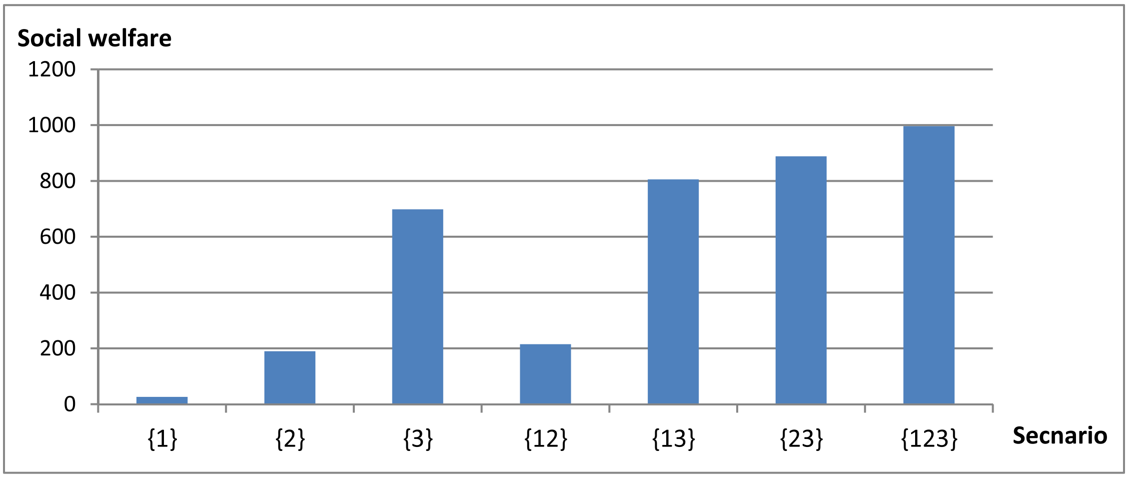

Fig. 1. Social welfare under different scenarios (β = 0.1).

(operator groups) to maximize expected social welfare, considering the related operators' IC constraints. From Fig. 1, we see that the government's allocation preference is: {123}>{23}>{13}>{3}>{12}>{2}>{1}. Higher adaptation costs make persuasion more challenging. This is why the government's most favorable coalition (which receives the highest probability) shifts from higher-ranking to lower-ranking as costs increase. For example, when the cost variation is −20 %, the government focuses all its persuasion efforts (allocating a probability of 1) on its most favorable coalition {123}. When costs increase to +10 %, due to the IC constraints of Ports HK and SZ, their received persuasion probabilities cannot exceed certain levels, preventing the government from allocating a probability of 1 to its preferred coalition {123} or {23}. Thus, its second preferred coalition {23} is chosen as the priority (with a persuasion probability of less than 1), and the government must distribute the remaining probability to its next preferred coalition without 1 and 2, i.e., coalition {3}. When the cost variation reaches 40 %, Port GZ is completely excluded due to its highest cost, and the government must persuade the coalition without Port 3.

Observation 2 tells us that the different transport operators have the different "weights" in the government's persuasion strategies. The operators who have the relative disadvantage on their adaptation costs face more risks to be excluded when the climate change needs more adaptation inputs.

4.4. Impacts of the operators' alliance strategies

Given the substantial adaptation costs, it is reasonable for operators to adopt cooperative strategies to save costs and maximize benefits, particularly due to the spillover effect. This study examines whether operators' cooperation enhances social welfare. Another key question is whether a grand coalition, where all facility operators form an alliance for joint investment or resource sharing on adaptation, is favored by both the operators and the government (especially under governance regimes like China's). We explore whether this grand coalition, if beneficial for all operators as a group, can be accepted by every member and whether it remains stable. If it benefits the government, could it be sustained through government subsidies? Our discussion focuses on cases where adaptation projects have a positive externality on social welfare.

First, we define a coalition scenario as one where a potential operators' alliance exists. For example, if no operators form an alliance, we denote it as {1,2,3}. If two operators form an alliance, there are three possible scenarios, denoted as {{12},3}, {{13},2}, or {{23},1}. If all operators form an alliance, we denote it as {123}, which we specifically call the grand coalition.

