https://dx.doi.org/10.1016/j.trd.2020.102603

The Climate Change Strategies of Seaports: Mitigation vs. Adaptation

Changmin Jiang [a,*], Shiyuan Zheng [b], Adolf K.Y. Ng [c], Ying-En Ge [b], Xiaowen Fu [d]

[a] Asper School of Business, University of Manitoba, Winnipeg, MB R3T 2N2, Canada
[b] College of Transport and Communication, Shanghai Maritime University, Shanghai, China
[c] St. John's College, University of Manitoba, Winnipeg, MB R3T 2N2, Canada
[d] Department of Industrial and Systems Engineering, Hong Kong Polytechnic University, Hong Kong, China

*Corresponding author
E-mail: changmin.jiang@umanitoba.ca

Feb 2020

Abstract:

The two major approaches that seaport operators adopt to address climate change impacts are mitigation (CCM), i.e., reducing greenhouse gas emissions, and adaptation (CCA), i.e., adjusting the facility to moderate the negative outcomes of climate change. This paper is among the first to construct an economic model to compare the impacts of CCM and CCA in affecting the outputs of the executing port and the other ports in its network, considering the effects of market interactions. We find that both strategies can increase the executing port's cargo traffic, and can either increase or decrease the other port's cargo traffic depending on the market relationships between the ports. We also implement a numerical case study on four Chinese ports (Ports of Shenzhen, Xiamen, Tianjin and Hong Kong) based on our model.

Keywords: Climate change mitigation, climate change adaptation, seaport, strategic complement, strategic substitute

Acknowledgements: Financial supports from the Social Science and Humanities Research Council of Canada (SSHRC 435-2017-0728, 430-2019-00725) and the National Natural Science Foundation of China (Grant: 71803131, 71671110) are gratefully acknowledged. Thanks are also given to the Science and Technology Commission of Shanghai Municipality (Grant No.: 17040501800). The authors are also grateful for the support of the Lloyd's Register Foundation, a charity that helps to protect life and property by supporting engineering-related education, public engagement, and the application of research, via Grant # G\100111.

1. Introduction

Climate change is one of the most critical challenges of our age. The impacts of climate change can already be observed in many places, including rising sea levels, melting ice and changing weather patterns. Transport facilities, such as seaports, airports and roads, are significantly affected by climate change (e.g., Koetse and Rietveld, 2009; Rothengatter, 2010; Yang and Ge, 2020). Among these facilities seaports are probably the most susceptible to the challenges associated with climate change, including sea level rise and powerful storms (Ng et al., 2019). The two major approaches used by seaports to deal with this global challenge are climate change mitigation (CCM) and climate change adaptation (CCA). It is worth noting that this dichotomy (CCM vs. CCA) is not the only categorization of climate strategies, but it is certainly a very popular one (e.g., Sharifi, 2020a; 2020b). Besides, we are not aware of other climate strategy classification in seaport management. While mitigation strives to reduce greenhouse gas emissions, adaptation attempts to adjust the facility and environment to avoid or moderate the negative outcomes of climate change (Hamin and Gurran, 2009). There are abundant examples for both CCM and CCA in the seaport sector. On the one hand, many major ports across the world have implemented or planned to implement emission reduction, i.e., CCM. For example, the Port of Rotterdam has over the years taken steps to reduce its own CO_2 emissions and the port authority organization has been CO2-neutral since 2011 (Azarkamand et al., 2020). In 2016, the Port of Rotterdam also proposed the vision for the whole port cluster to halve its emission by 2025. On the other hand, more and more ports have also invested in prevention of natural disaster caused by climate change, i.e., CCA. For instance, in response to sea level rise, the Port of Hamburg has a storm surge protection plan in place (Christodoulou et al., 2019). Facing budget constraint, seaports usually don't have enough resources to invest in both CCM and CCA simultaneously, so they have to prioritize one over the other (e.g., Gong et al., 2020). Meanwhile, as a crucial part of the global trade and transport network, seaports don't exist in silo (e.g., Ng et al., 2018). As CCM and CCA are among the most significant investments made by the ports, it is clear that ports need to be strategic when making such decision, especially taking into account the impacts of their climate change investment on other ports.

As discussed in details in the following section of literature review, there are several gaps in the literature. First, a quantitative framework in which both CCM and CCA can be analyzed is lacking in the transportation literature - most studies focus on one approach or another. For those that cover both approaches, with only a few exceptions, the comparisons are usually qualitative. This is most likely due to the fact that existing literature mainly focuses on the direct impacts of the two approaches, leading to a lack of comparability. Comparison is possible and can yield relevant results if we shift the focus to the indirect impacts, especially the strategic consequences (i.e., the impacts on other entities), of the climate change approaches. Second, the assessments for both approaches largely adopt 'standalone' methodologies that focus on the impacts of such approaches on individual ports, usually the ones that utilize these approaches. One major concern is that in addition to the direct consequences at the ports adopted CCM and CCA measures, the responses of other ports lead to indirect consequences too. In other words, it is inadequate to investigate the impacts of CCM and CCA on the executing port only. Climate is a system, and it is well known significant "network effects" are present in transport sectors such as aviation, maritime and rail industries. It is very likely that the CCM or CCA measures adopted by a particular port will trigger changes in other ports through market interactions. A standalone approach thus misses the big picture, and could lead to unexpected consequences in implementing certain climate strategies. For instance, the Climate Mitigation and Adaptation

Plan developed by the port of San Diego, California, USA, was not successfully implemented due to a lack of all-inclusive consideration at the planning stage (Messner et al., 2016). The Port of Vancouver, BC, Canada, also faced a lot of challenges and confusion in seeking action on climate change because a comprehensive evaluation of costs and benefits was not properly executed (Ng et al., 2019). However, one should note that gauging the difference between mitigation and adaptation is easier said than done. There is an urgent need for a comprehensive framework for the analysis of the consequences of both CCM and CCA, so that the appropriate approach can be chosen to achieve the desirable outcomes at specific markets.

This paper is a pioneer attempt to construct an economic model to gauge the difference between CCM and CCA, with market dynamics under consideration. We illustrate that in a game setting between two seaports, under which both the mitigation and the adaptation strategies of a port would have positive impacts on its own operations output (i.e., the cargo traffic processed by a port during a certain period of time[1]). In other words, if a port implements either the mitigation strategy or the adaption strategy, the cargo traffic it processes will increase. This is mainly due to the fact that both strategies reduce the climate risks that the ports face, thus increasing their incentives the process more cargo traffic. On the other hand, a port's adaptation strategy would pose different impacts on the other port's operations output, depending on the relationships between the ports. In particular, a port's adaptation strategy would decrease the cargo traffic of the other port when the outputs of the two ports are originally (meaning without considering the environmental factors) independent or strategic substitutes.[2] However, this impact might be

[1] It should be noted that while port clusters have many outputs (depending on transport or industry related objectives), the idea of 'operational output' also could have different meaning depending on the nature and characteristics of the port cluster. In this paper we only focus on the cargo traffic for its relevance to the climate strategies of ports.
[2] In economics, if the increase of a player's decision variable will decrease the other player's decision variable, the

reversed to become positive when the two ports are originally strategic complements instead. Intuitively, this is because a port will expand its own operations after the implementation of the adaptation strategy, which in turn will have two effects: 1) externality effect, i.e., an expansion of one port's operations leads to a higher level of GHG emission, which discourages the operations of the other port; 2) market interaction effect, i.e., if the two ports are substitutes (complements), the increase of one port's cargo traffic will lead to the decrease (increase) of another port's cargo traffic. When the two ports are independent, there is no market interaction effect. When the two ports are substitutes, the two effects are in line with each other, both decreasing the cargo traffic of the other port. But when the two ports are complements, the effects are contradictory and may cancel out. Also, the implication of a port's mitigation strategy on the other port's operations output is ambiguous, with a negative impact more (less) likely to appear when the two ports are originally strategic substitutes (complements) compared with the case when they are originally independent. Moreover, we show that the impact of a port's mitigation strategy on its own operations output is larger than that of its adaptation strategy. Compared with the case when the two ports are originally independent, this disparity is larger (smaller) when they are originally strategic complements (substitutes). Furthermore, the adaptation strategy of a port would decrease (increase) the operations level of the other port more (less) than its mitigation strategy.

It is worth noting that in order to obtain clear analytical conclusion, we have omitted many specific features in port operations in our model. Therefore, we do not claim that our results can

---

decisions are referred to as strategic substitutes. If the increase of a player's decision variable will increase the other player's decision variable instead, the decisions are called strategic complements. The decisions are independent from each other if neither relationship exists. In the context of our paper, if the increase of cargo traffic processed by a port decreases (increases) the cargo traffic process by another port, we consider the operation outputs of the two ports strategic substitutes (complements). The outputs of two ports are strategic substitutes (complements) when they compete (cooperate) with each other. Cooperation and coordination are common in the maritime sector. For example, while the Environmental Ship Index (ESI) working group does not discuss pricing mechanisms, it does discuss the basic underlying elements. Another example of port cooperation is the subsequent ports-of-call on a shipping route (e.g., Jiang et al., 2017).

be directly applied to generate professional report for immediate usage, as the contribution of this paper is to propose a modelling framework for future industry analysis to build on. We will implement a numerical case to illustrate how our modelling framework can be utilized in any specific case, but more realistic details are needed to facilitate a comprehensive appraisal.

The rest of the paper is structured as follows. Section 2 provides literature review on CCM and CCA, while section 3 illustrates the model set up. The major results can be found in section 4, while section 5 presents a numerical case study. Section 6 consists of the discussions and policy implications.

