Container Ports' Competition Under Services Differentiation and Uncertainty: Governments' Sequential Moves

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Abstract

This paper examines governments' optimal facility investments and ports' optimal pricing under service differentiation and uncertainty settings. We construct a two-period sequential game, in which governments 1 and 2 determine their facility investments at the beginning of the first and the second periods respectively and ports choose their service prices at the end of each period. It is found that government 1 may not have the first-mover advantage. Governments' optimal facility investments are positively correlated with their expected market demand and competing ports' marginal costs, but are not affected by variances of stochastic demand (or cost). Differences of governments' facility investments between uncertainty and no uncertainty are also investigated. Finally, we analyze how ports' equilibrium prices are affected by their facility levels, marginal costs, service substitution degrees, as well as uncertainty conditions.

Keywords: port competition, service differentiation, sequential game, uncertainty

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1. Introduction

International trades not only contribute to a country's economic development, but also affect our daily lives in multi-dimensional ways. Ports and shipping services influence trading mechanisms in the context of supply chain and maritime logistics directly (see Song and Lee (2009)). Moreover, many container ports in Asia have been drastically developed because of their central governments' policies, causing fierce competition to capture transshipment and gateway cargoes generated in the common hinterlands. Therefore, understanding more thoroughly about interactions among governments, port authorities, and shipping liners, as well as their decision-making behaviors becomes a necessary and important issue. Game theory, which characterizes the interactions among multiple agents seeking their maximum payoffs, can certainly help to achieve this goal. Researchers in the field of maritime economics have noticed this and begun applying it to port and shipping fields.

Chen et al. (2010) refer many studies applying the game theory to shipping and port fields. For readers' convenience, we only recite recent works here. In De Borger et al.'s (2008) significant paper, they study optimal prices of two ports having downstream congestible transport networks to a common hinterland. Their paper allows governments to decide their optimal facility investments, and finds that ports will internalize the hinterland congestion cost and charge their customers accordingly, and ports' capacities are negatively correlated with their pricing. Following De Borger et al., Zhang (2009) analyzes how hinterland access conditions affect ports' competition. However, Zhang focuses on un-congestible ports and allows them to compete in terms of both price and quantity. He discovers that in quantity competition, expanding inland road capacity may not increase port's service and profit. Oppositely, under price competition, enlarging a region's corridor capacity will raise its port's service price and reduce the competitor's. Yuen et al. (2008) analyze how gateway congestion pricing affects optimal road pricing and social welfare of the hinterland. They discover that gateway charges will rise when congestion pricing is considered. And the increasing gateway charge will result in lower road tolls and social welfare of the hinterland. On the other hand, using Cournot and Stackelberg games, Gkonis and Paraftis (2009) examine optimal transportation capacities of two liquefied natural gas companies. They discuss possible collusions among the shipping companies too. Permitting a landlord port to lease terminals to its competing operators, Saeed and Larson (2009) explore influences of various contracts between the port authority and terminal operators on port's pricing in Pakistan. This work adopts a Bertrand game to characterize competition between two terminal operators, and the simulation outcomes show that optimal contracts offered by the port authority have high unit fee and low annual rent. Anderson et al. (2008b) employ a simple game to study whether two competing ports will invest in new facilities. They find that the investment decisions would depend on costs of the new facilities. Also, Anderson et al. (2008a) analyze how investment decisions of individual ports affect the market as well as the actions of all other competiting ports. Gkonis et al. (2009) use game theory to tackle the security problem in merchant shipping. Under cooperative-game frameworks, Saeed and Larsen (2010) study the coalition behaviors of three terminals in Karachi port of Pakistan, while Park et al. (2009) investigate the delay-cost problem between charter and ship owners.

Observing container port developments over the last four decades in Asia, we find that governments often involve heavily in constructing port-related infrastructures and facilities to satisfy countries' trading needs or to attract port users (see Lee and Flynn (2010)). Although the game models mentioned above examine ports' pricing from various perspectives, few study governments' optimal facility investments under rapidly changing and uncertain environments of the global economy. Moreover, little research discusses ports' pricing under uncertainty. On the other hand, despite that ports' services should be regarded as differential products due to their dissimilar locations and hinterlands (see Zhang (2009)), few works inspect how ports' differential services affect their pricing. Thus, this paper tries to fill the research gaps by analyzing governments' optimal facility investments and ports' optimal pricing under uncertainty and services differentiation. We construct a two-period sequential game to characterize ports' non-synchronous developments. In the first period, government 1 selects a facility level, and then ports regulated by different governments compete in service prices. In the second period, government 2 decides a facility level, and then the ports decide their service prices again. This paper will contribute to maritime economics by shedding lights on how governments and ports behave under service differentiation and unpredictable economic surroundings, and on whether governments' sequential moves matter.

We discover in this paper that government 1 may not own the first-mover advantage against government 2. That is, government 2 may own higher expected social welfare than government 1 does. Governments' optimal facility investments will increase with their rising expected market demand and competing pots' marginal costs, but will not alter with changing variances of stochastic demand. Nevertheless, impacts of other model parameters, such as own ports' marginal costs and the service substitution degree, on governments' optimal facility investments are indefinite. The differences of government 2's optimal facility levels between uncertainty and no uncertainty are determined entirely by the conditional mean of stochastic demand, while these differences for government 1 would depend on whether ports implement short-sighted or far-sighted development polices. Moreover, ports will raise their service prices when governments' facility investments decrease, ports' marginal costs increase, or market demands become stronger. However, ports may raise or lower their service prices with rising service substitution degrees. All of these outcomes stay true as the cost-side uncertainty and the dependence of demand and supply of ports' services are considered.

Before this research, Ishii et al. (2009) explore the impact of stochastic demand on ports' equilibrium pricing. However, governments' facility investments are fixed, instead of endogenous, in their model. On the other hand, De Borger et al. (2008)

discuss governments' facility investments in ports, but they do not deal with any uncertain shocks. Compared to them, we examine uncertainty effects but ignore the part of congestible transport networks to hinterland. Chen et al. (2010) performs similar analyses assuming that governments move simultaneously, and it considers both additive and multiplicative uncertainties.

The rest of this paper is organized as follows. The model is presented in Section 2. Sections 3 and 4 contain optimal behaviors of government 2 and ports in period 2 and those of government 1 and ports in period 1, respectively. Section 5 illustrates some implications of the obtained equilibria. The robustness of our findings is examined in Section 6. Finally, the conclusions are drawn in Section 7.

2. The Model

We consider a game-theoretic model consisting of ports 1 and 2. The services offered by the two ports are perceived as differentiated products by ports users given their different geographic characteristics and sizes of hinterlands. The inverse market demand functions faced by ports 1 and 2 are

$$p_1 = 1 + \theta - q_1 - bq_2 \text{ and} \tag{1}$$

$$p_2 = 1 + \theta - q_2 - bq_1, \text{respectively,} \tag{2}$$

where p_i is the price of unit cargo (e.g., TEU) charged by port i, and q_i is the amount of cargo handled by port i, $i = 1, 2$. Parameter $b \in (0, 1)$ represents the service substitution degree of the two ports. The larger b is, the higher the service substitution degree is. Let θ be a random variable characterizing demand uncertainty with value range of $(-1, 1)$, mean $\bar{\theta}$, variance σ^2, and probability density function (pdf) $f(\theta)$. Larger realized values of θ mean higher market demands. By rearranging (1)-(2), the market demand functions for ports 1 and 2 become

$$q_1 = \frac{1+\theta}{1+b} - \frac{p_1}{1-b^2} + \frac{bp_2}{1-b^2} \text{ and} \tag{3}$$

$$q_2 = \frac{1+\theta}{1+b} + \frac{bp_1}{1-b^2} - \frac{p_2}{1-b^2}, \text{ respectively.} \tag{4}$$

Governments provide basic facilities to promote ports' developments. The facilities include, among others, maritime access infrastructure (e.g., breakwater, channels, and navigated aids), and land access infrastructure (e.g., road, railway and inland water ways). When the facilities are enough, ports' service provision costs will decrease with increasing facilities. In contrast, when the facilities are insufficient, ports' provision costs cannot be reduced. Thus, it is plausible to assume that port i's service provision cost, given cargo amount q_i and facility level K_i, is

$$C_i(q_i,\ K_i) = \begin{cases} c_i q_i & \text{if } K_i < 1, \\ \frac{c_i}{K_i} q_i & \text{if } K_i \geq 1, \end{cases} \tag{5}$$

where $c_i \in (0,\ 1)$ is port i's marginal (provision) cost when zero or less-than-one-unit facility is provided by its government, $i = 1,\ 2$. Note that the threshold value of one-unit facility can be replaced by any other positive numbers without changing the results. And the qualitative results stay true if $\frac{c_i q_i}{K_i}$ is replaced with $\frac{c_i q_i}{h(K_i)}$, where $h(\cdot)$ is an increasing and strictly concave function of K_i. To have meaningful analyses, we focus on the facility level greater than one unit throughout this paper. Accordingly, by (3)-(5), we can get port i's profit function

$$\pi_i(p_i,\ p_j) = (p_i - \frac{c_i}{K_i}) \left[\frac{1+\theta}{1+b} - \frac{p_i}{1-b^2} + \frac{bp_j}{1-b^2} \right],\ i,\ j \in \{1,\ 2 \mid i \neq j\}. \tag{6}$$

To highlight the real-world situation of ports' non-synchronous developments in various countries, we construct the ensuing two-period sequential game. In the first period, government 1 selects a facility level maximizing her expected social welfare. Then, a realized value of the random demand variable is observed. Next, ports choose service prices simultaneously to maximize their profits. In the second period, given government 1's choice, government 2 decides a facility level maximizing her expected social welfare. A realized value of the random demand variable is then observed. Finally, both ports choose their service prices again. In this game, ports are assumed to compete in pricing. Actually, the results will not alter if ports compete in quantity, and they are available upon request. Moreover, we presume here that governments and ports have asymmetric information about demand shocks, because port authorities can access the market more easily and directly. The subgame perfect equilibrium (hereafter SPE) of this game are derived by backward induction as follows.