We then run our models to calculate the government's optimal persuasion strategies and the expected social welfare under different coalition scenarios. We also calculate the total benefits of the three ports under these scenarios. The results, shown in Fig. 2, indicate that in our case, the expected social welfare and the total benefits of all ports are consistent. The grand coalition scenario yields the highest outcomes in terms of social welfare and total port benefits compared to other coalition scenarios. Additionally, we repeat our analysis when β changes, with results shown in Table 5. We find that the grand coalition leads to the best outcomes for both the government (in terms of expected social welfare) and the ports (in terms of their total benefits from adaptation projects). It is unsurprising that a higher spillover effect results in greater benefits for both the government and the ports. Note that this conclusion does not contradict Observation 1, which discusses social welfare under no operators' cooperation (scenario {1,2,3}), whereas here we analyze social welfare under the operators' grand coalition.

Next, we address whether the grand coalition can be maintained. If the operators' total benefits from joint adaptation (alliance) exceed the sum of their independent adaptation, all members may be incentivized to form the alliance, as each can benefit more from the alliance than from individual actions through a proper benefit allocation scheme. In our paper, we use the concept of the 'core,' which will be defined in the following analysis. If their benefit allocation is based on the core solution, it ensures that each operator gains higher utility in the grand coalition (the alliance formed by all three ports) than in any other scenarios (including individual actions or other alliances except the grand coalition). Each operator's allocated benefit in the core needs to be realized through subsidies provided by the government.

Here we use the cooperation game framework to describe the operators' alliance behaviour.

Definition 2. *A cooperation game (N, V) consists of two elements: a player set $N = \{1, 2, \cdots n\}$ and a characteristic function V: $2^N \to R$. The characteristic function is a mapping from every coalition $S \subseteq N$ to its utility, and satisfies $V(\phi) = 0$.*

In our case, we have three players (three port operators), and the characteristics reveals the total benefits of the alliance ports from their adaptation projects under different coalitions. Then we need to analyze how to allocate the total coalition benefits among the members, which corresponds the solutions of our port adaptation cooperative game. There are numerous solution concepts for a cooperative game. Two of them attract many attentions. One is the core, which is defined as follows.

Definition 3. *Let vector$\lambda = (\lambda_1, \lambda_2, \cdots \lambda_n) \in R^N$indicates each player's distribution in the cooperative game (N, V). If such a distribution satisfies the following properties, it is called the core of this cooperative game:*

$$\sum_{i \in S} \lambda_i \geq V(S), \forall S \subset N \tag{7}$$

$$\sum_{i=1}^{n} \lambda_i = V(N) \tag{8}$$

As mentioned, among all possible coalitions, the grand coalition is the most interesting because it leads to the highest total utility for all players. The question then arises: can this grand coalition be maintained? Or is it stable? The core can guarantee the stability of

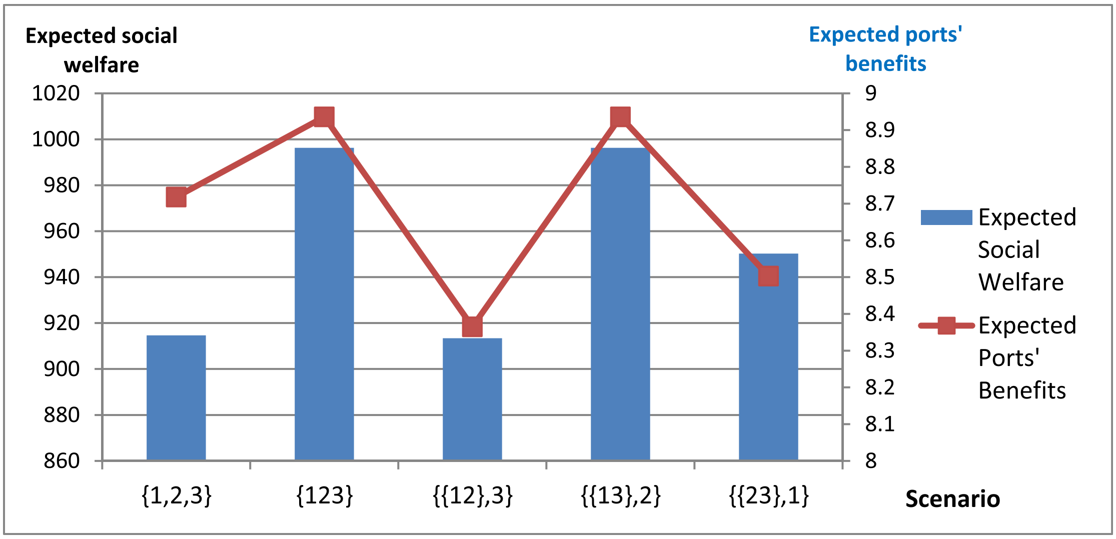

Fig. 2. Social welfare and ports' benefits under different scenarios (β = 0.1).