2. Literature Review

This paper adopts an economic modelling framework to analyze the different impacts of CCM and CCA in affecting the outputs of seaports under various market interactions between ports, so in this section, we will focus on three steams of economic modelling studies that are most relevant to our paper.

The first relevant stream of literature is the economic modelling studies of ports' CCM strategies. Homsombat et al. (2013) study two rival ports, showing that pollution spill-over and inter-port competition can cause the ports' efforts in pollution reduction to be distorted and lead to an excessive level of pollution. Cui and Notteboom (2017) consider a wider range of market interactions between the ports, including Cournot competition, Bertrand competition, and cooperation. They find that different market interactions between ports can indeed lead to different implications for policies to induce ports' emission reduction activities. Sheng et al.

(2017) investigate the economic and environmental effects of unilateral and uniform regulations to cut maritime emission. They point out that both types of regulations would favor a certain port over the other in terms of profitability, but a uniform regulation dominates a unilateral regulation in terms of total emission reduction. Park et al. (2018) further internalize the emission standards, studying the optimal emission regulations under different jurisdictions of the competing ports. It is found that the maximum reservation price of shipping operators, port capacity, and environmental damage costs of ports all play a role in determining the optimal emission standards.

The first relevant stream of literature is the economic modelling studies of ports' CCA strategies. Xiao et al. (2015) consider the optimal timing decision for a single port to invest in disaster prevention. They reveal that the port should choose immediate (postponed) investment if the probability of disasters is high (low). Wang and Zhang (2018) study the optimal adaptation investment magnitude of two ports, considering both inter-port and intra-port competition as well as cooperation. They show that inter-port competition increases adaptations, while intra-port coordination between port authority and terminal operator also increases adaptations. Combining Xiao et al. (2015) and Wang and Zhang (2018), Randrianarisoa and Zhang (2019) investigate both the timing and the magnitude of adaptation investment for two competing ports. They point out that stronger competition leads to earlier adaptation investment, while earlier adaptation can generate higher social welfare. Gong et al. (2020) consider a port's decision to allocate resource between capacity expansion and disaster prevention. They show that the port would always prioritize capacity investment over natural disaster prevention investment. Furthermore, whether the port is social welfare maximizing or profit maximizing operators also determines the resource allocation pattern. Wang et al. (2020) focus on the market structure of the terminal operator companies (TOC), suggesting that inter-port TOC joint venture would decrease the adaptation at both ports, which leads to an unfavorable outcome.

The third relevant stream of literature is the economic modelling analysis of both CCM and CCA from a holistic perspective. However, most of these papers are in a more general setting instead of considering ports specifically. One major drawback of such general setting is that it lacks the context to discuss the role of market interactions in determining the impacts of the climate strategies. Ingham et al. (2007) build a framework to incorporate uncertainty, learning, and both types of climate change strategies. They show that including adaptation would in fact lead to less action now to deal with climate change due to the prospect of future learning. Shalizi and Lecocq (2007) build a partial equilibrium optimization model for climate policies, including mitigation, proactive adaptation, and reactive adaptation, with the consideration of uncertainty. They show that uncertainty on the location of damages reduces the benefits of proactive adaptation, while reactive adaptation is generally subject to budget constraint. Hasson et al. (2010) use a one-shot public-goods game to study the potential trade-off between countries' investments in mitigation versus adaptation. They suggest that while CCM can be considered as a public good, CCA is a private good, as it only benefits the individual that makes the investment. As far as we know, Ng et al. (2018) is the only paper in the study of ports that considers both the CCM and the CCA strategies. However, they adopt a simplified model framework that does not incorporate the market interaction of ports. Therefore, our paper contributes to this stream of literature by being the first to consider both the CCM and the CCA strategies of ports under different market interactions. This new setting allows our study to review some new results, such as the indirect benefits of CCA in terms of its impacts on ports that are not implementing the strategy.

In Table 1, we have categorized all the papers discussed above according to the climate strategy they investigate, the market relationships they take into account, and the context of the studies. The contribution of this paper is quite clear when we fit it into this table, as it is the only paper that studies both CCM and CCA, considering all possible market interactions (independence, competition and cooperation) in the context of port. It should be noted that our model is an extension of the existing models, with all underlying mechanisms built on classic microeconomics and game theories.

Table 1: Categorization of Relevant Publications

Paper	Climate Change Approach	Market Relationships	Context
Homsombat et al. (2013)	CCM	Strategic substitute	Port
Cui and Notteboom (2017)	CCM	Strategic substitute	Port
Sheng et al. (2017)	CCM	Strategic substitute	Port
Park et al. (2018)	CCM	Strategic substitute	Port
Xiao et al. (2015)	CCA	Independence	Port
Wang and Zhang (2018)	CCA	Strategic substitute	Port
Randrianarisoa and Zhang (2019)	CCA	Strategic substitute	Port
Gong et al. (2020)	CCA	Independence	Port
Wang et al. (2020)	CCA	Strategic substitute	Port
Ng et al. (2018)	CCM, CCA	Independence	Port
Ingham et al. (2007)	CCM, CCA	Independence	General
Shalizi and Lecocq (2007)	CCM, CCA	Independence	General
Hasson et al. (2010)	CCM, CCA	Independence	General

3. Model Setting

We adopt the simple framework initially proposed by Ng et al. (2018) and add market interactions to the analysis. In particular, we consider two ports, 1 and 2, whose operational outputs (i.e., the cargo traffic processed by the ports) can be either independent, strategic substitute or strategic complement of each other. In other words, we study a duopoly model, but as pointed out by Politonomics (n.d.), the analysis and conclusions of duopolies can be extrapolated for oligopolies. If we extend our analysis to more than two ports, we should expect that mitigation would play a smaller role compared with adaptation, due to the fact that the environmental externality increases with an increasing number of ports (e.g., Carraro et al., 2013). However, the qualitative conclusions should be largely unchanged. It is also worth noting that the purpose of this setting is to build a general framework for analysis instead of capturing the specifics of port operations. Therefore, we omit many important details of the maritime transportation so as to obtain more general conclusions. A few examples of such specific features include: First, we treat the seaport and all other stakeholders (including the shipping lines that use the port) in an integrated manner without diving into the detailed interactions between these players. This is a commonly adopted simplification in transportation economic modelling studies (e.g., De Borger and Van Dender, 2006; D'alfonso and Nastasi, 2014), which would not invalidate the analytical results, even though such model may lack the ability to reflect the interactive dynamics within the structure. Second, we only consider profit maximization as the objective of the ports, but in reality, port authorities do mostly have other objectives than profit maximization. This can potentially be taken into account by maximizing a weighted average of different objectives (e.g., Yang and Zhang, 2012). Third, we consider clear-cut relationship for the ports. However, market interactions between two ports, in particular on a cluster level, may have many faces. For example, while Antwerp and Rotterdam could be considered as substitutes in the context of the container market, in the context of petrochemical complexes they are closer to strategic complements.

Before considering the impacts of the environmental system, the short-term profit function of port i ($i \in \{1,2\}$) is given by:

$$\max_{q_i} \Pi_i = q_i p_i(q_i, q_j) - c_i(q_i) \tag{1}$$

where q_i is the operational output of port i, while q_j is the operational output of the other port. In the case of container ports, the unit of these two variables is TEU. $p_i(q_i, q_j)$ is the inverse demand function of port i, and $c_i(q_i)$ is the operating cost function of port i. We make the standard assumptions about downward sloping demand and positive marginal operational cost, i.e., $\partial p_i/\partial q_i < 0$, $\partial^2 p_i/\partial {q_i}^2 > 0$ and $c_i'(q_i) > 0$. These assumptions have been proven to fit reality very well (e.g., Mankiw, 2014). By definition, when the two ports are independent, $\partial^2 \Pi_i/\partial q_i \partial q_j = 0$; when the two ports are strategic complements, $\partial^2 \Pi_i/\partial q_i \partial q_j > 0$; when the two ports are strategic substitutes, $\partial^2 \Pi_i/\partial q_i \partial q_j < 0$ (Bulow et al., 1985). We further assume that $|\partial^2 \Pi_i/\partial q_i \partial q_j| < |\partial^2 \Pi_i/\partial {q_i}^2|$, i.e., a port's own output has a larger impact on its marginal revenue compared with the other port's output, which is a very standard assumption that fits the reality (e.g., Frank, 2008). It should be noted that the relationship we discuss here are mostly market relationship or the original relationship as we will term it in the following text.

The ports' outputs cause damages on the environment (e.g., greenhouse gas (GHG) emission that contributes to climate change). The emission, e_i, is positively correlated with the output level, i.e., $e_i'(q_i) > 0$. For simplicity, we assume that $e_i''(q_i) = 0$. The environmental cost for each port, C_i, is a function of the total emissions from both ports, i.e., $C_i'(E) > 0$, $C_i''(E) > 0$ with $E = \sum_i e_i$. It should be noted that climate change is a function of all emissions across the globe and other non-emission factors. These non-emission factors include the fundamental infrastructures, equipment, training people cost, taxes, energy purification cost, etc. Even for calculating the loss due to emission, there is a threshold in hand. Usually, only the amount exceed certain value will be counted in the environmental loss. However, with all these under consideration, the analytical framework for partial equilibrium should still hold. Therefore, our setting aims to investigate partial equilibrium instead of general equilibrium. In other words, we assume that the emissions from all other sources are given exogenously and not affected by the operations of the ports under investigation. This is a proven and commonly adopted method in economics, which is particularly useful to analyze single markets (e.g., Francois and Hall, 1997). Besides, as we have seen in the literature review section, one of the most relevant paper to ours, i.e., Shalizi and Lecocq (2007), specifies that a partial equilibrium optimization model for climate policies has been adopted in that paper.