3. Optimal Behaviors of Government 2 and Ports in Period 2

Given both governments' facility levels $(K_1,\ K_2)$ and realized market demands in two periods $(\theta_1,\ \theta_2)$, ports will choose optimal service prices $(p_1^*,\ p_2^*)$ to solve the ensuing problem.

$$\max_{p_i>0}\ \pi_i(p_i,\ p_j) = (p_i - \frac{c_i}{K_i})\left[\frac{1+\theta_2}{1+b} - \frac{p_i}{1-b^2} + \frac{bp_j}{1-b^2}\right]$$

for $i,\ j \in \{1,\ 2 \mid i \neq j\}$. The first-order conditions for interior $(p_1^*,\ p_2^*)$ are

$$\frac{\partial \pi_1}{\partial p_1} = \frac{1+\theta_2}{1+b} + \frac{c_1}{(1-b^2)K_1} - \frac{2p_1^*}{(1-b^2)} + \frac{bp_2^*}{(1-b^2)} = 0 \text{ and} \tag{7}$$

$$\frac{\partial \pi_2}{\partial p_2} = \frac{1+\theta_2}{1+b} + \frac{c_2}{(1-b^2)K_2} - \frac{2p_2^*}{(1-b^2)} + \frac{bp_1^*}{(1-b^2)} = 0. \tag{8}$$

The second-order and stability conditions for $(p_1^*,\ p_2^*)$ hold because $\frac{\partial^2 \pi_i}{\partial p_i^2} = \frac{-2}{(1-b^2)} < 0$, $\frac{\partial^2 \pi_i}{\partial p_j \partial p_i} = \frac{b}{(1-b^2)} > 0$, and $\frac{\partial^2 \pi_i}{\partial p_i^2}\frac{\partial^2 \pi_j}{\partial p_j^2} - (\frac{\partial^2 \pi_i}{\partial p_j \partial p_i})^2 = \frac{4-b^2}{(1-b^2)^2} > 0$ for $i,\ j \in \{1,\ 2 \mid i \neq j\}$. Solving (7)-(8) yields

$$p_1^* = \frac{(1-b)(1+\theta_2)}{(2-b)} + \frac{1}{(4-b^2)}\left[\frac{c_2 b}{K_2} + \frac{2c_1}{K_1}\right] \text{ and} \tag{9}$$

$$p_2^* = \frac{(1-b)(1+\theta_2)}{(2-b)} + \frac{1}{(4-b^2)}\left[\frac{c_1 b}{K_1} + \frac{2c_2}{K_2}\right]. \tag{10}$$

Equations (9)-(10) imply that these optimal prices are affected by ports' facility levels, marginal costs, and service differentiation degree, as well as realized values of demand uncertainty. The relations are summarized below.

Lemma 1. For $i,\ j \in \{1,\ 2 \mid i \neq j\}$, *we have*

(i) $\frac{\partial p_i^*}{\partial K_i} = \frac{-2c_i}{(4-b^2)K_i^2} < 0$,

(ii) $\frac{\partial p_i^*}{\partial K_j} = \frac{-c_j b}{(4-b^2)K_j^2} < 0$,

(iii) $\frac{\partial p_i^*}{\partial c_i} = \frac{2}{(4-b^2)K_i} > 0$,

(iv) $\frac{\partial p_i^*}{\partial c_j} = \frac{b}{(4-b^2)K_j} > 0$,

(v) $\frac{\partial p_i^*}{\partial \theta_2} = \frac{(1-b)}{(2-b)} > 0$, *and*

(vi) $\frac{\partial p_i^*}{\partial b} \geq\ (\leq)\ 0$ *iff* $\theta_2 \leq\ (\geq)\ \theta_i^*$,

where $\theta_i^* = \frac{(4+b^2)c_j}{(2+b)^2 K_j} + \frac{4bc_i}{(2+b)^2 K_i} - 1 \in (-1,\ 0)$.

Proof. The proofs are straightforward, thus omitted.

When government i provides more facilities, port i's marginal costs and charging prices would decrease. Port j behaves the same because ports' service prices are strategic complements under the Bertrand competition. Theses are what Lemma 1(i)-(ii) say. On the other hand, as port i's marginal costs rise, it will charge its customers higher prices. Again, port j would do the same. These are the contents of Lemma 1(iii)-(iv). As market demands become larger, ports will raise their service prices as indicated by Lemma 1(v). Finally, part (vi) shows that the impacts of service substitution degree on ports' equilibrium prices are uncertain. When market demands are large enough ($\theta_2 \geq \theta_i^*$), port i will lower prices to attract more customers as competition with the other port becomes severer (i.e., b increases). In contrast, when market demands are not large enough ($\theta_2 < \theta_i^*$), port i will raise prices to compensate for its losses from the rising competition.

Substituting p_1^* and p_2^* into ports' profit functions in (6) generates their equilibrium profits, which are functions of facility levels and realized values of demand uncertainty as shown below.

$$\pi_1^*(K_1,\ K_2,\ \theta_2) = A_{\theta_2} + B_{\theta_2}(\tfrac{c_1}{K_1}) + D_{\theta_2}(\tfrac{c_2}{K_2}) + \tfrac{Fc_1c_2}{K_1K_2} + G(\tfrac{c_1}{K_1})^2 + H(\tfrac{c_2}{K_2})^2 \text{ and} \quad (11)$$

$$\pi_2^*(K_1,\ K_2,\ \theta_2) = A_{\theta_2} + B_{\theta_2}(\tfrac{c_2}{K_2}) + D_{\theta_2}(\tfrac{c_1}{K_1}) + \tfrac{Fc_1c_2}{K_1K_2} + G(\tfrac{c_2}{K_2})^2 + H(\tfrac{c_1}{K_1})^2, \quad (12)$$

where

$$A_{\theta_2} = \frac{(1-b)(1+\theta_2)^2}{(1+b)(2-b)^2} > 0, \tag{13}$$

$$B_{\theta_2} = \frac{2(1+\theta_2)(b^2-2)}{(1+b)(2+b)(2-b)^2} < 0, \tag{14}$$

$$D_{\theta_2} = \frac{2b(1+\theta_2)}{(1+b)(2+b)(2-b)^2} > 0, \tag{15}$$

$$F = \frac{2b(b^2-2)}{(1-b^2)(4-b^2)^2} < 0, \tag{16}$$

$$G = \frac{(b^2-2)^2}{(1-b^2)(4-b^2)^2} > 0, \text{ and} \tag{17}$$

$$H = \frac{b^2}{(1-b^2)(4-b^2)^2} > 0. \tag{18}$$

In particular, by letting $\theta_2 = 0$ in (11)-(12), we acquire ports' equilibrium profits under no uncertainty.

$$\pi_1^*(K_1,\ K_2,\ 0) = A + B(\frac{c_1}{K_1}) + D(\frac{c_2}{K_2}) + \frac{Fc_1c_2}{K_1K_2} + G(\frac{c_1}{K_1})^2 + H(\frac{c_2}{K_2})^2 \text{ and} \tag{19}$$

$$\pi_2^*(K_1,\ K_2,\ 0) = A + B(\frac{c_2}{K_2}) + D(\frac{c_1}{K_1}) + \frac{Fc_1c_2}{K_1K_2} + G(\frac{c_2}{K_2})^2 + H(\frac{c_1}{K_1})^2, \tag{20}$$

where

$$A = \frac{(1-b)}{(1+b)(2-b)^2} > 0, \tag{21}$$

$$B = \frac{2(b^2-2)}{(1+b)(2+b)(2-b)^2} < 0, \text{ and} \tag{22}$$

$$D = \frac{2b}{(1+b)(2+b)(2-b)^2} > 0. \tag{23}$$

Next, given ports' second-period equilibrium prices $(p_1^*,\ p_2^*)$, government 1's facility level K_1, and period 1's realized market demand θ_1, government 2 will choose K_2^* to maximize the ensuing expected social welfare.

$$\text{Max}_{K_2>1}\ SW_2(K_1,\ K_2,\ \theta_1) \equiv \int_{-1}^{1} \pi_2^*(K_1,\ K_2,\ \theta_2) f(\theta_2 \mid K_1,\ \theta_1) d\theta_2 - \gamma_2 K_2, \tag{24}$$

where $\gamma_2 > 0$ is unit investment cost faced by government 2 and $f(\theta_2 \mid K_1,\ \theta_1)$ is the conditional pdf of θ_2 given K_1 and θ_1. For simplicity, government 2's social welfare equals her port's profit subtracting facility investment cost without considering the surpluses of shipping lines and consumers located in the port's hinterlands. That is because the benefit of the former accrues to foreign firms and the consumers' is ignored due to our neglect of congestible transport networks to hinterlands. The same presumption is applied to government 1.

To facilitate subsequent analyses, denote

$$\begin{aligned}\mu(K_1,\ \theta_1) &= \int_{-1}^{1} \theta_2 f(\theta_2 \mid K_1,\ \theta_1) d\theta_2 \text{ and} \\ \sigma^2(K_1,\ \theta_1) &= \int_{-1}^{1} \theta_2^2 f(\theta_2 \mid K_1,\ \theta_1) d\theta_2 - [\mu(K_1,\ \theta_1)]^2\end{aligned}$$

the conditional mean and variance of θ_2 given K_1 and θ_1, respectively. In general, relative sizes of $\mu(K_1,\ \theta_1)$ and $\bar{\theta}$ (i.e., the unconditional mean of θ_2) are indefinite. Accordingly, we have

$$\begin{aligned}&\int_{-1}^{1} \pi_2^*(K_1,\ K_2,\ \theta_2) f(\theta_2 \mid K_1,\ \theta_1) d\theta_2 \\ =\ & A + B(\frac{c_2}{K_2}) + D(\frac{c_1}{K_1}) + \frac{Fc_1c_2}{K_1K_2} + G(\frac{c_2}{K_2})^2 + H(\frac{c_1}{K_1})^2 \\ &+\mu(K_1,\ \theta_1)[\frac{Dc_1}{K_1} + \frac{Bc_2}{K_2}] + A[2\mu(K_1,\ \theta_1) + \mu(K_1,\ \theta_1)^2 + \sigma^2(K_1,\ \theta_1)]. \quad (25)\end{aligned}$$

Equation (25) is derived in the Appendix. When there exists no uncertainty, government 2's social welfare function

$$\begin{aligned}&SW_2^{NU}(K_1,\ K_2) \\ \equiv\ & \pi_2^*(K_1,\ K_2,\ 0) - \gamma_2 K_2 \\ =\ & A + B(\frac{c_2}{K_2}) + D(\frac{c_1}{K_1}) + \frac{Fc_1c_2}{K_1K_2} + G(\frac{c_2}{K_2})^2 + H(\frac{c_1}{K_1})^2 - \gamma_2 K_2. \quad (26)\end{aligned}$$

Let K_2^{NU} be government 2's optimal facility investment under no uncertainty. Then, K_2^{NU} must satisfy the condition of

$$\frac{\partial SW_2^{NU}(K_1,\ K_2^{NU})}{\partial K_2} = 0 \quad (27)$$

for any given K_1. By (24)-(26), we can obtain

$$SW_2(K_1,\ K_2,\ \theta_1) \;=\; SW_2^{NU}(K_1,\ K_2)+\mu(K_1,\ \theta_1)[\frac{Dc_1}{K_1}+\frac{Bc_2}{K_2}] +A[2\mu(K_1,\ \theta_1)+\mu(K_1,\ \theta_1)^2+\sigma^2(K_1,\ \theta_1)]. \tag{28}$$

Differentiating (28) with respect to K_2 produces

$$\frac{\partial SW_2(K_1,\ K_2,\ \theta_1)}{\partial K_2}=\frac{\partial SW_2^{NU}(K_1,\ K_2)}{\partial K_2}-\frac{c_2B\mu(K_1,\ \theta_1)}{K_2^2}. \tag{29}$$

Thus, K_2^* must meet the necessary condition of

$$\frac{\partial SW_2(K_1,\ K_2^*,\ \theta_1)}{\partial K_2}=\frac{\partial SW_2^{NU}(K_1,\ K_2^*)}{\partial K_2}-\frac{c_2B\mu(K_1,\ \theta_1)}{(K_2^*)^2}=0 \tag{30}$$

for any given K_1. To make (30) the sufficient condition for K_2^* as well, the following assumption is needed.