Table 5
Impacts of the spillover effect on the ports' cooperation and their benefit distribution.

β	$E(SW)$ under full cooperation	Ports' total direct benefits	Ports' benefit distribution under the Shapley value	Whether the distributions belong to the core	The government's subsidy
0	994.70	7.33	$x_{HK} = 2.86x_{SZ} = 2.61$ $x_{GZ} = 1.86$	N	$t_{HK} = 0$ $t_{SZ} = 0$ $t_{GZ} = 0$
0.05	995.54	8.16	$x_{HK} = 3.00x_{SZ} = 3.02$ $x_{GZ} = 2.14$	Y	$t_{HK} = 0.14$ $t_{SZ} = 0.02$ $t_{GZ} = 0.11$
0.1	996.31	8.94	$x_{HK} = 3.27x_{SZ} = 3.29$ $x_{GZ} = 2.38$	Y	$t_{HK} = 0.27$ $t_{SZ} = 0.16$ $t_{GZ} = 0.34$
0.15	997.03	9.66	$x_{HK} = 3.66x_{SZ} = 3.56$ $x_{GZ} = 2.44$	Y	$t_{HK} = 0.20$ $t_{SZ} = 0.32$ $t_{GZ} = 0.41$
0.2	997.72	10.35	$x_{HK} = 4.00x_{SZ} = 3.84$ $x_{GZ} = 2.51$	Y	$t_{HK} = 0.15$ $t_{SZ} = 0.43$ $t_{GZ} = 0.44$

the grand coalition by ensuring that all players have no incentive to leave it. In the concept of the core, property (7) means that every player in any coalition (except the grand coalition itself) can obtain a higher payoff in the grand coalition than in any other coalition. Property (8) means that the sum of all players' payoffs in the grand coalition equals the total utility of the grand coalition. If these two properties are satisfied, all players receive better distributions in the grand coalition than in any other coalition, leading to no incentives for players to leave the grand coalition. Although the core has this desirable property of maintaining the stability of the grand coalition, it has three weaknesses: (i) it may not exist; (ii) it may not be unique; (iii) it can be difficult to find, especially as the number of players increases. Therefore, some alternatives are considered for allocating the grand coalition's utility to its members, such as the Shapley value (Shapley, 1953), which is defined as follows.

Definition 4. *The players' distributions under the Shapley value can be calculated as follows:*

$$x_i = \sum_{i \in S, S \subseteq N} \frac{(|S|-1)!(|N|-|S|)!}{|N|!}[V(S) - V(S \setminus \{i\})] \tag{9}$$

where $|S|$ and $|N|$ are the number of the players in coalition S and grand coalition, respectively, and $N\backslash\{i\}$ is the coalition which consists of all players except player i.

Shapley (1953) demonstrates that the Shapley value is the unique solution that satisfies three axioms: dummy, additivity, and equal treatment for equals. In Eq. (9), the term $V(S) - V(S\backslash\{i\})$ represents the marginal contribution of player (i) to the coalition (S). Thus, the Shapley value allocates payoffs among members based on their marginal contributions to the coalition. The Shapley value is notable for its existence and uniqueness. However, it may not belong to the core, potentially leading to instability in the grand coalition.

Using these concepts, we calculate each port's distribution in the grand coalition under different β using the Shapley value. We then check whether these Shapley value-based distributions belong to the core. Additionally, we compare each port's Shapley value with its benefit from non-alliance or independent actions. The difference between its Shapley value and independent action benefit can be used to determine the government's subsidy. All the results are shown in Table 5, leading to the following observation.

Observation 3. *When adaptation projects have a positive externality on social welfare, the operators' alliance strategies enhance social welfare, with their full alliance achieving the highest social welfare. Furthermore, if there is a spillover effect among the operators, the core of their cooperation game is not empty, and the Shapley value of their cooperation game belongs to its core.*

Observation 3 indicates that the spillover effect leads to "economies of scale" in port adaptation projects, resulting in Pareto improvements for all ports. This inclusion of the Shapley value in the core signifies that the grand coalition of all three ports is stable. As the spillover effect increases, the Shapley values for all ports grow, thereby enhancing the stability of the grand coalition. This observation also offers a practical method for allocating the benefits from the ports' adaptation coalition and can serve as a basis for the government to determine the corresponding adaptation subsidies.