To deal with these reversed environmental damages, the ports can adopt either CCM or CCA. For CCM, the ports can make technology investment to reduce its emission. With such investment, the emission of port i becomes $\lambda_{im} e_i(q_i)$, with $0 < \lambda_{im} < 1$ measuring the effectiveness of the technology. In particular, the larger λ_{im}, the less effective the technology. There incurs a cost for this investment, $I_m(\lambda_{im})$. We assume that $I_m{}'(\lambda_{im}) < 0$, meaning that more effective technology is costlier to adopt (e.g., Gong et al., 2020). For CCA, the technology investments that the ports do not reduce emission directly but rather reduce the environmental cost. In other words, we have the cost to be $\lambda_{ia} C_i(E)$, with $0 < \lambda_{ia} < 1$ denoting the effectiveness of the CCA technology. Similarly, the larger λ_{ia}, the less effective the CCA technology. There is also a cost associated this investment, $I_a(\lambda_{ia})$, with $I_a{}'(\lambda_{ia}) < 0$. It is worth noting that the two variables of interest, λ_{im} and λ_{ia}, only measure the effectiveness of the two climate strategies, not the work or effort that have been put into implementing the strategies. In other words, to quantify these two variables, we need to measure the change in the emission levels (for CCM) and the environmental cost levels (for CCA) after implementing the strategies. Also, this setting only aims at capturing the effects of the two climate strategies without getting into the details of relevant technologies. For example, the technologies and activities of CCM can be very diverse, including training the workers to produce less emission, using green energy to replace the traditional source, setting laws to ban certain emissions, and making high tax on consumption of CO2. As no functional form has been given to the environmental cost function and the climate investment function, our model only imposes some very mild and realistic assumptions, such as that a higher level of investment is needed to achieve a better result for either CCM or CCA.

With these factors under consideration, the long-term objective function of port i is:

$$\max_{q_i} \pi_i = \Pi_i - \lambda_{ia} C_i \left(\sum_k \lambda_{km} e_k \right) \quad (2)$$

where $k = i, j$. We assume that quantity (i.e., cargo traffic) is the decision variable of the two ports, a commonly adopted assumption in the economic modelling studies of ports (e.g., Bae et al., 2013; Balliauw et al., 2019). Another implict assumption in equation (2) is that the environmental costs are internalized in the decision-making of the ports. This assumption may not hold in reality due to many factors such as the principal-agent problem (e.g., Ng et al., 2018). The first order conditions are:

$$\frac{\partial \Pi_1}{\partial q_1} - \lambda_{1a} \lambda_{1m} C_1' e_1' = 0 \quad (3)$$

$$\frac{\partial \Pi_2}{\partial q_2} - \lambda_{2a} \lambda_{2m} C_2' e_2' = 0 \quad (4)$$

In this simple framework, CCM and CCA investments play their roles by decreasing λ_{im} and λ_{ia}, respectively. Therefore, we use comparative statics to investigate the impacts of such investments. The detailed mathematical derivation can be found in Appendix A. To illustrate the analytical process of the paper in a clearer fashion, the following Figure 1 provides a schematic representation of the model setting, the game structure and the propositions.

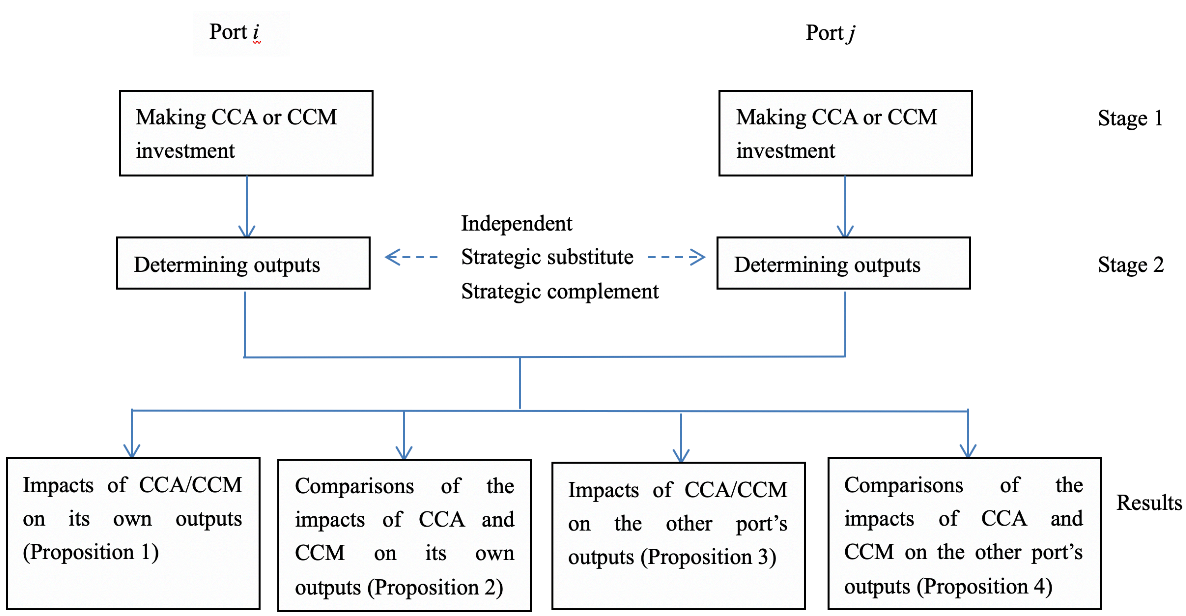

Figure 1. Flowchart for the Analytical Process of the Paper

4. Major Results

This paper aims to investigate the consequential output changes of a port adopting either CCM or CCA strategy, as well as the output changes of the other port. From the analysis in Section 3, a few notable conclusions can be obtained, which are summarized in the following propositions.

Proposition 1: The CCM and CCA strategies of a port both increase the port's own operational output.

The proofs of Proposition 1 and the following propositions can all be found in Appendix B. Since both the CCM and the CCA strategies can reduce the environmental costs of a port, a larger investment in both strategies would induce the port to increase its operations. This is a simple yet useful conclusion, as it suggests that we may need to be careful when acclaiming the climate strategies of ports and other facilities. Such investments, while indeed reducing the environmental impacts of the ports and strengthening their capabilities of resisting natural disasters, inevitably induce the ports to expand their operations, which may in turn weaken the benefits of these strategies. A similar observation is the traffic inducing effect of road building, which sometimes causes more congestion even though the initial objective of the projects is to relieve congestion (see Sloman et al. (2017) for a recent study).

If we dive deeper into Proposition 1, we can further analyze the magnitudes of such positive impacts for both CCM and CCA. A comparison between the two gives the following proposition.

Proposition 2: The marginal impact of a port's CCM strategy on its operational output is greater than that of its CCA strategy.

Proposition 2 conveys an important message. Although CCM is the more "orthodox" approach to deal with climate change, while CCA is generally considered a more passive response towards the outcome of climate change, this proposition suggests that CCA may be better than CCM in at least one aspect, i.e., CCA has a weaker stimulating effect on the operations, which would compromise the efforts to combat climate change. Of course, we are far from concluding that

CCA is superior to CCM, as our result focuses on marginal effects (i.e., changes in the effects of CCM and CCA), and CCM is definitely the only long-term solution to save the planet. Rather this proposition suggests that CCA also has some advantages so a mix of the two strategies should be the direction for the future.

We can also look at the impacts of both strategies on the operations of the other port, i.e. "spill-over" effect. Proposition 3 can be summarized from the corresponding analysis.

Proposition 3: The CCA strategy of a port decreases the other port's operational output when the two ports are originally independent or strategic substitutes. The impact is positive when the two ports are originally strategic complements and the complementarity is strong. The CCM strategy of a port can either increase or decrease the other port's output. The impact is more (less) likely to be negative when the two ports are originally strategic substitutes (complements) than when they are originally independent.

Proposition 3 reveals that a port's climate strategies not only have an impact on its own operations but would also influence the outputs of the other port through market dynamics. Whether the impacts are positive or negative depends on the relationship between the ports. The CCA approach does not directly affect the other port, so the other port will only decrease its own operational output as a response to the stimulated expansion of operations revealed in Proposition 1. As suggested by Proposition 1, the CCA strategy of a port increases its own operations output, which would in turn increase the environmental burden of the system. When the two ports are independent of each other, the other port feels the increase of the environmental cost, thus decrease its own operational level. When the two ports are strategic substitutes, the increase of the CCA executing port's operations would also put competitive pressure on the other port and decrease its output further. When the two ports are strategic complements, the increase of the CCA executing port's operations would instead boost the output of the other port, which may compensate its output decrease due to the intensified environmental cost. On the other hand, a port's CCM investment imposes a positive externality on the other port. Depending on whether the CCM executing port's net environmental cost increases or decreases, the other port's operations output would become smaller or larger, correspondingly. On top of this environmental impact, the relationship between the two ports also plays a role as discussed earlier, making the CCM project most likely to be environmentally detrimental when the two ports are strategic complements, followed by the case when they are independent and then the case when they are strategic substitutes.