Assumption 1: Given all $(K_1,\ \theta_1)$, social welfare function $SW_2(K_1,\ K_2,\ \theta_1)$ is strictly concave in K_2.

Proposition 1: *Under Assumption 1, the followings hold.*
(i) *If* $\mu(K_1,\ \theta_1)>0$, *we have* $K_2^*>K_2^{NU}$;
(ii) *If* $\mu(K_1,\ \theta_1)=0$, *we have* $K_2^*=K_2^{NU}$; *and*
(iii) *If* $\mu(K_1,\ \theta_1)<0$, *we have* $K_2^*<K_2^{NU}$.
Proof. See the Appendix.

Proposition 1 states that relative sizes of government 2's optimal facility investments under uncertainty and no uncertainty are determined solely by her conditional expectation about period 2's stochastic demand. When $\mu(K_1,\ \theta_1)>0$, government 2 would anticipate higher period 2's market demand after observing government 1's facility investment (K_1) and realized market demand of period 1 (θ_1). Since government 2 is optimistic about period 2's stochastic market demand, she will provide more facilities under uncertainty than under no uncertainty. This is what Proposition 1(i) shows. In contrast, if government 2 is pessimistic about the future market demand after observing K_1 and θ_1, i.e., $\mu(K_1,\ \theta_1)<0$, she will provide fewer facilities under uncertainty than under no uncertainty as indicated by Proposition 1(iii). However, if government 2 keeps her expectation neutral, i.e., $\mu(K_1,\ \theta_1) = 0$, her facility investments under uncertainty and no uncertainty are the same. That is the content of Proposition 1(ii).

Moreover, equations (29)-(30) suggest that government 2's optimal facility investment (K_2^*) is affected by the conditional mean of stochastic demand, government 1's facility investment, ports' marginal costs, and the service substitution degree. Nevertheless, K_2^* is not affected by the conditional variance of stochastic demand. These relations are summarized below.

Proposition 2: *Under Assumption 1, the followings hold.*
(i) $\frac{\partial K_2^*}{\partial \mu(K_1,\, \theta_1)} > 0$,
(ii) $\frac{\partial K_2^*}{\partial \sigma^2(K_1,\, \theta_1)} = 0$,
(iii) $\frac{\partial K_2^*}{\partial c_1} > 0$,
(iv) $\frac{\partial K_2^*}{\partial c_2} \geq\ (\leq)\ 0$ *iff* $[1 + \mu(K_1,\ \theta_1)]B + \frac{c_1 F}{K_1} + \frac{4c_2 G}{K_2^*} \leq\ (\geq)\ 0$,
(v) $\frac{\partial K_2^*}{\partial K_1} \geq\ (\leq)\ 0$ *iff* $\frac{\partial \mu(K_1,\, \theta_1)}{\partial K_1} \geq\ (\leq)\ \frac{c_1 F}{B K_1^2}$, *and*
(vi) $\frac{\partial K_2^*}{\partial b} \geq\ (\leq)\ 0$ *iff* $[1 + \mu(K_1,\ \theta_1)]\frac{\partial B}{\partial b} + \frac{c_1}{K_1}\frac{\partial F}{\partial b} + \frac{2c_2}{K_2^*}\frac{\partial G}{\partial b} \leq\ (\geq)\ 0$.
Proof. See the Appendix.

When government 2 expects higher future market demand, she will provide more facilities as indicated by Proposition 2(i). The conditional variance of stochastic demand does not appear in the first-order condition of (30), thus it will not affect government 2's optimal facility investment as shown in Proposition 2(ii). On the other hand, Proposition 2(iii) shows that government 2 will provide more facilities as port 1's marginal cost (c_1) increases. With rising c_1, both ports will raise their service prices by Lemma 1(iii)-(iv). Then, by equation (4), port 2's cargo handling amount will increase with port 1's rising prices due to their service substitution relation, but decrease with its own rising prices. However, the former effect will dominate, and the reason is provided as follows. Plugging (9)-(10) into (4) yields port 2's equilibrium cargo amount

$$q_2^* = \frac{1+\theta_2}{(1+b)(2-b)} + \frac{b}{(1-b^2)(4-b^2)}(\frac{c_1}{K_1}) + \frac{(b^2-2)}{(1-b^2)(4-b^2)}(\frac{c_2}{K_2}). \tag{31}$$

Equation (31) implies that $\frac{\partial q_2^*}{\partial c_1} = \frac{b}{(1-b^2)(4-b^2)K_1} > 0$. This means that port 2's equilibrium service price and amount will increase with port 1's rising marginal costs, so will port 2's equilibrium profit and government 2's expected social welfare. Thus, it is optimal for government 2 to provide more facilities. Nevertheless, as stated by Proposition 2(iv), the impact of port 2's marginal costs (c_2) on government 2's optimal facility investments is unsure. As shown by Lemma 1(iii)-(iv), rising c_2 will lead to ports' higher equilibrium prices. And port 2's cargo handling amount increases with port 1's rising equilibrium price, but decreases with port 2's rising price as indicated by equation (4). However, unlike Proposition 2 (iii), the later effect dominates because of $\frac{\partial q_2^*}{\partial c_2} = \frac{(b^2-2)}{(1-b^2)(4-b^2)K_2} < 0$ implied by (31). It means that ports 2's equilibrium cargo amount will fall. Then, port 2's equilibrium profit and government 2's expected social welfare may rise or fall because port 2's equilibrium service price and amount change oppositely. When the price effect dominates, which occurs if $[1+\mu(K_1,\ \theta_1)]B + \frac{c_1F}{K_1} + \frac{4c_2G}{K_2^*} < 0$, government 2 will provide more facilities since her expected social welfare will increase with rising c_2. In contrast, government 2 will provide fewer facilities with rising c_2 when the quantity effect dominates, which happens if $[1+\mu(K_1,\ \theta_1)]B + \frac{c_1F}{K_1} + \frac{4c_2G}{K_2^*} > 0$. And government 2 will keep her facility investments unchanged if the two effects are equal.

When government 2 is optimistic or not very pessimistic about the future market demand after seeing that government 1 provides more facilities, i.e., $\frac{\partial\mu(K_1,\,\theta_1)}{\partial K_1} > 0$ or $\frac{\partial\mu(K_1,\,\theta_1)}{\partial K_1} < 0$ with small $|\frac{\partial\mu(K_1,\,\theta_1)}{\partial K_1}|$, she will invest more as well. In contrast, if government 2 is pessimistic enough about the future market demand after observing that government 1 provides more facilities, i.e., $\frac{\partial\mu(K_1,\,\theta_1)}{\partial K_1} < 0$ with large $|\frac{\partial\mu(K_1,\,\theta_1)}{\partial K_1}|$, she will invest fewer facilities. This is the content of Proposition 2(v). Finally, the impact of ports' service substitution degree (b) on government 2's optimal facility investment is unsure. In Lemma 1(vi), impacts of b on ports' equilibrium service prices are indefinite. Accordingly, influences of b on ports' equilibrium cargo handling amounts and on government 2's expected social welfare are unclear as well. As in Proposition 2 (iv), when the price effect dominates, which happens at $[1+\mu(K_1,\ \theta_1)]\frac{\partial B}{\partial b}+\frac{c_1}{K_1}\frac{\partial F}{\partial b}+\frac{2c_2}{K_2^*}\frac{\partial G}{\partial b}<0$, government 2 will provide more facilities with rising b. And she will provide fewer facilities with rising b when the quantity effect dominates.

4. Optimal Behaviors of Government 1 and Ports in Period 1

In this section, we will derive ports' equilibrium service prices and government 1's optimal facility investment in the first period. In our two-period model, there are two ways to construct ports' first-period objective functions. First, ports are assumed short-sighted, i.e., they care period 1's payoffs only when choosing service prices in period 1. Second, ports are presumed far-sighted, i.e., they consider the sum of first-period's payoff and discounted second-period's payoff when selecting optimal service prices in period 1. Since government 1 cares the benefit of port 1 only, it is plausible that government 1 is far-sighted (short-sighted) when port 1 is far-sighted (short-sighted).[1] The two cases are discussed in Sections 4.1 and 4.2, respectively.

4.1. Short-Sighted Ports

Here ports choose service prices to maximize their first-period payoffs only. Under the circumstance, given $(K_1,\ \theta_1)$, ports 1's and 2's profit functions in period 1 are respectively

$$\pi_1(p_1,\ p_2) = (p_1-\frac{c_1}{K_1})[\frac{1+\theta_1}{1+b}-\frac{p_1}{1-b^2}+\frac{bp_2}{1-b^2}] \text{ and} \tag{32}$$

$$\pi_2(p_1,\ p_2) = (p_2-c_2)[\frac{1+\theta_1}{1+b}-\frac{p_2}{1-b^2}+\frac{bp_1}{1-b^2}]. \tag{33}$$

[1]Actually, the outcomes in the case of short-sighted port 1 and far-sighted government 1 are the same as those with port 1 and government 1 being both far-sighted, since the first-period behavior of far-sighted and short-sighted port 1 is the same.

Note that port 2's marginal production cost is c_2, instead of $\frac{c_2}{K_2}$, because government 2 does not invest in period 1. Accordingly, port i will select $\hat{p}_i$ to solve the following problem.

$$\hat{p}_i \in \arg\max_{p_i>0} \ \pi_i(p_i,\ p_j)$$

for $i,\ j = 1,\ 2$. And we can get

$$\hat{p}_1 = \frac{(1-b)(1+\theta_1)}{(2-b)} + \frac{1}{(4-b^2)}\left[c_2 b + \frac{2c_1}{K_1}\right] \text{ and} \tag{34}$$

$$\hat{p}_2 = \frac{(1-b)(1+\theta_1)}{(2-b)} + \frac{1}{(4-b^2)}\left[\frac{c_1 b}{K_1} + 2c_2\right]. \tag{35}$$

Equations (34)-(35) suggest that $\hat{p}_1$ and $\hat{p}_2$ own the following properties.