5. Conclusion

Our study developed a Bayesian persuasion model to analyze government strategies for persuading transport facility operators to undertake climate change adaptation projects. We found that a straightforward signaling strategy effectively conveys disaster information when there are no spillover effects and adaptation projects positively impact social welfare. However, higher adaptation costs and larger spillover effects complicate persuasion efforts. Our model calibration for port adaptation in the Greater Bay Area of China revealed that larger spillover effects can lead to varying impacts on social welfare, depending on the nature of the adaptation projects.

The results underscore the importance of transparent disaster information disclosure and tailored persuasion strategies based on operators' willingness to invest. Governments, particularly those applying the Asian Doctrine governance regime like China, should consider the spillover effects and externalities of adaptation projects when designing policies. In cases where adaptation projects positively impact social welfare, encouraging alliances among operators can enhance overall benefits. Additionally, implementing a benefit distribution scheme based on the Shapley value can maintain stability within operator coalitions. Policymakers must also address the uneven impacts of adaptation costs on different operators to ensure inclusive and effective persuasion efforts.

This study has several limitations. First, the model's assumptions may not fully capture the complexities of real-world scenarios. Future research could explore more dynamic models that account for varying disaster probabilities and operator behaviors over time. Developing a multi-period adaptation investment model under the government's persuasion strategy could provide further insights. In such a dynamic model, the government's signal in the current period can be assessed by facility operators based on its "reputation," which is determined by the consistency between its signal and the realized state in the previous period. Thus, the government's persuasion strategy would need to consider both its current performance and its reputation for future belief updates by facility operators. This promising but challenging extension could yield more interesting results. Second, the calibration of our model relied on limited data, which may affect the generalizability of our findings. Further empirical studies with comprehensive data are needed to validate and refine our model. Lastly, investigating the role of technological advancements and financial incentives in enhancing adaptation investments could provide valuable insights for policymakers.

CRediT authorship contribution statement

Shiyuan Zheng: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Changmin Jiang:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

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Appendix. : Proofs and examples

Proof of Proposition 1.

Observing the objective function (4a), we find that the coefficients of $\varphi_0^S, \forall S \subseteq N, S \neq \phi$ are negative. Moreover, larger φ_0^ϕ helps to keep the constraint (4c). All these lead to $\varphi_0^S = 0, \forall S \subseteq N, S \neq \phi$ and $\varphi_0^\phi = 1$.

Therefore, constraints (4b) and (4c) become:

$$\sum_{S \subseteq N, i \in S} \varphi_1^S (F(1 + (|S| - 1)\beta) - r_i) \geq \sum_{S \subseteq N, i \in S} \varphi_1^S F((|S| - 1)\beta), \forall i \tag{10b}$$

$$(1-\mu_0)\sum_{S\subseteq N, i\notin S}\varphi_1^S[F(1+|S|\beta)-r_i]-(1-\mu_0)\sum_{S\subseteq N, i\notin S}\varphi_1^S F(|S|\beta)\le \mu_0 r_i, \forall i \tag{10c}$$

Observing constraint (10b), we know that larger r_i reduces the LHS of (10b), and makes constraint (10b) more difficult to satisfy. Constraint (10b) guarantees the operators i's willingness to follow the government's recommendation, and thereby its difficulty to satisfy makes the persuasion more difficult.

To the constraint (10c), we know that $\frac{\partial F(1+|S|\beta)}{\partial\beta}-\frac{\partial F(|S|\beta)}{\partial\beta}=|S|[F'(1+|S|\beta)-F'(|S|\beta)]$, where $F'(x)=\frac{\partial F(x)}{\partial x}$. Because the function F is concave, we have $\frac{\partial F(1+|S|\beta)}{\partial\beta}-\frac{\partial F(|S|\beta)}{\partial\beta}<0$, which means that the LHS of (10c) decreases as β increases. In other words, the constraint (10c) is easy to satisfy as the spillover effect β increases. Constraint (10c) means that operator i obtains less utility if he does not follow the government's recommendation. If this constraint is easy to satisfy, it makes operator i more possible not to follow the government's recommendation, and thereby makes the persuasion more difficult. □

Proof of Proposition 2.