Proposition 3 offers some fresh insights into climate policies. First, similar to Proposition 2, it shows another aspect where CCA may outperform CCM. In particular, CCA is shown to have a smaller distortion effect on the other player in the system. One intrinsic challenge of CCM is its enormous positive externality. The CCM efforts of a person or an organization benefit everyone else in the world. With such immense positive externality comes a very serious "free-riding" problem and inefficiencies. Due to the interconnectedness of the global environmental system, coordination to eliminate such free-riding has been proven extremely hard. This is also the main reason why it is very easy for international efforts to come up with climate change solutions (such as the Intergovernmental Panel on Climate Change, IPCC) to get into deadlock. CCA, on the other hand, does not generate so much positive externality so would be easier to manage, and there are also fewer stake holders to coordinate. Second, another useful lesson from this proposition is that regulators may need to be more careful in acclaiming a CCM project when the executing facility is positioned in a complementary network. In such a system, it may be fairer to assess the efforts of all facilities/organizations within the network. Based on these results, we can come up with some possible policy suggestion. First, contradictory to the common belief that CCA relies on individual actions (as opposed to CCM that takes collective efforts while), when administering CCA projects in particular sectors, governments and international regulatory bodies should take a holistic view and solicit coordination among the other stakeholders that are complementary to the project taker. For example, with the complementarity within supply chains, when a company (e.g., a port) adopts a CCA project, the regulator needs to make sure that the company's upstream and downstream partners are also committed to the climate course, so as to prevent the environmental benefit of this project from being compromised. Second, the regulator should be aware of the fact that when a climate project is executed, no matter whether it is CCM or CCA, the competitors of the executing company is less concerning compared with its complementary firms. The subsequent changes in such complementary firms' operations should be closely monitored in order to reach a comprehensive evaluation of the project's environmental impact.

Finally, we can also look into the magnitudes of the cross effects of both CCM and CCA, and then find out their differences. The conclusion is summarized in Proposition 4.

Proposition 4: The CCA strategy of a port has a larger (smaller) marginal effect in reducing (increasing) the operation level of other ports compared with the CCM strategy.

Proposition 4 adds more evidence to support the advantages of CCA compared with CCM. Together with the previous propositions, it shows that when a port implements CCA, it is more likely to reduce the total environmental costs than when CCM is executed.

5. Case Study

In order to make our modelling investigation more concrete and applicable to reality, we will analyze a specific case to illustrate the detailed impacts of CCM and CCA under various port relationships in this section. In particular, we have chosen four Chinese ports (Ports of Shenzhen, Xiamen, Tianjin and Hong Kong) to implement the case study. We consider the Port of Shenzhen as our focal point, as the Port of Shenzhen has already implemented certain CCM strategies and has concrete planning for CCA strategies. In particular, for CCM, the Guangdong Provincial Department of Transport issued a Green Port Action Plan of Guangdong Province (2014–2020) in 2014, which sets objectives for energy efficiency and CO2 reduction. The Port of Shenzhen was chosen by the as one of the green port pilots for shore power, LNG trailers, and LNG tugs (Fung et al., 2014). As for CCA, there also exists plans closely related to the Port of Shenzhen, such as the 21 square miles of landfill along Shenzhen's coast (Kimmelman and Haner, 2017). The Ports of Shenzhen and Hong Kong are two international hub ports and locate nearby. Therefore, they are substitutes to each other. The Port of Xiamen locates in the south east coast of China and is a feeder port of Shenzhen. Therefore, the relationship between Shenzhen and Xiamen is complementary. The Port of Tianjin, on the other hand, locates in the north of China and thereby has no direct competition or complementarity with the other three ports. Therefore, it is treated as independent of the others.

We estimate the parameters for the case study with information from different sources. We first refer to Luo et al. (2012) for the functional form of port service demand. Then we use the throughputs of the four ports in 2017 to estimate the parameters in the demand function. For the port operation cost, following Zheng et al. (2014), we assume that it is a linear function of the port output and the marginal cost is $59\$/\text{TEU}$. We further assume that emission is also a linear function of the port output. We refer to Song (2014), who concluded that the social cost of CO_2 emissions from the Port of Shanghai was \$2.1 per TEU in 2009. He also suggested a social cost of \$29 per ton of CO_2 emissions, which implies that CO_2 emissions per TEU equate to 2.1/29 = 0.0724 t. Last but not least, we use a quadratic form, $C_i = (\lambda_{im} e_i)^2$ to describe the port environment cost function, which is commonly applied in environment economics. The parameters and their values used in the case study are summarized in the following table.

Table 2. Parameters and their values

Parameter	Concept	Values
p_i	The inverse demand function of port i	$p_i = A_i - bq_i - cq_j$
		$b = 1/150000$
		$c \in [-b, b]$. When $c > 0$, two ports are substitutable. When $c < 0$, two ports are complementary. When $c = 0$, two ports are independent.
		For Port of Shenzhen, $A_i = 168$. For Port of Xiamen, $A_i = 69$. For Port of Tianjin, $A_i = 100$. For Port of Hong Kong, $A_i = 138$.
c_i	The operating cost function of port i	$c_i = \theta q_i$, $\theta = 59\$/\text{TEU}$
e_i	The emission function	$e_i = \delta q_i$, δ = 0.0724 t/TEU
C_i	The environment cost of each port	$C_i = (\lambda_{im} e_i)^2$
λ_{im}	The effectiveness of the CCM technology	$0 < \lambda_{im} < 1$
λ_{ia}	The effectiveness of the CCA technology	$0 < \lambda_{ia} < 1$

According to the models, we calculate the ports' outputs and the marginal effects of the ports' environmental strategies on their outputs under different port relationships. The results are illustrated in the following figures. As discussed earlier, we use the Port of Shenzhen as the focal point and investigate the effects of its climate change strategies on the other ports' outputs. In the figures, QT indicates Port of Tianjin, QX indicates Port of Xiamen, and QH indicates Port of

Hong Kong. It should be noted that for the clarity of presentation, we need to fix λ_{ia} when we study the impact of λ_{im}, and vice versa. Figures 2 and 3 show the marginal impacts of λ_{ia} and λ_{im} on the output of Shenzhen, the executing port. In both Figure 2 and 3, we find that both λ_{ia} and λ_{im} are negatively related to the output of the port of Shenzhen [3], whatever the relationship between the port of Shenzhen and the other ports. These results are consistent with Propositions 1 and 2. Moreover, we find that the impacts of λ_{im} on the outputs are greater than λ_{ia}, which has also been proved by Proposition 2.

Figures 4 and 5 show the effects of Shenzhen's CCA and CCM strategies on the other ports' outputs. We find that the increase of λ_{ia} (i.e., the decrease of CCA effectiveness) increases the outputs of QT and QH, which is consistent with the clear-cut part of Proposition 3. Besides, we can also see that the increase of λ_{ia} decreases the outputs of QX. From Proposition 3, we can conclude that the complementarity between the Port of Shenzhen and the Port of Xiamen is rather strong. Moreover, the increase of λ_{im} decreases the outputs of QT, QH and QX, with the impact on QH being greater than that on QT, which in turn is greater than that on QX. These results are also consistent with Proposition 3.

Figures 6 and 7 show the difference of the marginal impacts of Shenzhen's CCM strategy and CCA strategy on its own outputs under the different scenarios when λ_{ia} and λ_{im} vary, respectively. Figures 8 and 9 show the difference of the marginal impacts of Shenzhen's CCM strategy and CCA strategy on the other ports' outputs under the different scenarios when λ_{ia} and λ_{im} vary, respectively. We find that all the differences are positive, which illustrates that the marginal impacts of Shenzhen's CCM strategy are greater than CCA strategy on both its own

[3] In Figure 2 and 4, the decreasing trend of the data is not obvious because of the relatively small magnitude. The data that shows this decreasing trend is available upon request.

outputs and the other ports' outputs. Because the marginal impacts of Shenzhen's CCM strategy and CCA strategy on the outputs are both negative, these results are consistent with Proposition 4.

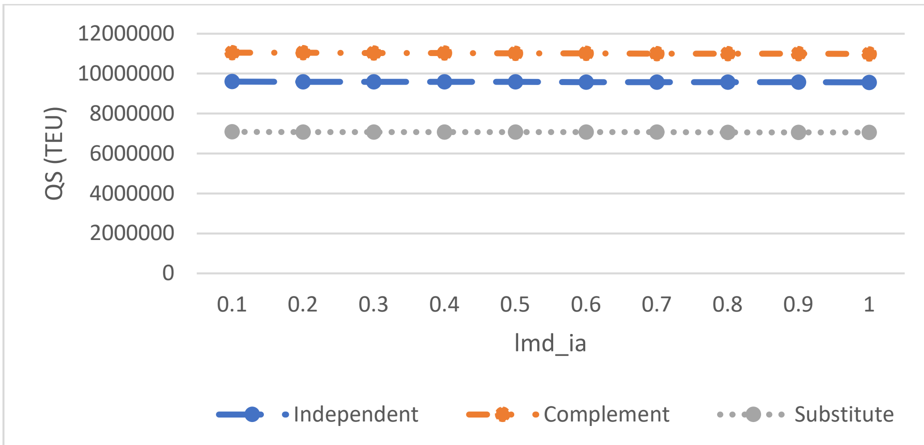

Figure 2. The impacts of λ_{ia} on Shenzhen' outputs under different port relationships