Lemma 2. For $i,\ j \in \{1,\ 2 \mid i \neq j\}$, *we have*

(i) $\frac{\partial \hat{p}_1}{\partial K_1} = \frac{-2c_1}{(4-b^2)K_1^2} < 0$ *and* $\frac{\partial \hat{p}_2}{\partial K_2} = 0$,

(ii) $\frac{\partial \hat{p}_1}{\partial K_2} = 0$ *and* $\frac{\partial \hat{p}_2}{\partial K_1} = \frac{-c_1 b}{(4-b^2)K_1^2} < 0$,

(iii) $\frac{\partial \hat{p}_1}{\partial c_1} = \frac{2}{(4-b^2)K_1} > 0$ *and* $\frac{\partial \hat{p}_2}{\partial c_2} = \frac{b}{(4-b^2)} > 0$,

(iv) $\frac{\partial \hat{p}_1}{\partial c_2} = \frac{b}{4-b^2} > 0$ *and* $\frac{\partial \hat{p}_2}{\partial c_1} = \frac{b}{(4-b^2)K_1} > 0$,

(v) $\frac{\partial \hat{p}_i}{\partial \theta_1} = \frac{(1-b)}{(2-b)} > 0$, *and*

(vi) $\frac{\partial \hat{p}_i}{\partial b} \geq\ (\leq)\ 0$ *iff* $\theta_1 \leq\ (\geq)\ \hat{\theta}_i$,

where $\hat{\theta}_1 = \frac{4bc_1}{(2+b)^2 K_1} + \frac{c_2(4+b^2)}{(2+b)^2} - 1$ *and* $\hat{\theta}_2 = \frac{4bc_2}{(2+b)^2} + \frac{c_1(4+b^2)}{(2+b)^2 K_1} - 1$.

Proof. The proofs are similar to those of Lemma 1.

All the intuitions of Lemma 2 are the same as Lemma 1's except that government 2's facility investment has no effect on ports' equilibrium pricing. That is because government 2 makes her investment decision in period 2, instead of period 1.

Substituting $(\hat{p}_1,\ \hat{p}_2)$ into ports' profit functions of (32)-(33) yields their first-period equilibrium profits,

$$\hat{\pi}_1(K_1,\ \theta_1) = A_{\theta_1} + B_{\theta_1}(\frac{c_1}{K_1}) + D_{\theta_1}c_2 + \frac{Fc_1c_2}{K_1} + G(\frac{c_1}{K_1})^2 + Hc_2^2 \text{ and} \tag{36}$$

$$\hat{\pi}_2(K_1,\ \theta_1) = A_{\theta_1} + B_{\theta_1}c_2 + D_{\theta_1}(\frac{c_1}{K_1}) + \frac{Fc_1c_2}{K_1} + Gc_2^2 + H(\frac{c_1}{K_1})^2, \tag{37}$$

where the definitions of A_{θ_1}, B_{θ_1} and D_{θ_1} are the same as (13)-(15) except that θ_2 is replaced with θ_1. In particular, by letting $\theta_1 = 0$ in (36)-(37), we can get both ports' first-period equilibrium profits under no uncertainty,

$$\hat{\pi}_1(K_1,\ 0) = A + B(\frac{c_1}{K_1}) + Dc_2 + \frac{Fc_1c_2}{K_1} + G(\frac{c_1}{K_1})^2 + Hc_2^2 \text{ and} \quad (38)$$

$$\hat{\pi}_2(K_1,\ 0) = A + Bc_2 + D(\frac{c_1}{K_1}) + \frac{Fc_1c_2}{K_1} + Gc_2^2 + H(\frac{c_1}{K_1})^2. \quad (39)$$

Given $(\hat{p}_1,\ \hat{p}_2)$, government 1's optimal facility investment K_1^* will solve the problem of

$$\max_{K_1>1} SW_1(K_1) \equiv \int_{-1}^{1} \hat{\pi}_1(K_1,\ \theta_1)f(\theta_1)d\theta_1 - \gamma_1 K_1,$$

where $\gamma_1 > 0$ is the unit investment cost faced by government 1. Employing the method deriving (25), we can acquire

$$\int_{-1}^{1} \hat{\pi}_1(K_1,\ \theta_1)f(\theta_1)d\theta_1 = A + B(\frac{c_1}{K_1}) + Dc_2 + \frac{Fc_1c_2}{K_1} + G(\frac{c_1}{K_1})^2 + Hc_2^2 + \bar{\theta}[\frac{c_1B}{K_1} + Dc_2] + A(2\bar{\theta} + \bar{\theta}^2 + \sigma^2). \quad (40)$$

Similarly, denote

$$SW_1^{NU}(K_1) \equiv \hat{\pi}(K_1,\ 0) - \gamma_1 K_1 = A + B(\frac{c_1}{K_1}) + Dc_2 + \frac{Fc_1c_2}{K_1} + G(\frac{c_1}{K_1})^2 + Hc_2^2 - \gamma_1 K_1 \quad (41)$$

government 1's social welfare under no uncertainty, and K_1^{NU} government 1's optimal facility investment under no uncertainty. That is, K_1^{NU} must satisfy the condition of

$$\frac{\partial SW_1^{NU}(K_1^{NU})}{\partial K_1} = 0.$$

By (40)-(41), we have

$$SW_1(K_1) = SW_1^{NU}(K_1) + \bar{\theta}\left[\frac{c_1B}{K_1} + Dc_2\right] + A(2\bar{\theta} + \bar{\theta}^2 + \sigma^2). \quad (42)$$

Differentiating both sides of (42) with respect to K_1 produces the necessary condition for K_1^*,

$$\frac{\partial SW_1(K_1^*)}{\partial K_1} = \frac{\partial SW_1^{NU}(K_1^*)}{\partial K_1} - \frac{c_1\bar{\theta}B}{(K_1^*)^2} = 0. \quad (43)$$

To make (43) the sufficient condition as well, the following assumption is needed.

Assumption 2: Social welfare function $SW_1(K_1)$ is strictly concave in K_1.

Proposition 3: *Under Assumption 2, the followings hold.*
(i) *If* $\bar{\theta} > 0$, *we have* $K_1^* > K_1^{NU}$;
(ii) *If* $\bar{\theta} = 0$, *we have* $K_1^* = K_1^{NU}$; *and*
(iii) *If* $\bar{\theta} < 0$, *we have* $K_1^* < K_1^{NU}$.
Proof. The proofs are similar to Proposition 1's, thus omitted.

Proposition 3 demonstrates that relative sizes of government 1's optimal facility investments under uncertainty and no uncertainty depend entirely on the sign of unconditional mean $\bar{\theta}$. Because Proposition 3's intuitions are similar to Proposition 1's, they are not explained.

By analyzing (43), we summarize impacts of the mean and variance of stochastic demand, ports' marginal costs, and the service substitution degree on short-sighted government 1's optimal facility investment below.

Proposition 4: *Under Assumption 2, the followings hold.*
(i) $\frac{\partial K_1^*}{\partial \bar{\theta}} > 0$,
(ii) $\frac{\partial K_1^*}{\partial \sigma^2} = 0$,
(iii) $\frac{\partial K_1^*}{\partial c_2} > 0$,
(iv) $\frac{\partial K_1^*}{\partial c_1} \geq \ (\leq)\ 0$ *iff* $(1+\bar{\theta})B + c_2 F + \frac{4c_1 G}{K_1^*} \leq \ (\geq)\ 0,$ *and*
(v) $\frac{\partial K_1^*}{\partial b} \geq \ (\leq)\ 0$ *iff* $(1+\bar{\theta})\frac{\partial B}{\partial b} + c_2 \frac{\partial F}{\partial b} + \frac{2c_1}{K_1^*}\frac{\partial G}{\partial b} \leq \ (\geq)\ 0.$
Proof. The proofs are similar to Proposition 2's.

And Proposition 4's intuitions are completely the same as Proposition 2's.

4.2. Far-Sighted Ports

In the far-sighted case, ports choose service prices to maximize their total payoffs, which equal the sum of first-period's payoff and discounted second-period's equilibrium profit. Precisely, given $(K_1,\ \theta_1,\ \theta_2)$ and port 2's optimal facility level $K_2^* = K_2^*(K_1,\ \theta_1)$, ports 1's and 2's total payoffs are respectively

$$\Pi_1(K_1,\ \theta_1,\ \theta_2) = (p_1 - \frac{c_1}{K_1})[\frac{1+\theta_1}{1+b} - \frac{p_1}{1-b^2} + \frac{bp_2}{1-b^2}] + \delta\pi_1^*(K_1,\ K_2^*,\ \theta_2) \text{and} \tag{44}$$

$$\Pi_2(K_1,\ \theta_1,\ \theta_2) = (p_2 - c_2)[\frac{1+\theta_1}{1+b} - \frac{p_2}{1-b^2} + \frac{bp_1}{1-b^2}] + \delta\pi_2^*(K_1,\ K_2^*,\ \theta_2), \tag{45}$$

where $\delta \in (0,\ 1)$ is the common discounted factor for ports, and $\pi_1^*(K_1,\ K_2^*,\ \theta_2)$ and $\pi_2^*(K_1,\ K_2^*,\ \theta_2)$ are ports' second-period equilibrium profits evaluated at K_2^*, whose definitions are given in (11)-(12). Consequently, port i will pick price $\tilde{p}_i$ to maximize its total payoff. That is,

$$\tilde{p}_i \in \arg\max_{p_i>0}\ \Pi_i(K_1,\ \theta_1,\ \theta_2),\ i = 1,\ 2.$$

Since ports' equilibrium second-period profits are not affected by $\tilde{p}_1$ and $\tilde{p}_2$, it is equivalent to having $\tilde{p}_i$ maximizing first-period's profit as in Section 4.1. Thus, we have $\tilde{p}_i = \hat{p}_i,\ i = 1,\ 2$, which are defined in (34)-(35). Therefore, $\tilde{p}_1$ and $\tilde{p}_2$ own the properties of Lemma 2. Substituting (36)-(37) into (44)-(45) will generate ports 1's and 2's equilibrium total payoffs,

$$\Pi_1^*(K_1,\ \theta_1,\ \theta_2) = \hat{\pi}_1(K_1,\ \theta_1) + \delta\pi_1^*(K_1,\ K_2^*,\ \theta_2) \text{ and} \tag{46}$$

$$\Pi_2^*(K_1,\ \theta_1,\ \theta_2) = \hat{\pi}_2(K_1,\ \theta_1) + \delta\pi_2^*(K_1,\ K_2^*,\ \theta_2), \text{ respectively.} \tag{47}$$

In particular, by letting $\theta_1 = \theta_2 = 0$ in (46)-(47), we can acquire ports' equilibrium total payoffs under no uncertainty,

$$\Pi_1^*(K_1,\ 0,\ 0) = \hat{\pi}_1(K_1,\ 0) + \delta\pi_1^*(K_1,\ K_2^*(K_1,\ 0),\ 0) \text{ and} \tag{48}$$

$$\Pi_2^*(K_1,\ 0,\ 0) = \hat{\pi}_2(K_1,\ 0) + \delta\pi_2^*(K_1,\ K_2^*(K_1,\ 0),\ 0), \tag{49}$$

where $\hat{\pi}_1(K_1,\ 0)$ and $\hat{\pi}_2(K_1,\ 0)$ are defined in (38)-(39), and $K_2^*(K_1,\ 0)$ is derived from (30) assuming $\theta_1 = 0$.