From Proposition 1 we know that $\varphi_0^S=0, \forall S\subseteq N, S\neq\Phi$ and $\varphi_0^\Phi=1$. When $\beta=0$ and $k=1$, Problem (4a) – (4e) can be transferred as:

$$\max\sum_{S\subseteq N}\varphi_1^S[|S|F(1)-\sum_{i\in S}r_i+G(|S|)] \tag{11a}$$

s.t.

$$\sum_{S\subseteq N, i\in S}\varphi_1^S[F(1)-r_i]\ge 0, \forall i \tag{11b}$$

$$-r_i\mu_0+(1-\mu_0)\sum_{S\subseteq N, i\notin S}\varphi_1^S[F(1)-r_i]\le 0, \forall i \tag{11c}$$

$$\sum_{S\subseteq N}\varphi_1^S=1 \tag{11d}$$

$$\varphi_1^S\ge 0, \forall S\subseteq N \tag{11e}$$

When $F(1)\ge r_n$, we know that the term $|S|F(1)-\sum_{i\in S}r_i+G(|S|)$ is the largest in the objective function (11a) when $S=N$. Therefore, $\varphi_1^N=1$ and $\varphi_1^S=0, \forall S\subset N$ can make the objective function (4a) maximum and satisfy all constraints, i.e., (11b) – (11e).

When $r_1<\cdots<r_{i-1}\le F(1)<r_i<\cdots<r_n$, to keep constraint (11b) hold leads to $\varphi_1^S=0, \forall S\subseteq N, i\in S, (i+1)\in S, \ldots, n\in S$. Moreover, we know that the term $|S^*|F(1)-\sum_{i\in S}r_i+G(|S^*|)$ is the largest in the objective function (11a) when $S^*=\{1,2,\cdots,i-1\}$. Therefore, $\varphi_1^{S^*}=1$ and $\varphi_1^S=0, \forall S\subseteq N, S\neq S^*$ can make the objective function (4a) maximum and satisfy all constraints, i.e., (11b) – (11e).

When $F(1)<r_1$, to keep constraint (11b) hold leads to $\varphi_1^S=0, \forall S\subseteq N, S\neq\Phi$ and $\varphi_1^\phi=1$. □

An illustrative example on the government's persuasion problem with two operators.

The benefits of the two operators and the social welfare under different scenarios are listed in Tables 6-8. Based on these tables, we can construct the government's persuasion problem as:

$$\begin{aligned}&\max\mu_0[\varphi_0^1(-r_1)+\varphi_0^2(-r_2)+\varphi_0^{12}(-r_1-r_2)]+(1-\mu_0)[\varphi_1^1(F(1)+F(\beta)-r_1+kG(1))\\&+\varphi_1^2(F(1)+F(\beta)-r_2+kG(1))+\varphi_1^{12}(2F(1+\beta)-r_1-r_2+kG(2))]\end{aligned} \tag{12a}$$

s.t.

$$\begin{aligned}&\mu_0[\varphi_0^1(-r_1)+\varphi_0^{12}(-r_1)]+(1-\mu_0)[\varphi_1^1(F(1)-r_1)+\varphi_1^2F(\beta)+\varphi_1^{12}(F(1+\beta)-r_1)]\\&\ge(1-\mu_0)[\varphi_1^2F(\beta)+\varphi_1^{12}F(\beta)]\end{aligned} \tag{12b}$$

$$\begin{aligned}&\mu_0[\varphi_0^2(-r_1)+\varphi_0^\phi(-r_1)]+(1-\mu_0)[\varphi_1^2(F(1+\beta)-r_1)+\varphi_1^{12}F(\beta)+\varphi_1^\phi(F(1)-r_1)]\\&\le(1-\mu_0)[\varphi_1^2F(\beta)+\varphi_1^{12}F(\beta)]\end{aligned} \tag{12c}$$

$$\begin{aligned}&\mu_0[\varphi_0^2(-r_2)+\varphi_0^{12}(-r_2)]+(1-\mu_0)[\varphi_1^1F(\beta)+\varphi_1^2(F(1)-r_2)+\varphi_1^{12}(F(1+\beta)-r_2)]\\&\ge(1-\mu_0)[\varphi_1^1F(\beta)+\varphi_1^{12}F(\beta)]\end{aligned} \tag{12d}$$