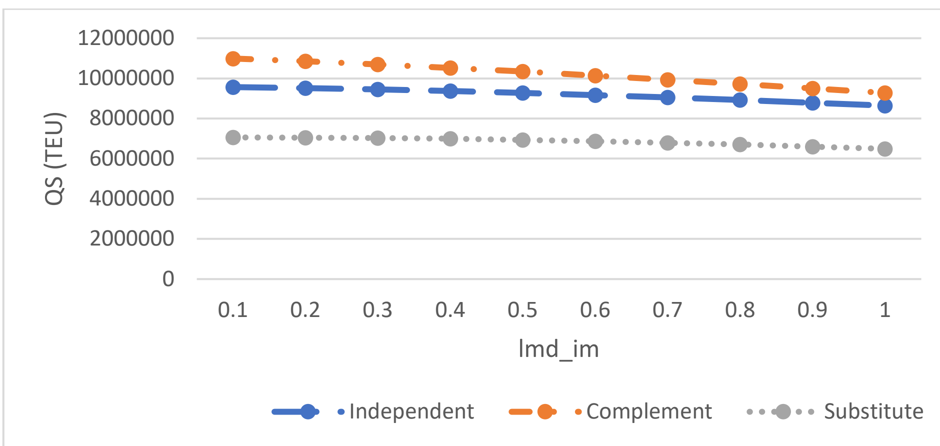

Figure 3. The impacts of λ_{im} on Shenzhen' outputs under different port relationships

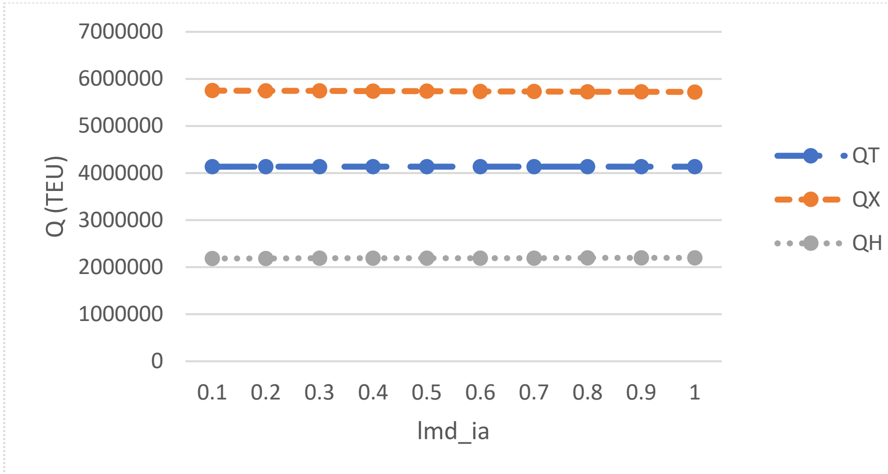

Figure 4. The effects of Shenzhen's CCA strategies on the other ports' outputs

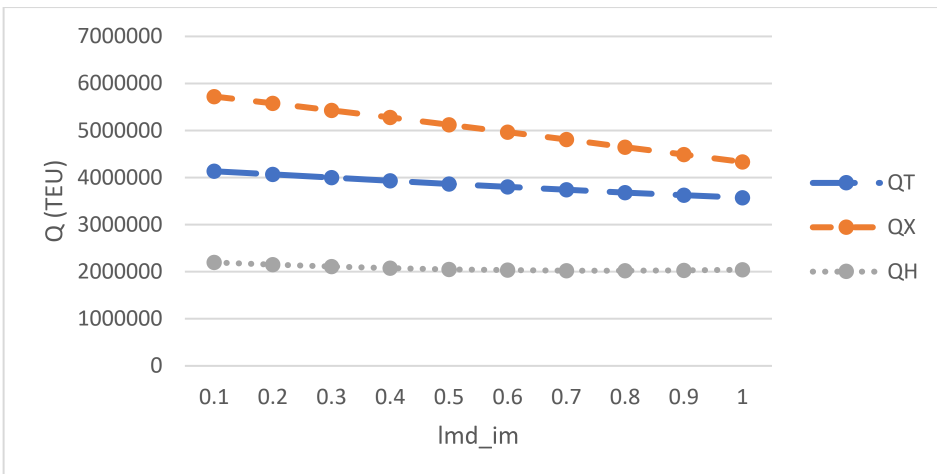

Figure 5. The effects of Shenzhen's CCM strategies on the other ports' outputs

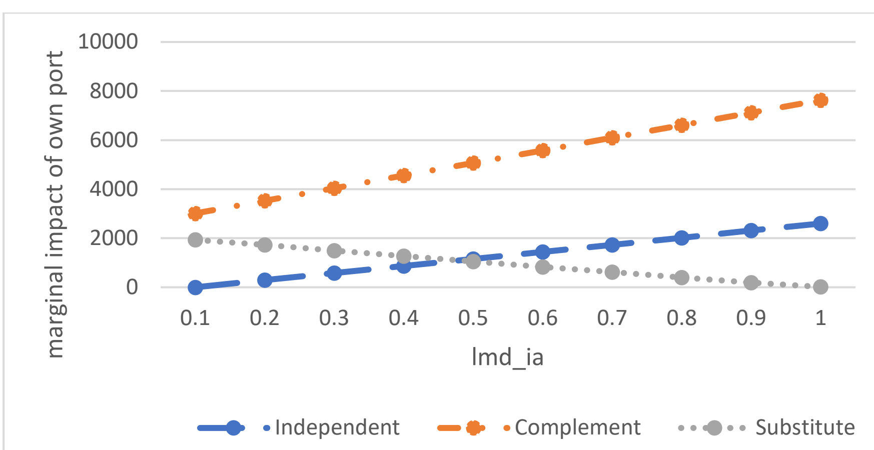

Figure 6. The difference of the marginal impacts of Shenzhen's CCM strategy and CCA strategy on its own outputs under the different scenarios when λ_{ia} varies

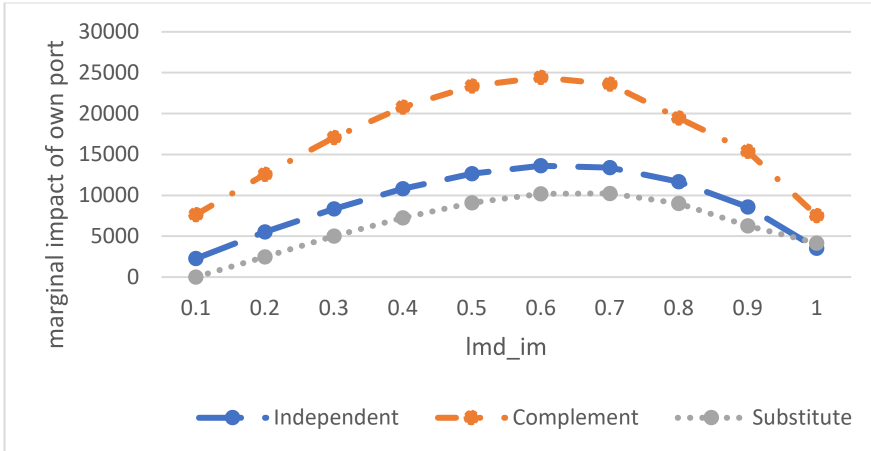

Figure 7. The difference of the marginal impacts of Shenzhen's CCM strategy and CCA strategy on its own outputs under the different scenarios when λ_{im} varies

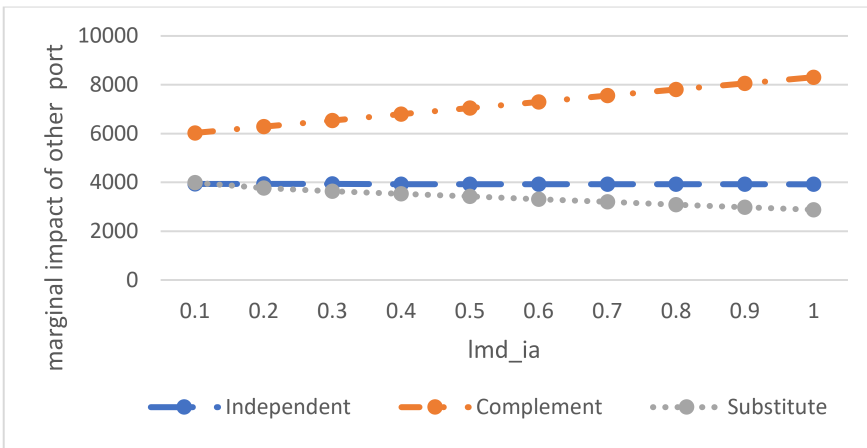

Figure 8. The difference of the marginal impacts of Shenzhen's CCM strategy and CCA strategy on the other ports' outputs under the different scenarios when λ_{ia} varies

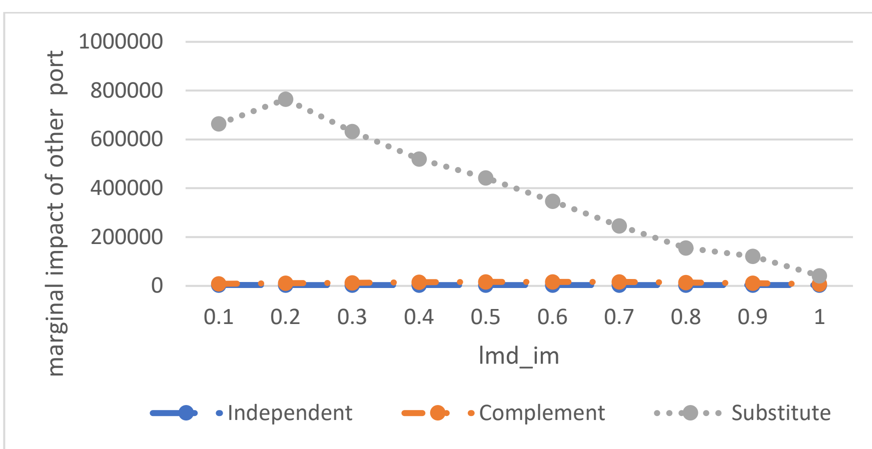

Figure 9. The difference of the marginal impacts of Shenzhen's CCM strategy and CCA strategy on the other ports' outputs under the different scenarios when λ_{im} varies

6. Discussion and Concluding Remarks

In particular, we show that in a two-port setting, a port's CCM strategy and CCA strategy both have a positive impact on its own output. However, a port's CCA strategy has a negative impact on the other port's output when the two ports are originally independent or strategic substitutes. The impact might be positive when the two ports are originally strategic complements. A port's CCM strategy may have either a positive or a negative impact on the other port's output. The impact is more (less) likely to be negative when the two ports are originally strategic substitutes (complements) than when they are originally independent. Furthermore, a port's CCM strategy has a larger impact on its output compared with its CCA strategy. The difference is larger (smaller) when the two ports are originally strategic complements (substitutes) than when they are originally independent. Besides, a port's CCA strategy has a larger (smaller) effect in reducing (increasing) the operation level of other ports compared with its CCM strategy.