Finally, given $(\tilde{p}_1,\ \tilde{p}_2)$, government 1 will choose $\tilde{K}_1$ to maximize her expected social welfare. That is,

$$\tilde{K}_1 \in \arg\max_{K_1>1}\ \ TSW_1(K_1) \equiv E\Pi_1^*(K_1) - \gamma_1 K_1,$$

where $E\Pi_1^*(K_1) = \int_{-1}^{1}[\int_{-1}^{1}\Pi_1^*(K_1,\ \theta_1,\ \theta_2)f(\theta_2 \mid K_1,\ \theta_1)d\theta_2]f(\theta_1)d\theta_1$ is government 1's expected equilibrium total payoff earned by port 1. By simple calculations, we have

$$\begin{aligned}
& E\Pi_1^*(K_1) \\
= \ & \int_{-1}^{1}\hat{\pi}_1(K_1,\ \theta_1)f(\theta_1)d\theta_1 + \delta\int_{-1}^{1}\left[\int_{-1}^{1}\pi_1^*(K_1,\ K_2^*,\ \theta_2)f(\theta_2 \mid K_1,\ \theta_1)d\theta_2\right]f(\theta_1)d\theta_1 \\
= \ & A + B\frac{c_1}{K_1} + Dc_2 + \frac{Fc_1c_2}{K_1} + G(\frac{c_1}{K_1})^2 + Hc_2^2 + \bar{\theta}[\frac{Bc_1}{K_1} + Dc_2] \\
& + A(2\bar{\theta} + \bar{\theta}^2 + \sigma^2) + \delta E\pi_1^*(K_1), \qquad (50)
\end{aligned}$$

where $E\pi_1^*(K_1) = \int_{-1}^{1}[\int_{-1}^{1}\pi_1^*(K_1,\ K_2^*,\ \theta_2)f(\theta_2 \mid K_1,\ \theta_1)d\theta_2]f(\theta_1)d\theta_1$ is government 1's expected second-period equilibrium profit earned by port 1.

To compare with the optimal facility level under no uncertainty, denote

$$TSW_1^{NU}(K_1) \equiv \Pi_1^*(K_1,\ 0,\ 0) - \gamma_1 K_1 \qquad (51)$$

government 1's total social welfare under no uncertainty, which consists of port 1's equilibrium total payoff under no uncertainty subtracting the investment cost. Let K_1^{NU} be the facility level maximizing TSW_1^{NU}. Then, K_1^{NU} must meet the condition of

$$\frac{\partial TSW_1^{NU}(K_1^{NU})}{\partial K_1} = 0.$$

By (50)-(51), $TSW_1(K_1)$ can be rewritten as

$$TSW_1(K_1) = TSW_1^{NU}(K_1) + \bar{\theta}[\frac{c_1 B}{K_1} + Dc_2] + A(2\bar{\theta} + \bar{\theta}^2 + \sigma^2) + \delta\triangle(K_1), \qquad (52)$$

where $\triangle(K_1) = E\pi_1^*(K_1) - \pi_1^*(K_1,\ K_2^*(K_1,\ 0),\ 0)$ represents the difference between government 1's expectations about port 1's second-period equilibrium profits under uncertainty and no uncertainty, given facility level K_1. Differentiating both sides of (52) with respect to K_1 yields

$$\frac{\partial TSW_1(K_1)}{\partial K_1} = \frac{\partial TSW_1^{NU}(K_1)}{\partial K_1} - \frac{c_1\bar{\theta}B}{K_1^2} + \delta\frac{\partial\triangle(K_1)}{\partial K_1}. \tag{53}$$

Thus, $\tilde{K}_1$ must satisfy the necessary condition of

$$\frac{\partial TSW_1(\tilde{K}_1)}{\partial K_1} = \frac{\partial TSW_1^{NU}(\tilde{K}_1)}{\partial K_1} - \frac{c_1\bar{\theta}B}{(\tilde{K}_1)^2} + \delta\frac{\partial\triangle(\tilde{K}_1)}{\partial K_1} = 0. \tag{54}$$

To make (54) sufficient condition for $\tilde{K}_1$ as well, the following assumption is needed.

Assumption 3: Social welfare function $TSW_1(K_1)$ is strictly concave in K_1.

Proposition 5: *Under Assumption 3, we have the followings.*
(i) *If* $\delta\frac{\partial\triangle(K_1^{NU})}{\partial K_1} - \frac{c_1\bar{\theta}B}{(K_1^{NN})^2} > 0$, *then* $\tilde{K}_1 > K_1^{NU}$;
(ii) *If* $\delta\frac{\partial\triangle(K_1^{NU})}{\partial K_1} - \frac{c_1\bar{\theta}B}{(K_1^{NU})^2} = 0$, *then* $\tilde{K}_1 = K_1^{NU}$; *and*
(iii) *If* $\delta\frac{\partial\triangle(K_1^{NU})}{\partial K_1} - \frac{c_1\bar{\theta}B}{(K_1^{NU})^2} < 0$, *then* $\tilde{K}_1 < K_1^{NU}$.
Proof. See the Appendix.

Unlike Proposition 3, Proposition 5 shows that the difference between government 1's optimal facilities under uncertainty and no uncertainty depends not only on the mean of stochastic demand ($\bar{\theta}$), but on other parameters such as the service substitution degree (b), the discount factor (δ), and ports' marginal costs (c_1 and c_2).

Moreover, impacts of the mean and variance of stochastic demand, ports' marginal costs, and the service substitution degree on far-sighted government 1's optimal facility levels are summarized below.

Proposition 6: *Under Assumption 3, we have the followings.*
(i) $\frac{\partial\tilde{K}_1}{\partial\bar{\theta}} > 0$,
(ii) $\frac{\partial\tilde{K}_1}{\partial\sigma^2} = 0$,
(iii) $\frac{\partial\tilde{K}_1}{\partial c_2} \geq (\leq)\ 0$ *iff* $\frac{\partial^2\Pi_1^*(\tilde{K}_1,0,0)}{\partial c_2\partial K_1} \geq (\leq)\ -\delta\frac{\partial^2\Delta(K_1)}{\partial c_2\partial K_1}$,
(iv) $\frac{\partial\tilde{K}_1}{\partial c_1} \geq (\leq)\ 0$ *iff* $\frac{\partial^2\Pi_1^*(\tilde{K}_1,0,0)}{\partial c_1\partial K_1} \geq (\leq)\ \frac{\bar{\theta}B}{(\tilde{K}_1)^2} - \delta\frac{\partial^2\Delta(\tilde{K}_1)}{\partial c_1\partial K_1}$, *and*

(v) $\frac{\partial \tilde{K}_1}{\partial b} \geq\ (\leq)\ 0$ *iff* $\frac{\partial^2 \Pi_1^*(\tilde{K}_1,\,0,\,0)}{\partial b \partial K_1} \geq\ (\leq)\ \frac{c_1 \bar{\theta}}{(\tilde{K}_1)^2}\frac{\partial B}{\partial b} - \delta \frac{\partial^2 \Delta(\tilde{K}_1)}{\partial b \partial K_1}$.
Proof. The proofs are similar to Proposition 4's.

The intuitions of Proposition 6(i)-(ii), (iv), and (v) are the same as those of Proposition 4, while the finding of Proposition 6(iii) differs from that of Proposition 4(iii) and its reason is given below. The impact of port 2's marginal cost (c_2) on government 1's optimal facility level consists of a direct and an indirect effects. The direct effect refers to c_2 affecting government 1's optimal first-period facility level, and is positive as displayed in Proposition 4(iii). However, government 2's optimal facility level (K_2^*) will alter with varying K_1. Accordingly, government 1's second-period equilibrium social welfare will also change with varying K_1, which is the indirect effect. Far-sighted government 1 would consider this indirect effect when making decision at period 1. Since Proposition 2(v) demonstrates that the influence of K_1 on K_2^* is unsure, the impact of port 2's marginal costs on government 1's optimal facility level is also indefinite.

5. Some Implications of Subgame Perfect Equilibria

In sequential games without considering uncertainty and asymmetric information, first movers usually own some advantages over the followers. Our settings allow uncertainty and asymmetric information. Thus, it is worthy exploring the conditions under which the first-mover advantage exists.

We first compare equilibrium expected social welfares of both governments when ports are short-sighted. Substituting SPE ($K_1^*,\ (\hat{p}_1,\ \hat{p}_2),\ K_2^*, (p_1^*,\ p_2^*)$) into (28) and (42) generates governments 1's and 2's equilibrium expected social welfares,

$$\begin{aligned} SW_1^* &\equiv \hat{\pi}_1(K_1^*,\ 0) - \gamma_1 K_1^* + \bar{\theta}\left[\frac{Bc_1}{K_1^*} + Dc_2\right] + A[2\bar{\theta} + \bar{\theta}^2 + \sigma^2] \text{ and} \\ SW_2^* &\equiv \pi_2^*(K_1^*,\ K_2^*,\ 0) - \gamma_2 K_2^* + \mu(K_1^*,\ \theta_1)[\frac{Bc_2}{K_2^*} + \frac{Dc_1}{K_1^*}] \\ &\quad + A[2\mu(K_1^*,\ \theta_1) + \mu(K_1^*,\ \theta_1)^2 + \sigma^2(K_1^*,\ \theta_1)], \end{aligned}$$

where

$$\hat{\pi}_1(K_1^*,\ 0) = A + \frac{c_1 B}{K_1^*} + Dc_2 + \frac{c_1 c_2 F}{K_1^*} + G(\frac{c_1}{K_1^*})^2 + Hc_2^2 \text{ and}$$
$$\pi_2^*(K_1^*,\ K_2^*,\ 0) = A + \frac{c_2 B}{K_2^*} + \frac{c_1 D}{K_1^*} + \frac{c_1 c_2 F}{K_1^* K_2^*} + G(\frac{c_2}{K_2^*})^2 + H(\frac{c_1}{K_1^*})^2.$$

Let us consider a simple case with $c_1 = c_2 = c$, $\gamma_1 = \gamma_2 = \gamma$, and $\bar{\theta} = 0$, meaning that ports' marginal costs are symmetric, governments face the same unit investment cost, and the unconditional mean of stochastic demand is zero. Under the circumstance, we have $K_1^* = K_1^{NU} = K_2^{NU}$, $K_2^* > K_2^{NU} = K_1^*$, and

$$\begin{aligned} SW_1^* - SW_2^* &= [\hat{\pi}_1(K_1^*,\ 0) - \pi_2^*(K_1^*,\ K_2^*,\ 0)] - \gamma(K_1^* - K_2^*) - c\mu(K_1^*,\ \theta_1)[\frac{B}{K_2^*} + \frac{D}{K_1^*}] \\ &\quad + A(\sigma^2 - \sigma^2(K_1^*,\ \theta_1)) - A[2\mu(K_1^*,\ \theta_1) + \mu(K_1^*,\ \theta_1)^2]. \end{aligned} \tag{55}$$

The signs of the first, third, fourth, and fifth terms on the RHS of (55) are unsure, and the second term is positive. In general, relative sizes of the conditional and unconditional means (or variances) of stochastic demand could be positive or negative. By analyzing (55), we can obtain the followings.