$$\begin{aligned}&\mu_0[\varphi_0^1(-r_2)+\varphi_0^\phi(-r_2)]+(1-\mu_0)[\varphi_1^1(F(1+\beta)-r_2)+\varphi_1^{12}F(\beta)+\varphi_1^\phi(F(1)-r_2)]\\&\le(1-\mu_0)[\varphi_1^1F(\beta)+\varphi_1^{12}F(\beta)]\end{aligned} \tag{12e}$$

$$\varphi_0^1+\varphi_0^2+\varphi_0^{12}+\varphi_0^\Phi=1 \tag{12f}$$

$$\varphi_1^1+\varphi_1^2+\varphi_1^{12}+\varphi_1^\Phi=1 \tag{12 g12 g}$$

$$0 \le \varphi_\omega^S \le 1, \forall \omega = 0, 1, \forall S = \{1\}, \{2\}, \{1, 2\}, \Phi \tag{12h}$$

The objective function (12a) represents the government's aim to maximize expected social welfare by selecting appropriate signals, i.e., φ_ω^S, to send to the operators. Constraint (12b) is the incentive compatibility (IC) constraint for operator 1, ensuring that the expected benefit of following the government's recommendation is greater than taking no action. Constraint (12c) is another IC constraint for operator 1, ensuring that the expected benefit of not following the government's recommendation is less than taking no action. Constraints (12d) and (12e) serve as the IC constraints for operator 2. Constraints (12f) through (12 h) describe the characteristics of the probabilities under different scenarios.

Table 6
Operator 1′s utility under different scenarios.

U_1 S ω	{1}	{2}	{1,2}	Φ	Whether to follow recommendation
0	$-r_1$	0	$-r_1$	0	Y
1	$F(1) - r_1$	$F(\beta)$	$F(1+\beta) - r_1$	0	
0	0	$-r_1$	0	$-r_1$	N
1	0	$F(1+\beta) - r_1$	$F(\beta)$	$F(1) - r_1$	
0	0	0	0	0	No action
1	0	$F(\beta)$	$F(\beta)$	0	

Table 7
Operator 2′s utility under different scenarios.

U_2 S ω	{1}	{2}	{1,2}	Φ	Whether to follow recommendation
0	0	$-r_2$	$-r_2$	0	Y
1	$F(\beta)$	$F(1) - r_2$	$F(1+\beta) - r_2$	0	
0	$-r_2$	0	0	$-r_2$	N
1	$F(1+\beta) - r_2$	0	$F(\beta)$	$F(1) - r_2$	
0	0	0	0	0	No action
1	$F(\beta)$	0	$F(\beta)$	0	

Table 8
Social welfare under different scenarios.

SW S ω	{1}	{2}	{1,2}	Φ
0	$-r_1$	$-r_2$	$-r_1 - r_2$	0
1	$F(1) + F(\beta) - r_1 + kG(1)$	$F(1) + F(\beta) - r_2 + kG(1)$	$2F(1+\beta) - r_1 - r_2 + kG(2)$	0

Data availability

No data was used for the research described in the article.