From the propositions, we can easily compare the impacts of CCM and CCA under different market structures. Since both strategies reduce the cost associated with climate change, they in turn encourage the port that implements the strategies and (possibly) other ports to produce more, generating more emissions that would compromise the efforts. In this sense, CCA seems to be a better option than CCM as it stimulates fewer compromising responses, both on the port implementing the strategy and on the other port. There are constellations for either strategy to decrease the production level of the other port, but it is more likely to be seen in CCA compared with CCM. This is mainly because CCM offers a chance for a non-acting player to free ride the benefit of a lower emission level, distorting this action player's incentive to invest in counteracting climate change. While in the case of CCA, the benefits of the strategy stay largely with the party of action, thus limiting the incentive distortion inflicted on other parties. From the perspective of policymaker or social planner, when coordinated efforts are hard to achieve, which is normally the case in reality given a fragmented decision-making process involving different states and various levels of government agencies, it may be in fact more efficient to encourage CCA instead of CCM. Admittedly, this is only one aspect of the big picture. For example, adaptation is also regarded as a passive approach against climate change in contrast to the more active mitigation. However, a very important factor that is often left unnoticed is that climate change is less about individual entity and more about group efforts. Under such situation coordination cost is crucial to be taken into account. The 'passivity' nature of adaptation means a lower coordination cost for the whole system. This explains why, despite its clear benefits, individual stakeholders are often reluctant from actively participating in CCA. Indeed, the *status quo* ensures that while climate change impacts are not addressed properly, it simultaneously causes established social/political systems to meltdown due to their inability to effectively tackle such challenges, as exemplified by the 'institutional erosion' phenomenon that exists in several transportation and urban ports (Ng et al., 2019). Thus, from a policy perspective, we argue that the government should actively intervene research and the implementation of CCA as it would lead to a significant improvement in general social welfare but highly difficult to be implemented through individual incentives or conventional market solutions.

On the other hand, we can conclude from the analysis that market structure also plays a very important role in evaluating the difference between CCM and CCA. In particular, when the ports are substitutes, i.e., they are competing with each other, CCM is less likely to be significantly more detrimental than CCA. On the one hand, although mitigation will always have a larger positive impact on the port's own production level compared with adaptation, when the two ports are strategic substitutes, this margin will be smaller. This is because a mutually suppressing effect due to competition, i.e., a higher production level of one port will lead to a lower production level of the other port. In contrast, when the two are strategic complements, e.g., when they are upstream-downstream partners of a supply chain, the effect turns into mutually enhancing, stimulating the extra production to an even higher level. On the other hand, when the two ports are strategic complements, not only CCM is more likely to induce the other port to produce and emit more, but also CCA may lead to an increase of production level from the other port, which is not possible in the case of strategic substitutes. This should call upon attention from the policymaker and central planner, as it suggests that CCA may have an even larger advantage compared with CCM in terms of inducing fewer compromising responses if the ports are strategic complements. One possible policy suggestion is that government initiatives aiming at the CCA of a sector with multiple, complementary stakeholders (e.g., a supply chain) should focus more on adaptation compared with the case of regulating a particular industry where companies are merely competing with each other. Further empirical research is required so as to verify our conclusions and suggestions. Still, from this study, we can conclude that triggering and accelerating the development and pace, respectively, of CCA is likely to enhance the welfare of the society as a whole. Also, it is highly inappropriate to just 'copy-and-paste' strategies and solutions in CCM towards CCA planning and management, with the development of more innovative solutions and strategies dedicated to CCA an absolute necessity. Hence, we call for more public support to the research and planning of CCA.

Whereas our study offers some fresh insights, there are some limitations in our model mainly due to the simplifications for the sake of mathematical tractability. Most importantly, our major conclusions are all based on comparative statics, without exact equilibrium results that are dependent on levels of various costs. This may cause the loss of further insights. First, we are not able to attain the conditions under which CCM and CCA may generate negative net environmental impacts. Intuitively, this should not be a very common result, if even possible at all. A more clearly specified model needs to be analyzed to give out close-form results, based on which richer results can be obtained. Second, due to the simplification of the analysis, all results in fact assume that only one port takes action while the other port is passive. The more intricate and nuanced market interactions and their corresponding impacts are not available from our analysis. This problem would also be resolved if we can design a specified model and obtain close-form results. However, additional restrictive assumptions are needed to obtain specific solutions. Third, as we aim at general analysis, not much specific analysis is provided by this paper. Future industry analysis should build on our framework, adding more specifics and details. We hope this paper could lead to more advanced studies on this important topic. Fourth, we only consider two ports in this paper. In order to achieve results that are closer to reality, future studies should extend the analysis to more than two ports (i.e., the case of oligopoly).

Reference

Azarkamand, S., Wooldridge, C., & Darbra, R. M. (2020). Review of Initiatives and Methodologies to Reduce CO2 Emissions and Climate Change Effects in Ports. International Journal of Environmental Research and Public Health, 17(11), 3858.

Bae, M. J., Chew, E. P., Lee, L. H., & Zhang, A. (2013). Container transshipment and port competition. Maritime Policy & Management, 40(5), 479-494.

Balliauw, M., Kort, P. M., & Zhang, A. (2019). Capacity investment decisions of two competing ports under uncertainty: A strategic real options approach. Transportation research part B: Methodological, 122, 249-264.

Becker, A. H., Acciaro, M., Asariotis, R., Cabrera, E., Cretegny, L., Crist, P., … Velegrakis, A. F. (2013). A note on climate change adaptation for seaports: A challenge for global ports, a challenge for global society. *Climatic Change*, *120*(4), 683–695. https://doi.org/10.1007/s10584-013-0843-z

Becker, A., Ng, A.K.Y., McEvoy, D. and Mullett, J. (2018): 'Implications of climate change for shipping: ports and supply chains'. *Wiley Interdisciplinary Reviews: Climate Change* 9(2): wcc.508 (18 pages).

Bosello, F., Carraro, C., & De Cian, E. (2010). Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage. *Climate Change Economics*, *1*(2), 71–92.

Bulow, J. I., Geanakoplos, J. D., & Klemperer, P. D. (1985). Multimarket oligopoly: Strategic substitutes and complements. Journal of Political economy, 93(3), 488-511.

Carraro, C., Katsoulacos, Y., & Xepapadeas, A. (Eds.). (2013). Environmental policy and market structure (Vol. 4). Springer Science & Business Media.

Christodoulou, A., Christidis, P., & Demirel, H. (2019). Sea-level rise in ports: a wider focus on impacts. Maritime Economics & Logistics, 21(4), 482-496.

Cui, H., & Notteboom, T. (2017). Modelling emission control taxes in port areas and port privatization levels in port competition and co-operation sub-games. Transportation Research Part D: Transport and Environment, 56, 110-128.

D'alfonso, T., & Nastasi, A. (2014). Airport–Airline interaction: some food for thought. Transport Reviews, 34(6), 730-748.

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

Francois, J. F., & Hall, H. K. (1997). Partial equilibrium modeling. Applied methods for trade policy analysis: A handbook, 122-155.

Frank, R. H. (2008). Microeconomics and Behavior. Boston: McGraw-Hill Irwin,.

Fung, F., Zhu, Z., Becque, R., & Finamore, B. (2014). Prevention and control of shipping and port air emissions in China. Natural Resources Defence Council (NRDC) White Paper.

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

Hamin, E. M., & Gurran, N. (2009). Urban form and climate change: Balancing adaptation and mitigation in the US and Australia. Habitat international, 33(3), 238-245.

Hasson, R., Löfgren, Å., & Visser, M. (2010). Climate change in a public goods game: investment decision in mitigation versus adaptation. Ecological Economics, 70(2), 331-338.

Homsombat, W., Yip, T. L., Yang, H., & Fu, X. (2013). Regional cooperation and management of port pollution. *Maritime Policy & Management*, 40(5), 451-466.

Ingham, A., Ma, J., & Ulph, A. (2007). Climate change, mitigation and adaptation with uncertainty and learning. Energy Policy, 35(11), 5354-5369.

Jiang, C., Wan, Y., & Zhang, A. (2017). Internalization of port congestion: strategic effect behind shipping line delays and implications for terminal charges and investment. Maritime Policy & Management, 44(1), 112-130.