Lemma 3: *Suppose* $c_1 = c_2 = c$, $\gamma_1 = \gamma_2 = \gamma$, *and* $\bar{\theta} = 0$. *Then we have* $SW_2^* > SW_1^*$ *if* $\mu(K_1^*,\ \theta_1) > 0$ *and* $\sigma^2(K_1^*,\ \theta_1) > \sigma^2 + t_1$. *In contrast, we have* $SW_1^* > SW_2^*$ *if* $\mu(K_1^*,\ \theta_1) < 0$ *and* $\sigma^2 > \sigma^2(K_1^*,\ \theta_1) + t_2$. *Here* $t_1 = \frac{1}{A}\{|\hat{\pi}_1(K_1^*,\ 0) - \pi_2^*(K_1^*,\ K_2^*,\ 0)| + \gamma(K_2^* - K_1^*) + c\mu(K_1^*,\ \theta_1)|\frac{B}{K_2^*} + \frac{D}{K_1^*}|\} > 0$ *and* $t_2 = \frac{1}{A}\{|\hat{\pi}_1(K_1^*,\ 0) - \pi_2^*(K_1^*,\ K_2^*,\ 0)| - c\mu(K_1^*,\ \theta_1)|\frac{B}{K_2^*} + \frac{D}{K_1^*}|\} > 0$.

Proof. See the Appendix.

Positive $\mu(K_1^*,\ \theta_1)$ implies that government 2 is optimistic about the future market demand. Thus, she will provide more facilities. On the other hand, the condition of $\sigma^2(K_1^*,\ \theta_1)$ being bigger enough than σ^2 suggests that government 2 will face larger variations of the future market demand than government 1. Proposition 2(ii) and Proposition 4(ii) show that the (conditional) variance of stochastic demand will not affect governments' optimal facility levels. However, as indicated by (12)-(15) and (36), ports' equilibrium profits are convex functions of realized stochastic demands (θ_1 or θ_2). This in turn reflects that governments are risk-lovers in facing demand uncertainty. Thus, the larger the variance of stochastic demand is, the higher equilibrium social welfares governments will have. Hence, government 2 may own the second-mover advantage. In contrast, under negative conditional means and large enough unconditional variances of stochastic demand, government 1 will have the first-mover advantage because government 2 has little incentive to provide more facilities and risk-loving government 1 faces bigger variations of the future market demand. Outcomes of Lemma 3 state that governments developing their ports later may have larger benefits (or equilibrium expected social welfare) than those moving earlier especially when the future market demand has high volatility.

Finally, similar results could be acquired when ports are far-sighted.

6. Extensions

In this section, we show that our findings in Sections 2-5 stay true qualitatively when uncertainty comes from the cost side, or when customers' service demands depend on ports' facility levels. All the proofs are available upon request.

6.1. Cost Uncertainty

In the real world, uncertainty could arise from the cost side, such as oil price shocks, random cargo loading and unloading situations, and wage disputes between port authorities and labor unions. Let us consider the following stochastic cost function for port i,

$$C_i(q_i,\ K_i,\ \epsilon) = [\frac{c_i}{K_i} - \epsilon]q_i,\ i = 1,\ 2, \tag{56}$$

where ϵ represents the cost-side uncertainty of ports with mean $\bar{\epsilon}$ and variance σ_ϵ^2. The larger ϵ is, the lower marginal costs ports have. On the other hand, the market demands faced by ports 1 and 2 are

$$q_1 = \frac{1}{1+b} - \frac{p_1}{1-b^2} + \frac{bp_2}{1-b^2} \text{ and} \tag{57}$$

$$q_2 = \frac{1}{1+b} + \frac{bp_1}{1-b^2} - \frac{p_2}{1-b^2}, \text{ respectively.} \tag{58}$$

By (56)-(58), port i's profit function is

$$\pi_i(p_i,\ p_j) = [p_i - \frac{c_i}{K_i} + \epsilon][\frac{1}{1+b} - \frac{p_i}{1-b^2} + \frac{bp_j}{1-b^2}]$$

for $i,\ j = 1,\ 2$. Accordingly, the associated first-order conditions for interior equilibrium prices are

$$\frac{\partial \pi_1}{\partial p_1} = \frac{1}{1+b} - \frac{\epsilon}{1-b^2} + \frac{c_1}{(1-b^2)K_1} - \frac{2p_1}{1-b^2} + \frac{bp_2}{1-b^2} = 0 \text{ and} \tag{59}$$

$$\frac{\partial \pi_2}{\partial p_2} = \frac{1}{1+b} - \frac{\epsilon}{1-b^2} + \frac{c_2}{(1-b^2)K_2} - \frac{2p_2}{1-b^2} + \frac{bp_1}{1-b^2} = 0. \tag{60}$$

Equations (59)-(60) can be reduced to (7)-(8) if θ_2 in (7)-(8) is replaced by $\frac{-\epsilon}{(1-b)}$. It suggests that the cost-side uncertainty defined in (56) rescales the demand uncertainty defined in (1)-(2). Thus, the outcomes in Sections 2-5 would remain true qualitatively.

6.2. Dependence of Demand and Supply of Ports' Services

In Sections 2-5, the demand and supply of ports' services are implicitly assumed independent. However, they may not be. For instance, shipping lines are attracted by the ports with more facilities to save time. We will address this issue here and show that considering the dependence of demand and supply of ports' services will not alter the results.

Let the inverse demand functions faced by ports 1 and 2 be

$$p_1 = 1 + \theta + K_1 - q_1 - bq_2 \text{ and} \tag{61}$$

$$p_2 = 1 + \theta + K_2 - q_2 - bq_1, \text{respectively.} \tag{62}$$

The larger facility levels ports have, the more service demands ports face. By rearranging (61)-(62), we can obtain demand functions of ports 1 and 2,

$$
\begin{aligned}
q_1 &= \frac{1+\theta}{1+b} + \frac{K_1 - bK_2}{1-b^2} - \frac{p_1}{1-b^2} + \frac{bp_2}{1-b^2} \text{ and} \\
q_2 &= \frac{1+\theta}{1+b} + \frac{K_2 - bK_1}{1-b^2} + \frac{bp_1}{1-b^2} - \frac{p_2}{1-b^2}, \text{ respectively.}
\end{aligned}
$$

Ports' cost functions are assumed the same as those in (5). Then, port i's profit function

$$\pi_i(p_i,\ p_j) = (p_i - \frac{c_i}{K_i})[\frac{1+\theta}{1+b} + \frac{K_i - bK_j}{1-b^2} - \frac{p_i}{1-b^2} + \frac{bp_j}{1-b^2}],\ i,\ j = 1,\ 2. \tag{63}$$

Consequently, we can acquire ports' equilibrium prices,

$$
\begin{aligned}
\check{p}_1 &= \frac{(1-b)(1+\theta_2)}{(2-b)} + \frac{1}{(4-b^2)}\left[\frac{c_2 b}{K_2} + \frac{2c_1}{K_1}\right] + \frac{(2-b^2)K_1 - bK_2}{4-b^2} \text{ and} \\
\check{p}_2 &= \frac{(1-b)(1+\theta_2)}{(2-b)} + \frac{1}{(4-b^2)}\left[\frac{c_1 b}{K_1} + \frac{2c_2}{K_2}\right] + \frac{(2-b^2)K_2 - bK_1}{4-b^2}.
\end{aligned}
$$

Here $\check{p}_1$ and $\check{p}_2$ own the same properties as those in Lemma 1 except that the sign of $\frac{\partial \check{p}_i}{\partial K_i}$ becomes uncertain.[2]

Substituting equilibrium price $(\check{p}_1,\ \check{p}_2)$ into ports' profit functions in (63) produces ports' equilibrium profit functions below.

$$
\begin{aligned}
\check{\pi}_1(K_1,\ K_2,\ \theta_2) = \ & A_{\theta_2} + B_{\theta_2}(\frac{c_1}{K_1}) + D_{\theta_2}(\frac{c_2}{K_2}) + \frac{Fc_1c_2}{K_1K_2} + G(\frac{c_1}{K_1})^2 + H(\frac{c_2}{K_2})^2 \\
& + \frac{[(2-b^2)K_1 - bK_2]^2}{(4-b^2)^2(1-b^2)} + \frac{2(1+\theta_2)[(2-b^2)K_1 - bK_2]}{(4-b^2)(1+b)(2-b)} \\
& + \frac{c_1}{K_1}[\frac{2(b^2-2)[(2-b^2)K_1 - bK_2]}{(4-b^2)^2(1-b^2)}] + \frac{c_2}{K_2}[\frac{2b[(2-b^2)K_1 - bK_2]}{(4-b^2)^2(1-b^2)}]
\end{aligned}
$$

[2] Contrary to Lemma 1(i), we have $\frac{\partial \check{p}_i}{\partial K_i} = \frac{-2c_i + (2-b^2)K_i^2}{(4-b^2)K_i^2}$, hence $\frac{\partial \check{p}_i}{\partial K_i} \geq\ (\leq)\ 0$ iff $2c_i \leq\ (\geq)\ (2-b^2)K_i^2,\ i = 1,\ 2$. As in Lemma 1(i), rising K_i will lead to lower marginal costs of port i, hence port i will decrease its service price. However, under the settings of (61)-(62), rising K_i will raise cargo handling demands for port i, so will its service price. Thus, the total effect of K_i on $\check{p}_i$ is indefinite.