References

Airports Council International (ACI), 2018. Airports' resilience and adaptation to a changing climate. ACI Policy Brief.
Alam, E., Ray-Bennett, N.S., 2021. Disaster risk governance for district-level landslide risk management in Bangladesh. Int. J. Disaster Risk Reduct. 59, 102220.
Alizamir, S., de Vericourt, F., Wang, S., 2020. Warning against recurring risks: an information design approach. Manag. Sci. 66 (10), 4612–4629.
Anunrojwong, J., Iyer, K., Manshadic, V., 2023. Information design for congested social services: optimal need-based persuasion. Manag. Sci. 69 (7), 3778–3796.
Arieli, I., Babichenko, Y., 2019. Private Bayesian persuasion. J. Econ. Theory. 182, 185–217.
Becker, A.H., Acciaro, M., Asariotis, R., Cabrera, E., Cretegny, L., Crist, P., Esteban, M., Mather, A., Messner, S., Naruse, S., Ng, A.K., 2013. A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. Clim. Change 120 (4), 683–695.
Becker, A., Inoue, S., Fischer, M., Schwegler, B., 2012. Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators. Clim. Change 110 (1–2), 5–29.
Bergemann, D., Morris, S., 2019. Information design: a unified perspective. J. Econ. Lit. 57 (1), 44–95.
Candogon, O., 2020. Information design in Operations. Tutorials Oper. Res. 11, 176–201.
Candogan, O., 2022. Reduced form information design: Persuading a privately informed receiver. Working paper.
Drakopoulos, K., Jain, S., Randhawa, R., 2021. Persuading customers to buy early: the value of personalized information provision. Manag. Sci. 67 (2), 828–853.
Dughmi, S., 2017. Algorithmic information structure design: a survey. ACM SIGecom Exchanges 15 (2), 2–24.
Gentzkow, M., 2019. Bayesian persuasion and information design. Annu Rev. Econom. 11, 249–272.
Gong, L., Xiao, Y.B., Jiang, C., Zheng, S., Fu, X., 2020. Seaport investments in capacity and natural disaster prevention. Trans. Res. Part D: Trans. Environ. 85, 102367.
Griese, K.M., Franz, M., Busch, J.N., Isensee, C., 2021. Acceptance of climate adaptation measures for transport operations: conceptual and empirical overview. Trans. Res. Part D 101, 103068.
Halsnas, K., Larsen, M.A.D., Sunding, T.P., Dømgaard, M.L., 2023. The value of advanced flood models, damage costs and land use data in cost-effective climate change adaptation. Clim. Serv. 32, 100424.
Herrera, J.S.C., MacAskill, K., 2021. Navigating institutional complexity for the adaptation of urban transport infrastructure. Trans. Res. Part D 101, 103073.
Jain, V., 2018. Bayesian persuasion with cheap talk. Econ. Lett. 170, 91–95.