Kimmelman, M., & Haner, J. (2017, April 7). Rising waters imperil a world of progress in southern China delta. The New York Times. Retrieved from www. nytimes.com

Koetse, M. J., & Rietveld, P. (2009). The impact of climate change and weather on transport: An overview of empirical findings. Transportation Research Part D: Transport and Environment, 14(3), 205-221.

Mankiw, N. G. (2014). Principles of Economics. Cengage Learning.

Martens, P., McEvoy, D., & Change, C. (2009). The Climate Change Challenge: Linking Vulnerability, Adaptation, and Mitigation. *Environmental Sustainability*, *1*(1), 14–18.

Messner, S., Becker, A. & Ng, A.K.Y. (2016): 'Seaport adaptation for climate change: the roles of stakeholders and the planning process'. In: Ng, A.K.Y., Becker, A., Cahoon, S., Chen, S.L., Earl, P. and Yang, Z. (Eds.): *Climate Change and Adaptation Planning for Ports*. Routledge, Abingdon, pp. 9-23.

Ng, A. K., Monios, J., & Zhang, H. (2019). Climate adaptation management and institutional erosion: insights from a major Canadian port. Journal of Environmental Planning and Management, 62(4), 586-610.

Ng, A. K., Wang, T., Yang, Z., Li, K. X., & Jiang, C. (2018). How is business adapting to climate change impacts appropriately? Insight from the commercial port sector. Journal of Business Ethics, 150(4), 1029-1047.

Ng, A. K., Jiang, C., Larson, P., Prentice, B., & Duval, D. (2018). Transport Nodal System. Elsevier.

Park, H. K., Chang, Y. T., & Zou, B. (2018). Emission control under private port operator duopoly. *Transportation Research Part E: Logistics and Transportation Review*, 114, 40-65.

Policonomics (n.d.). Oligopoly I: Oligopolies. Retrieved August 3, 2020, from https://policonomics.com/lp-oligopoly1-oligopoly/

Randrianarisoa, L.M, & Zhang, A., 2019. Adaptation to Climate Change Effects and Competition Between Ports: Invest Now or Later? *Transportation Research Part B: Methodological,* 123, 279-322.

Rothengatter, W. (2010). Climate change and the contribution of transport: Basic facts and the role of aviation. *Transportation Research Part D: Transport and Environment*, 15(1), 5-13.

Shalizi, Z., & Lecocq, F. (2007). Balancing expenditures on mitigation of and adaptation to climate change: an exploration of issues relevant to developing countries. The World Bank.

Sharifi, A. (2020a). Trade-offs and conflicts between urban climate change mitigation and adaptation measures: A literature review. Journal of Cleaner Production, 122813.

Sharifi, A. (2020b). Co-benefits and synergies between urban climate change mitigation and adaptation measures: A literature review. Science of The Total Environment, 141642.

Sheng, D., Li, Z. C., Fu, X., & Gillen, D. (2017). Modeling the effects of unilateral and uniform emission regulations under shipping company and port competition. *Transportation Research Part E: Logistics and Transportation Review*, 101, 99-114.

Sloman, L., Hopkinson, L., & Taylor, I. (2017). The impact of road projects in England. TfQL Community Interest Company: Machynlleth, Wales.

Watson, R. T., Zinyowera, M. C., & Moss, R. H. (1996). *Climate Change 1995 impacts, adaptations and mitigation of climate change: Scientific-technical analysis*.

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

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

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

Yang Y.C. and Ge Y.E. (2020) Adaptation strategies for port infrastructure and facilities at the Kaohsiung port under climate change. *Transport Policy*, 97: 232-244.

Yang, H., & Zhang, A. (2012). Effects of high-speed rail and air transport competition on prices, profits and welfare. Transportation Research Part B: Methodological, 46(10), 1322-1333.

Appendix A: Detailed Mathematical Derivation Process

First, we differentiate equations (3) and (4) with respect to λ_{1a}, obtaining:

$$\frac{\partial^2\Pi_1}{\partial q_1{}^2}\frac{\partial q_1}{\partial\lambda_{1a}}+\frac{\partial^2\Pi_1}{\partial q_1\partial q_2}\frac{\partial q_2}{\partial\lambda_{1a}}-\lambda_{1m}C_1'e_1'-\lambda_{1a}\lambda_{1m}C_1''e_1'(\lambda_{1m}e_1'\frac{\partial q_1}{\partial\lambda_{1a}}+\lambda_{2m}e_2'\frac{\partial q_2}{\partial\lambda_{1a}})=0 \tag{5}$$

$$\frac{\partial^2\Pi_2}{\partial q_2{}^2}\frac{\partial q_2}{\partial\lambda_{1a}}+\frac{\partial^2\Pi_2}{\partial q_2\partial q_1}\frac{\partial q_1}{\partial\lambda_{1a}}-\lambda_{2a}\lambda_{2m}C_2''e_2'(\lambda_{1m}e_1'\frac{\partial q_1}{\partial\lambda_{1a}}+\lambda_{2m}e_2'\frac{\partial q_2}{\partial\lambda_{1a}})=0 \tag{6}$$

Solving equations (5) and (6) simultaneously, we have:

$$\frac{\partial q_1}{\partial\lambda_{1a}}=\frac{\lambda_{1m}C_1'e_1'(\lambda_{2m}{}^2\lambda_{2a}C_2''e_2'{}^2-\frac{\partial^2\Pi_2}{\partial q_2{}^2})}{M} \tag{7}$$

$$\frac{\partial q_2}{\partial\lambda_{1a}}=\frac{\lambda_{1m}C_1'e_1'(\frac{\partial^2\Pi_2}{\partial q_2\partial q_1}-\lambda_{1m}\lambda_{2m}\lambda_{2a}C_2''e_2'e_1')}{M} \tag{8}$$

where

$$M=\lambda_{2m}{}^2\lambda_{2a}C_2''e_2'{}^2\frac{\partial^2\Pi_1}{\partial q_1{}^2}+\lambda_{1m}{}^2\lambda_{1a}C_1''e_1'{}^2\frac{\partial^2\Pi_2}{\partial q_2{}^2}-\frac{\partial^2\Pi_1}{\partial q_1{}^2}\frac{\partial^2\Pi_2}{\partial q_2{}^2}-(\lambda_{1m}\lambda_{2m}\lambda_{2a}C_2''e_1'e_2'\frac{\partial^2\Pi_1}{\partial q_1\partial q_2}$$
$$+\lambda_{1m}\lambda_{2m}\lambda_{1a}C_1''e_1'e_2'\frac{\partial^2\Pi_2}{\partial q_2\partial q_1}-\frac{\partial^2\Pi_1}{\partial q_1\partial q_2}\frac{\partial^2\Pi_2}{\partial q_2\partial q_1})$$

Second, we differentiate equations (3) and (4) with respect to λ_{1m}, obtaining:

$$\frac{\partial^2\Pi_1}{\partial q_1{}^2}\frac{\partial q_1}{\partial\lambda_{1m}}+\frac{\partial^2\Pi_1}{\partial q_1\partial q_2}\frac{\partial q_2}{\partial\lambda_{1a}}-\lambda_{1a}C_1'e_1'-\lambda_{1m}\lambda_{1a}C_1''e_1'\left(e_1+\lambda_{1m}e_1'\frac{\partial q_1}{\partial\lambda_{1m}}+\lambda_{2m}e_2'\frac{\partial q_2}{\partial\lambda_{1m}}\right) \tag{9}$$
$$=0$$

$$\frac{\partial^2 \Pi_2}{\partial {q_2}^2}\frac{\partial q_2}{\partial \lambda_{1m}} + \frac{\partial^2 \Pi_2}{\partial q_2 \partial q_1}\frac{\partial q_1}{\partial \lambda_{1m}} - \lambda_{2m}\lambda_{2a}C_2''e_2'(e_1 + \lambda_{1m}e_1'\frac{\partial q_1}{\partial \lambda_{1m}} + \lambda_{2m}e_2'\frac{\partial q_2}{\partial \lambda_{1m}}) = 0 \quad (10)$$

Solving equations (9) and (10) simultaneously, we have:

$$\frac{\partial q_1}{\partial \lambda_{1m}} = \frac{\lambda_{1a}{\lambda_{2m}}^2\lambda_{2a}C_1'C_2''e_1'{e_2'}^2 + \lambda_{2m}\lambda_{2a}C_2''e_1e_2'\frac{\partial^2 \Pi_1}{\partial q_1 \partial q_2} - (C_1' + \lambda_{1m}C_1''e_1)\lambda_{1a}e_1'\frac{\partial^2 \Pi_2}{\partial {q_2}^2}}{M} \quad (11)$$

$$\frac{\partial q_2}{\partial \lambda_{1m}} = -\frac{\lambda_{1m}\lambda_{1a}\lambda_{2m}\lambda_{2a}C_1'C_2''{e_1'}^2e_2' - (C_1' + \lambda_{1m}e_1C_1'')\lambda_{1a}e_1'\frac{\partial^2 \Pi_2}{\partial q_2 \partial q_1} + \lambda_{2m}\lambda_{2a}C_2''e_1e_2'\frac{\partial^2 \Pi_1}{\partial {q_1}^2}}{M} \quad (12)$$