and

$$\begin{aligned}\check{\pi}_2(K_1,\ K_2,\ \theta_2) &= A_{\theta_2} + B_{\theta_2}(\frac{c_2}{K_2}) + D_{\theta_2}(\frac{c_1}{K_1}) + \frac{Fc_1c_2}{K_1K_2} + G(\frac{c_2}{K_2})^2 + H(\frac{c_1}{K_1})^2 \\ &+\frac{[(2-b^2)K_2-bK_1]^2}{(4-b^2)^2(1-b^2)} + \frac{2(1+\theta_2)[(2-b^2)K_2-bK_1]}{(4-b^2)(1+b)(2-b)} \\ &+\frac{c_2}{K_2}[\frac{2(b^2-2)[(2-b^2)K_2-bK_1]}{(4-b^2)^2(1-b^2)}] + \frac{c_1}{K_1}[\frac{2b[(2-b^2)K_2-bK_1]}{(4-b^2)^2(1-b^2)}],\end{aligned}$$

where the definitions of $A_{\theta_2},\ B_{\theta_2},\ D_{\theta_2},\ F, G$, and H are given in (13)-(18). By letting $\theta_2 = 0$, we can get ports' equilibrium second-period profits under no uncertainty as follows.

$$\begin{aligned}\check{\pi}_1(K_1,\ K_2,\ 0) &= A + B(\frac{c_1}{K_1}) + D(\frac{c_2}{K_2}) + \frac{Fc_1c_2}{K_1K_2} + G(\frac{c_1}{K_1})^2 + H(\frac{c_2}{K_2})^2 \\ &+\frac{[(2-b^2)K_1-bK_2]^2}{(4-b^2)^2(1-b^2)} + \frac{2[(2-b^2)K_1-bK_2]}{(4-b^2)(1+b)(2-b)} \\ &+\frac{c_1}{K_1}[\frac{2(b^2-2)[(2-b^2)K_1-bK_2]}{(4-b^2)^2(1-b^2)}] + \frac{c_2}{K_2}[\frac{2b[(2-b^2)K_1-bK_2]}{(4-b^2)^2(1-b^2)}]\end{aligned}$$

and

$$\begin{aligned}\check{\pi}_2(K_1,\ K_2,\ 0) &= A + B(\frac{c_2}{K_2}) + D(\frac{c_1}{K_1}) + \frac{Fc_1c_2}{K_1K_2} + G(\frac{c_2}{K_2})^2 + H(\frac{c_1}{K_1})^2 \\ &+\frac{[(2-b^2)K_2-bK_1]^2}{(4-b^2)^2(1-b^2)} + \frac{2[(2-b^2)K_2-bK_1]}{(4-b^2)(1+b)(2-b)} \\ &+\frac{c_2}{K_2}[\frac{2(b^2-2)[(2-b^2)K_2-bK_1]}{(4-b^2)^2(1-b^2)}] + \frac{c_1}{K_1}[\frac{2b[(2-b^2)K_2-bK_1]}{(4-b^2)^2(1-b^2)}],\end{aligned}$$

where A, B, and D are defined in (21)-(23). Denote

$$S\check{W}_2^{NU}(K_1,\ K_2) = \check{\pi}_2(K_1,\ K_2,\ 0) - \gamma_2 K_2$$

government 2's social welfare and $\check{K}_2^{NU}$ government 2's optimal facility level under no uncertainty. Then, government 2's expected social welfare under uncertainty is

$$S\check{W}_2(K_2,\ K_1,\ \theta_2) = E\check{\pi}_2(K_1,\ K_2) - \gamma_2 K,$$

where $E\check{\pi}_2(K_1,\ K_2) = \int \check{\pi}_2(K_1,\ K_2,\ \theta_2) f(\theta_2 \mid K_1,\ \theta_1) d\theta_2$. By simple calculations, we can get

$$\begin{aligned}E\check{\pi}_2(K_1,\ K_2) &= \check{\pi}_2(K_1,\ K_2,\ 0) + \mu(K_1,\ \theta_1)\{B + D + \frac{2[(2-b^2)K_2-bK_1]}{(4-b^2)(1+b)(2-b)}\} \\ &+A[2\mu(K_1,\ \theta_1) + \mu(K_1,\ \theta_1)^2 + \sigma^2(K_1,\ \theta_1)].\end{aligned}$$

Then we have

$$\begin{aligned} S\check{W}_2(K_1,\ K_2) &= S\check{W}_2^{NU}(K_1,\ K_2) + \mu(K_1,\ \theta_1)\{B + D + \frac{2[(2-b^2)K_2 - bK_1]}{(4-b^2)(1+b)(2-b)}\} \\ &\quad + A[2\mu(K_1,\ \theta_1) + \mu(K_1,\ \theta_1)^2 + \sigma^2(K_1,\ \theta_1)]. \end{aligned}$$

Accordingly, we have

$$\frac{\partial S\check{W}_2(K_1,\ K_2,\ \theta_1)}{\partial K_2} = \frac{\partial S\check{W}_2^{NU}(K_1,\ K_2)}{\partial K_2} + \frac{2(2-b^2)\mu(K_1,\ \theta_1)}{(4-b^2)(1+b)(2-b)}.$$

Evaluating the facility level at $\check{K}_2^{NU}$ yields

$$\begin{aligned} \frac{\partial S\check{W}_2(K_1,\ \check{K}_2^{NU})}{\partial K_2} &= \frac{\partial S\check{W}_2^{NU}(K_1,\ \check{K}_2^{NU})}{\partial K_2} + \frac{2(2-b^2)\mu(K_1,\ \theta_1)}{(4-b^2)(1+b)(2-b)} \\ &= \frac{2(2-b^2)\mu(K_1,\ \theta_1)}{(4-b^2)(1+b)(2-b)} \end{aligned}$$

since $\frac{\partial S\check{W}_2^{NU}(K_1,\ \check{K}_2^{NU})}{\partial K_2} = 0$. Thus, as in Section 2, relative sizes of $\check{K}_2$ and $\check{K}_2^{NU}$ depend on the sign of $\mu(K_1,\ \theta_1)$ because $\frac{2(2-b^2)}{(4-b^2)(1+b)(2-b)} > 0$. This means that Proposition 1's outcomes remain true. And it is easy to check that $\check{p}_2$ owns all properties of Proposition 2.

Now let us move back to period 1. The equilibrium prices in period 1 for short-sighted ports are

$$\begin{aligned} \bar{p}_1 &= \frac{(1-b)(1+\theta_1)}{(2-b)} + \frac{1}{(4-b^2)}\left[c_2 b + \frac{2c_1}{K_1}\right] + \frac{(2-b^2)K_1 - bK_2^*}{4-b^2} \text{ and} \\ \bar{p}_2 &= \frac{(1-b)(1+\theta_1)}{(2-b)} + \frac{1}{(4-b^2)}\left[\frac{c_1 b}{K_1} + 2c_2\right] + \frac{(2-b^2)K_2^* - bK_1}{4-b^2}. \end{aligned}$$

And ports' equilibrium profits in period 1 are

$$\begin{aligned} \check{\pi}_1(K_1,\ \theta_1) &= A_{\theta_1} + B_{\theta_1}(\frac{c_1}{K_1}) + D_{\theta_1}c_2 + F\frac{c_1c_2}{K_1} + G(\frac{c_1}{K_1})^2 + Hc_2^2 \\ &\quad + \frac{[(2-b^2)K_1 - bK_2]^2}{(4-b^2)^2(1-b^2)} + \frac{2(1+\theta_1)[(2-b^2)K_1 - bK_2]}{(4-b^2)(1+b)(2-b)} \\ &\quad + \frac{c_1}{K_1}[\frac{2(b^2-2)[(2-b^2)K_1 - bK_2]}{(4-b^2)^2(1-b^2)}] + c_2[\frac{2b[(2-b^2)K_1 - bK_2]}{(4-b^2)^2(1-b^2)}] \end{aligned}$$

and

$$
\begin{aligned}
\breve{\pi}_2(K_1,\ \theta_1) \quad = \quad & A_{\theta_1} + B_{\theta_1} c_2 + D_{\theta_1}(\frac{c_1}{K_1}) + \frac{F c_1 c_2}{K_1} + G c_2^2 + H(\frac{c_1}{K_1})^2 \\
& + \frac{[(2-b^2)K_2 - bK_1]^2}{(4-b^2)^2(1-b^2)} + \frac{2(1+\theta_1)[(2-b^2)K_2 - bK_1]}{(4-b^2)(1+b)(2-b)} \\
& + c_2[\frac{2(b^2-2)[(2-b^2)K_2 - bK_1]}{(4-b^2)^2(1-b^2)}] + \frac{c_1}{K_1}[\frac{2b[(2-b^2)K_2 - bK_1]}{(4-b^2)^2(1-b^2)}].
\end{aligned}
$$

Again, denote $S\check{W}_1^{NU}(K_1) = \breve{\pi}_1(K_1,\ 0) - \gamma_1 K_1$ government 1's social welfare under no uncertainty, where $\breve{\pi}_1(K_1,\ 0)$ is from $\breve{\pi}_1(K_1,\ \theta_1)$ evaluated at $\theta_1 = 0$. Then, government 1 will choose $\check{K}_1$ to maximize her expected social welfare

$$
S\check{W}_1(K_1) \equiv \int_{-1}^{1} \breve{\pi}_1(K_1,\ \theta_1) f(\theta_1) d\theta_1 - \gamma_1 K_1.
$$

By some calculations, we have

$$
\begin{aligned}
\int_{-1}^{1} \breve{\pi}_1(K_1,\ \theta_1) f(\theta_1) d\theta_1 \quad = \quad & \breve{\pi}_1(K_1,\ 0) + \bar{\theta}\{B + D + \frac{2[(2-b^2)K_1 - bK_2]}{(4-b^2)(1+b)(2-b)}\} \\
& + A[2\bar{\theta} + \bar{\theta}^2 + \sigma^2].
\end{aligned}
$$

Accordingly,

$$
\frac{\partial S\check{W}_1(\check{K}_1)}{\partial K_1} = \frac{\partial S\check{W}_1^{NU}(\check{K}_1)}{\partial K_1} + \frac{2(2-b^2)\bar{\theta}}{(4-b^2)(1+b)(2-b)} = 0.
$$

Therefore, relative sizes of $\check{K}_1$ and $\check{K}_1^{NU}$ depend on the sign of $\bar{\theta}$. Proposition 3 remains true, and $\check{K}_1$ owns the properties of Proposition 4.

Finally, similar conclusions can be drawn when ports are far-sighted.

7. Conclusions and Policy Implications

This paper studies governments' optimal facility investments and ports' optimal pricing in a two-period model considering demand uncertainty and differential products. In our sequential game, government 1 selects a facility level at the beginning of the first period, while government 2 chooses hers at the beginning of the second period. And ports decide their service prices at the end of the two periods. Moreover, governments and ports have asymmetric information about uncertain market demands.