Jiang, C., Zheng, S., Ng, A.K., Ge, Y.E., Fu, X., 2020. The climate change strategies of seaports: mitigation vs. adaptation. Trans. Res. Part D: Trans. Environ. 89, 102603.
Kamenica, E., 2019. Bayesian persuasion and information design. Annu Rev. Econom. 11, 249–272.
Kamenica, E., Gentzkow, M., 2011. Bayesian persuasion. Am. Econ. Rev. 101 (6), 2590–2615.
Lee, P.T.W., Flynn, M., 2011. Charting a new paradigm of container hub port development policy: the Asian doctrine. Trans. Rev. 31 (6), 791–806.
Lee, P.T.W., Lam, J.S.L., 2017. A review of port devolution and governance models with compound eyes approach. Trans. Rev. 37 (4), 507–520.
Lin, Y., Ng, A.K., Zhang, A., Xu, Y., He, Y., 2020. Climate change adaptation by ports: the attitude of Chinese port organizations. Marit. Policy Manag. 47 (7), 873–884.
Melkonyan, A., Hollmann, R., Gruchmann, T., Daus, D., 2024. Climate mitigation and adaptation strategies in the transport sector: an empirical investigation in Germany. Transp. Res. Interdiscip. Perspect. 25, 101102.
Meyer, V.J., 2009. Reinventing the Dutch Delta: complexity and conflicts. Built. Environ. 35 (4), 432–451.
Ng, A.K.Y., Chen, S.L., Cahoon, S., 2013. Climate change and the adaptation strategies of ports: the Australian experiences. Res. Trans. Bus. Manag. 8, 186–194.
Panahi, R., Ng, A.K., Pang, J., 2020. Climate change adaptation in the port industry: a complex of lingering research gaps and uncertainties. Transp. Policy (Oxf) 95, 10–29.
Papanastasiou, Y., Bimpikis, K., Savva, N., 2018. Crowdsourcing exploration. Manag. Sci. 64 (4), 1727–1746.
Randrianarisoa, L.M., Zhang, A., 2019. Adaptation to climate change effects and competition between ports: invest now or later? Trans. Res. Part B: Methodol. 123, 279–322.
Randrianarisoa, L.M., Wang, K., Zhang, A., 2020. Insights from recent economic modeling on port adaptation to climate change effects. Maritime Transport and Regional Sustainability 45–71.
Seddighi, H., Baharmand, H., 2020. Exploring the role of the sharing economy in disasters management. Technol. Soc. 63, 101363.
Shi, Z.J., Srinivasan, K., Zhang, K., 2022. Design of platform reputation systems: optimal information disclosure. Mark. Sci. 42 (3), 500–520.
Szydlowski, M., 2021. Optimal financing and disclosure. Manag. Sci. 67 (1), 436–454.
Wang, K., Zhang, A., 2018. Climate change, natural disasters and adaptation investments: inter- and intra-port competition and cooperation. Trans. Res. Part B 117, 158–189.
Wang, K., Yang, H., Zhang, A., 2020. Seaport adaptation to climate change-related disasters: terminal operator market structure and inter-and intra-port coopetition. Spat. Econ. Anal. 15 (3), 311–335.
Wang, T., Ng, A.K.Y., 2022. Responding to the barriers in climate adaptation planning among transport systems: insights from the case of the port of Montreal. Int. J. Sustain. Transp. 16 (10), 942–956.
Wang, X., Li, Y., Zhang, Q., 2024. Prioritising local sea level rise adaptation pathways in Shenzhen and Hong Kong using cost-benefit analysis. Ocean Coast Manag. 253, 107158.
World Economic Forum and PwC. Nature-Positive Cities: A New Model for Urban Resilience. https://orca.cardiff.ac.uk/id/eprint/144383/1/NP2030%20Summary.pdf.
Wu, X., Wang, K., Fu, X., Jiang, C., Zheng, S., 2024. How would co-opetition with dry ports affect seaports' adaptation to disasters? Trans. Res. Part D 130, 104194.
Shapley, L.S., 1953. A value for n-person games. In: Kuhn, H.E., Tucker, A.W. (Eds.), Contributions to the Theory of Games II, Annals of Mathematical Studies, Contributions to the Theory of Games II, Annals of Mathematical Studies, 28. Princeton University Press, Princeton, NJ, pp. 307–317.
Vajjarapu, H., Verma, A., 2021. Composite adaptability index to evaluate climate change adaptation policies for urban transport. Int. J. Disast. Risk Red. 58, 102205.
Xia, W., Lindsey, R., 2021. Port adaptation to climate change and capacity investments under uncertainty. Trans. Res. Part B 152, 180–204.
Xiao, Y., Fu, X., Ng, A.K.Y., Zhang, A., 2015. Port investments on coastal and marine disasters prevention. Trans. Res. Part B 78, 202–221.
Yang, R.F., Hu, R., Xiao, Y.B., Deng, X., Wang, K., 2022. Seaport's investment under disaster information asymmetry between public and private operators. Transp. Policy (Oxf) 119, 89–112.
Yang, P., Iyer, K., Frazier, P., 2019. Information Design in Spatial Resource Competition. Working paper.
Yang, Z., Ng, A.K.Y., Lee, P.T.W., Wang, T., Qu, Z., Rodrigues, V.S., Pettit, S., Harris, I., Zhang, D., Lau, Y., 2018. Risk and cost evaluation of port adaptation measures to climate change impacts. Trans. Res. Part D: Trans. Environ. 61, 444–458.
Zheng, S., Wang, K., Jiang, C., 2024. Climate Change Adaptation Projects of Transport Facilities: Is a Demonstrator Necessary? Ann. Oper. Res. https://doi.org/10.1007/s10479-024-06010-8.
Zheng, S., Wang, K., Li, Z.C., Fu, X., Chan, F.T.S., 2021a. Subsidy or minimum Requirement? Regulation of port adaptation investment under disaster ambiguity. Trans. Res. Part B 150, 457–481.
Zheng, S., Fu, X., Wang, K., Li, H., 2021b. Seaport adaptation to climate change disasters: subsidy policy vs. adaptation sharing under minimum requirement. Trans. Res. Part E 155, 102488.
Zheng, S., Wang, K., Chan, F., Fu, X., Li, Z., 2022a. Subsidy on Transport Adaptation Investment: modeling decisions under incomplete information and ambiguity. Trans. Res. Part B 162, 103–129.
Zheng, S., Wang, K., Fu, X., Zhang, A., Ge, Y., 2022b. The effects of information publicity and government subsidy on port adaptation: strategy and welfare analysis for the maritime industry. Trans. Res. Part B 166, 284–312.
Zheng, S., Jia, R., Shang, W.L., Fu, X., Kun, W., 2023. Promote transport facility resilience: persuasion or subsidy? Trans. Res. Part A 176, 103822.