We focus on the initial state when $\lambda_{1m} = \lambda_{2m} = \lambda_{1a} = \lambda_{2a} = 1$. Therefore, equations (7), (8), (11) and (12) become:

$$\frac{\partial q_1}{\partial \lambda_{1a}} = \frac{C_1'e_1'(C_2''{e_2'}^2 - \frac{\partial^2 \Pi_2}{\partial {q_2}^2})}{\bar{M}} \quad (13)$$

$$\frac{\partial q_2}{\partial \lambda_{1a}} = \frac{C_1'e_1'(\frac{\partial^2 \Pi_2}{\partial q_2 \partial q_1} - C_2''e_1'e_2')}{\bar{M}} \quad (14)$$

$$\frac{\partial q_1}{\partial \lambda_{1m}} = \frac{C_1'C_2''e_1'{e_2'}^2 + C_2''e_1e_2'\frac{\partial^2 \Pi_1}{\partial q_1 \partial q_2} - (C_1' + C_1''e_1)e_1'\frac{\partial^2 \Pi_2}{\partial {q_2}^2}}{\bar{M}} \quad (15)$$

$$\frac{\partial q_2}{\partial \lambda_{1m}} = -\frac{C_1'C_2''{e_1'}^2e_2' - (C_1' + e_1C_1'')e_1'\frac{\partial^2 \Pi_2}{\partial q_2 \partial q_1} + C_2''e_1e_2'\frac{\partial^2 \Pi_1}{\partial {q_1}^2}}{\bar{M}} \quad (16)$$

where

$$\bar{M} = C_2'' {e_2'}^2 \frac{\partial^2 \Pi_1}{\partial {q_1}^2} + C_1'' {e_1'}^2 \frac{\partial^2 \Pi_2}{\partial {q_2}^2} - \frac{\partial^2 \Pi_1}{\partial {q_1}^2} \frac{\partial^2 \Pi_2}{\partial {q_2}^2} - (C_2'' e_1' e_2' \frac{\partial^2 \Pi_1}{\partial q_1 \partial q_2} + C_1'' e_1' e_2' \frac{\partial^2 \Pi_2}{\partial q_2 \partial q_1} - \frac{\partial^2 \Pi_1}{\partial q_1 \partial q_2} \frac{\partial^2 \Pi_2}{\partial q_2 \partial q_1})$$

If we also impose symmetry on the two ports, equations (13)-(16) become:

$$\frac{\partial q_i}{\partial \lambda_{ia}} = \frac{(C'' {e'}^2 - \frac{\partial^2 \Pi_i}{\partial {q_i}^2}) C' e'}{\bar{M}} \tag{17}$$

$$\frac{\partial q_j}{\partial \lambda_{ia}} = \frac{C' e' (\frac{\partial^2 \Pi_i}{\partial q_i \partial q_j} - C'' {e'}^2)}{\bar{M}} \tag{18}$$

$$\frac{\partial q_i}{\partial \lambda_{im}} = \frac{C' C'' {e'}^3 - C'' {e'}^2 (\frac{\partial^2 \Pi_i}{\partial {q_i}^2} - \frac{\partial^2 \Pi_i}{\partial q_i \partial q_j}) - C' e' \frac{\partial^2 \Pi_i}{\partial {q_i}^2}}{\bar{M}} \tag{19}$$

$$\frac{\partial q_j}{\partial \lambda_{im}} = - \frac{C' C'' {e'}^3 - C' e' \frac{\partial^2 \Pi_i}{\partial q_i \partial q_j} + C'' {e'}^2 (\frac{\partial^2 \Pi_i}{\partial {q_i}^2} - \frac{\partial^2 \Pi_i}{\partial q_i \partial q_j})}{\bar{M}} \tag{20}$$

where

$$\bar{M} = \left(2C'' {e'}^2 - \frac{\partial^2 \Pi_i}{\partial {q_i}^2} - \frac{\partial^2 \Pi_i}{\partial q_i \partial q_j}\right)\left(\frac{\partial^2 \Pi_i}{\partial {q_i}^2} - \frac{\partial^2 \Pi_i}{\partial q_i \partial q_j}\right)$$

From the condition $|\partial^2 \Pi_i / \partial q_i \partial q_j| < |\partial^2 \Pi_i / \partial {q_i}^2|$, we can easily derive that $\bar{M} < 0$.

Appendix B: Proofs of Propositions

2.1 Proof of Proposition 1:

Since $\partial^2\Pi_i/\partial {q_i}^2 < 0$, $\bar{M} < 0$, $C''e'^2 > 0$ and $C'e' > 0$, it is easy to conclude that $\partial q_i/\partial\lambda_{ia} < 0$.

Also, since $|\partial^2\Pi_i/\partial q_i\partial q_j| < |\partial^2\Pi_i/\partial {q_i}^2|$ while $\partial^2\Pi_i/\partial {q_i}^2 < 0$, meaning that $\partial^2\Pi_i/\partial {q_i}^2 - \partial^2\Pi_i/\partial q_i\partial q_j < 0$, so we have $-C''e'^2(\partial^2\Pi_i/\partial {q_i}^2 - \partial^2\Pi_i/\partial q_i\partial q_j) > 0$ due to the fact that $-C''e'^2 < 0$. Besides, as $C'C''e'^3 > 0$, $-C'e' * \partial^2\Pi_i/\partial {q_i}^2 > 0$ and $\bar{M} < 0$, we can conclude that $\partial q_i/\partial\lambda_{im} < 0$.

Since ${I_m}'(\lambda_{im}) < 0$ and ${I_a}'(\lambda_{ia}) < 0$, we can conclude that the efforts of CCM and CCA will both increase the output of the executing port.

Q.E.D.

2.2 Proof of Proposition 2:

From equations (17) and (19), we have

$$\frac{\partial q_i}{\partial\lambda_{ia}} - \frac{\partial q_i}{\partial\lambda_{im}} = \frac{(C''e'^2 - \frac{\partial^2\Pi_i}{\partial {q_i}^2})C'e'}{\bar{M}} - \frac{C'C''e'^3 - C''e'^2(\frac{\partial^2\Pi_i}{\partial {q_i}^2} - \frac{\partial^2\Pi_i}{\partial q_i\partial q_j}) - C'e'\frac{\partial^2\Pi_i}{\partial {q_i}^2}}{\bar{M}}$$

$$= \frac{C''e'^2(\frac{\partial^2\Pi_i}{\partial {q_i}^2} - \frac{\partial^2\Pi_i}{\partial q_i\partial q_j})}{\bar{M}} > 0$$

as $\bar{M} < 0$ and $C''e'^2(\partial^2\Pi_i/\partial {q_i}^2 - \partial^2\Pi_i/\partial q_i\partial q_j) < 0$.

Since we have proven that $\partial q_i/\partial\lambda_{ia} < 0$ and $\partial q_i/\partial\lambda_{im} < 0$, we can conclude that the CCM strategy has a larger marginal effect to stimulate a port's output compared with the CCA strategy. That is, with the same improvements in the effectiveness of CCM and CCA, mitigation measures will lead to a larger increase in port output.

Q.E.D.

2.3 Proof of Proposition 3:

From equation (18) we can see that when $\partial^2\Pi_i/\partial q_i\partial q_j \leq 0$, we have $\partial q_j/\partial\lambda_{ia} > 0$; while when $\partial^2\Pi_i/\partial q_i\partial q_j > 0$, $\partial q_j/\partial\lambda_{ia}$ can be either positive or negative.

From equation (20), we are not able to tell whether $\partial q_j/\partial\lambda_{im}$ is positive or negative, but we know that it has the same sign as $C'C''e'^3 - C'e'\partial^2\Pi_i/\partial q_i\partial q_j + C''e'^2(\partial^2\Pi_i/\partial {q_i}^2 - \partial^2\Pi_i/\partial q_i\partial q_j)$. The latter is more likely to be positive when $\partial^2\Pi_i/\partial q_i\partial q_j < 0$.

Q.E.D.

2.4 Proof of Proposition 4:

From equations (18) and (20), we have

$$\frac{\partial q_j}{\partial \lambda_{ia}} - \frac{\partial q_j}{\partial \lambda_{im}} = \frac{C'e'(\frac{\partial^2 \Pi_i}{\partial q_i \partial q_j} - C''e'^2)}{\bar{M}} + \frac{C'C''e'^3 - C'e'\frac{\partial^2 \Pi_i}{\partial q_i \partial q_j} + C''e'^2(\frac{\partial^2 \Pi_i}{\partial q_i^2} - \frac{\partial^2 \Pi_i}{\partial q_i \partial q_j})}{\bar{M}}$$

$$= \frac{C''e'^2(\frac{\partial^2 \Pi_i}{\partial q_i^2} - \frac{\partial^2 \Pi_i}{\partial q_i \partial q_j})}{\bar{M}} > 0$$

as $\bar{M} < 0$ and $C''e'^2(\partial^2 \Pi_i/\partial q_i^2 - \partial^2 \Pi_i/\partial q_i \partial q_j) < 0$.

As we can see from the comparison between equations (18) and (20), if $\partial q_j/\partial \lambda_{ia}$ is negative, then $\partial q_j/\partial \lambda_{im}$ must be negative. Therefore, we can conclude when $\partial q_j/\partial \lambda_{ia}$ and $\partial q_j/\partial \lambda_{im}$ are both positive, then $|\partial q_j/\partial \lambda_{ia}| - |\partial q_j/\partial \lambda_{im}| > 0$; when $\partial q_j/\partial \lambda_{ia}$ and $\partial q_j/\partial \lambda_{im}$ are both negative, then $|\partial q_j/\partial \lambda_{ia}| - |\partial q_j/\partial \lambda_{im}| < 0$; and the last possibility is that $\partial q_j/\partial \lambda_{ia}$ is positive while $\partial q_j/\partial \lambda_{im}$ is negative.

Q.E.D.