Several outcomes are uncovered in this paper. First, the differences of government 2's optimal facility levels between uncertainty and no uncertainty are determined solely by the conditional mean of stochastic demand, while the difference for government 1 depends on the unconditional mean of stochastic demand only when ports are short-sighted. If ports implement far-sighted development policy, other model parameters, such as ports' marginal costs and service substitution degrees, could also affect the distinction of government 1's facility levels between uncertainty and no uncertainty. Second, governments' optimal facility investments will increase with rising (conditional) means of stochastic demand and their competing ports' marginal costs. In contrast, impacts of own ports' marginal costs and service substitution degrees on governments' optimal facility investments are unsure. And the (conditional) variance of stochastic demand has no effect on governments' optimal facility investments. Moreover, government 2 may provide more or fewer facilities as government 1 invests more. Third, government 1 may not have the first-mover advantage. That is, government 2 may enjoy the second-mover advantage. Fourth, ports will raise their service prices when governments' facility investments decrease, ports' marginal costs increase, or market demands become stronger. However, impact of the service differentiation degree on ports' equilibrium prices is uncertain.

All the above results remain true qualitatively when we extend the model by considering the cost-side uncertainty and the dependence of demand and supply of ports' services. Since we do not take congestible transport networks to ports' hinterlands into account, this research can be further expanded by analyzing how governments and ports behave when they face uncertainty and congestible transport networks at the same time.

Finally, several policy implications can be drawn based on our results. First, under the settings of additive uncertainty and governments' simultaneous move, Chen et al. (2010) show that the mean stochastic demand is the only factor in determining the difference of governments' optimal facility investments between uncertainty and no uncertainty. However, under the settings of additive uncertainty and governments' sequential moves here, this difference could also depend on factors such as ports' marginal costs, service substitution degrees and discount rates. It implies that timing of governments' facility investments matters. Second, we specify the conditions under which government 1 or government 2 has a higher expected social welfare. This information is useful for governments when developing their ports. Third, the outcomes of how ports' equilibrium prices are affected by governments' facility investments, ports' marginal costs, the service substitution degree, and uncertain market situations actually provide some empirically testable hypotheses.

Appendix

Derivation of Equation (25): Taking the expectation of (13) with respect to θ_2 yields

$$\begin{aligned}
& \int_{-1}^{1} A_{\theta_2} f(\theta_2 \mid K_1,\ \theta_1) d\theta_2 \\
= \ & \frac{(1-b)}{(1+b)(2-b)^2} \left[\int_{-1}^{1} (1 + 2\theta_2 + \theta_2^2) f(\theta_2 \mid K_1,\ \theta_1) d\theta_2 \right] \\
= \ & A \left[1 + 2\mu(K_1,\ \theta_1) + \mu(K_1,\ \theta_1)^2 + \sigma^2(K_1,\ \theta_1) \right].
\end{aligned}$$

Similarly, we can get

$$\begin{aligned}
\int_{-1}^{1} B_{\theta_2} f(\theta_2 \mid K_1,\ \theta_1) d\theta_2 &= B[1 + \mu(K_1,\ \theta_1)] \\
\int_{-1}^{1} D_{\theta_2} f(\theta_2 \mid K_1,\ \theta_1) d\theta_2 &= D[1 + \mu(K_1,\ \theta_1)]
\end{aligned}$$

Note that G, F, and H are independent of θ_2. Substituting these three equalities into $\int_{-1}^{1} \pi_2^*(K_1,\ K_2,\ \theta_2) f(\theta_2 \mid K_1,\ \theta_1) d\theta_2$ produces (25). □

Proof of Proposition 1: Given $(K_1,\ \theta_1)$, evaluating (29) at K_2^{NU} yields

$$\frac{\partial SW_2(K_1,\ K_2^{NU},\ \theta_1)}{\partial K_2} = \frac{\partial SW_2^{NU}(K_1,\ K_2^{NU})}{\partial K_2} - \frac{c_2 B\mu(K_1,\ \theta_1)}{(K_2^{NU})^2} = -\frac{c_2 B\mu(K_1,\ \theta_1)}{(K_2^{NU})^2}$$

by (27). Since $B < 0$, the sign of $\frac{\partial SW_2(K_1,\, K_2^{NU},\, \theta_1)}{\partial K_2}$ is determined solely by the sign of $\mu(K_1,\ \theta_1)$. If $\mu(K_1,\ \theta_1) > 0$, we have $\frac{\partial SW_2(K_1,\, K_2^{NU},\, \theta_1)}{\partial K_2} > 0$. Strict concavity of SW_2 and (30) imply that $K_2^* > K_2^{NU}$. In contrast, if $\mu(K_1,\ \theta_1) < 0$, we have $\frac{\partial SW_2(K_1,\, K_2^{NU},\, \theta_1)}{\partial K_2} < 0$, hence $K_2^* < K_2^{NU}$. Finally, if $\mu(K_1,\ \theta_1) = 0$, we have $\frac{\partial SW_2(K_1,\, K_2^{NU},\, \theta_1)}{\partial K_2} = 0$, thus $K_2^* = K_2^{NU}$. $\square$

Proof of Proposition 2: (i) Differentiating (30) with respect to $\mu(K_1,\ \theta_1)$ generates

$$\frac{\partial K_2^*}{\partial \mu(K_1,\ \theta_1)} = \frac{c_2 B}{(K_2^*)^2} \cdot [\frac{\partial^2 SW_2(K_2^*)}{\partial K_2^2}]^{-1} > 0$$

by strict concavity of SW_2 and $B < 0$.

(ii) This is because σ^2 does not appear in (29).

(iii) Differentiating (30) with respect to c_1 yields

$$\frac{\partial K_2^*}{\partial c_1} = \frac{c_2 F}{K_1 (K_2^*)^2} \cdot [\frac{\partial^2 SW_2(K_2^*)}{\partial K_2^2}]^{-1} > 0$$

by strict concavity of SW_2 and $F < 0$.

(iv) Differentiating (30) with respect to c_2 produces

$$\begin{aligned} \frac{\partial K_2^*}{\partial c_2} \quad &= \quad \frac{\frac{1}{(K_2^*)^2}\{[1+\mu(K_1,\ \theta_1)]B + \frac{c_1 F}{K_1} + \frac{4c_2 G}{K_2^*}\}}{\frac{\partial^2 SW_2}{\partial K_2^2}} \geq\ (\leq)\ 0 \\ &\text{iff} \quad [1+\mu(K_1,\ \theta_1)]B + \frac{c_1 F}{K_1} + \frac{4c_2 G}{K_2^*} \leq\ (\geq)\ 0. \end{aligned}$$

(v) Differentiating (30) with respect to K_1 generates

$$\begin{aligned} \frac{\partial K_2^*}{\partial K_1} \quad &= \quad \frac{\frac{c_2}{K_1^2}[B\frac{\partial \mu(K_1,\,\theta_1)}{\partial K_1} - \frac{c_1 F}{K_1^2}]}{\frac{\partial^2 SW_2(K_2^*)}{\partial K_2^2}} \geq\ (\leq)\ 0 \\ &\text{iff} \quad \frac{\partial \mu(K_1,\ \theta_1)}{\partial K_1} \geq\ (\leq)\ \frac{c_1 F}{B K_1^2}. \end{aligned}$$

(vi) Differentiating (30) with respect to b yields

$$\begin{aligned}\frac{\partial K_2^*}{\partial b} &= \frac{\frac{c_2}{(K_2^*)^2}\{[1+\mu(K_1,\ \theta_1)]\frac{\partial B}{\partial b}+\frac{c_1}{K_1}\frac{\partial F}{\partial b}+\frac{2c_2}{K_2^*}\frac{\partial G}{\partial b}\}}{\frac{\partial^2 SW_2}{\partial K_2^2}} \geq\ (\leq)\ 0 \\ &\text{iff} \quad [1+\mu(K_1,\ \theta_1)]\frac{\partial B}{\partial b}+\frac{c_1}{K_1}\frac{\partial F}{\partial b}+\frac{2c_2}{K_2^*}\frac{\partial G}{\partial b} \leq\ (\geq)\ 0.\end{aligned}$$

□

<u>*Proof of Proposition 5*</u>: Evaluating (53) at K_1^{NU} produces

$$\begin{aligned}\frac{\partial TSW_1(K_1^{NU})}{\partial K_1} &= \frac{\partial TSW_1^{NU}(K_1^{NU})}{\partial K_1} - \frac{c_1\bar{\theta}B}{(K_1^{NU})^2} + \delta\frac{\partial\triangle(K_1^{NU})}{\partial K_1} \\ &= -\frac{c_1\bar{\theta}B}{(K_1^{NU})^2} + \delta\frac{\partial\triangle(K_1^{NU})}{\partial K_1}\end{aligned}$$

by the definition of K_1^{NU}. Thus, we have

$$\frac{\partial TSW_1(K_1^{NU})}{\partial K_1} \geq\ (\leq)\ 0 \ \text{ iff } \delta\frac{\partial\triangle(K_1^{NU})}{\partial K_1} - \frac{c_1\bar{\theta}B}{(K_1^{NU})^2} \geq\ (\leq)\ 0.$$

Then, by Assumption 3 and (54), we have

$$\tilde{K}_1 \geq\ (\leq)\ K_1^{NU} \text{ iff } \delta\frac{\partial\triangle(K_1^{NU})}{\partial K_1} - \frac{c_1\bar{\theta}B}{(K_1^{NU})^2} \geq\ (\leq)\ 0.$$

□

<u>*Proof of Lemma 3*</u>: By (22)-(23), we have $|B| > D$ due to $0 < b < 1$. However, $\frac{1}{K_1^*} > \frac{1}{K_2^*}$ by $K_2^* > K_1^*$. Thus, the sign of $(\frac{B}{K_2^*}+\frac{D}{K_1^*})$ is unsure. If $\mu(K_1^*,\ \theta_1) > 0$, the fifth term on the RHS of (55) is negative. Then, $SW_2^* > SW_1^*$ if $\sigma^2(K_1^*,\ \theta_1) > \sigma^2 + \frac{1}{A}\{|\hat{\pi}_1(K_1^*,\ 0) - \pi_2^*(K_1^*,\ K_2^*,\ 0)| + \gamma(K_2^* - K_1^*) + c\mu(K_1^*,\ \theta_1)|\frac{B}{K_2^*}+\frac{D}{K_1^*}|\} > 0$. In contrast, if $-1 < \mu(K_1^*,\ \theta_1) < 0$, the fifth term on the RHS of (55) is positive. Then, we have $SW_1^* > SW_2^*$ if $\sigma^2 > \sigma^2(K_1^*,\ \theta_1) + \frac{1}{A}\{|\hat{\pi}_1(K_1^*,\ 0) - \pi_2^*(K_1^*,\ K_2^*,\ 0)| - c\mu(K_1^*,\ \theta_1)|\frac{B}{K_2^*}+\frac{D}{K_1^*}|\} > 0$. □

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