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Capacity investment decisions of two competing ports under uncertainty: a strategic real options approach

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Abstract

Ports worldwide operate in an uncertain environment and compete with nearby ports to attract cargo. The extent of competition is influenced by the geographical location and differentiated services offered at ports. In this paper, we study the flexible investment decision of two ports with an option to delay investment in a capacity level that is not ex-ante determined. Ports compete on quantity (Cournot competition) under demand uncertainty and congestion. In a leader-follower timing game, we consider both the entry deterrence and accommodation strategies for the leader port. If one of the ports only has a limited cost advantage, the leader role will be endogenous and will be the result of preemption. Uncertainty is included in the model by a geometric Brownian motion, allowing us to analyse the impact of growth and uncertainty (variability) independently. We find that higher growth, uncertainty and port customers' aversion to waiting lead to a larger project installed at a later moment. If competition intensifies however, the option value of waiting is reduced, leading to earlier investment, but surprisingly also in less capacity. Finally, if more shares of the ports are publicly owned, the investment will be larger and take place earlier.

Highlights:

- The paper contributes to the strategic real options literature and to port capacity investment decision making.
- We consider congestion in the capacity investment decision of two competing ports under uncertainty.
- Competition and small cost differences drive the leader's investment threshold and capacity down, whereas the follower will invest later in more capacity.
- If more shares of the port are publicly owned, earlier and larger capacity investments will be made.

Keywords: port capacity; port competition; heterogeneous ports; investment size and timing; real options game; strategic real options.

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1 Introduction

In ports worldwide, important activities are performed to facilitate international and regional trade, such as cargo handling (Verhoeven, 2015). In order to generate income and welfare, ports need to attract throughput (Meersman et al., 2015; Xiao et al., 2012). However, they experience competition from nearby ports with overlapping hinterlands to attract this cargo (De Langen et al., 2012). Examples can be found all over the world: ports in the Hamburg-Le Havre range, the Spanish ports, East-Asian ports and ports on the East and West Coast of the USA (Jacobs, 2007; Meersman & Van de Voorde, 2002; Yap et al., 2006; Ng, 2006; Cullinane et al., 2005). A number of reasons cause this competition (De Langen, 2007). A port should strive to be part of the logistics chain with the lowest generalised cost to serve the hinterland. Such a competitive advantage increases the probability of the port handling the goods (Heaver et al., 2000; De Langen et al., 2012; Talley et al., 2014). Location, service quality and efficiency play an important role herein (Meersman et al., 2010). One of the critical problems in the port is congestion (Novaes et al., 2012). Shipping lines are averse to the waiting time and logistics costs caused by delays. Since delay costs depend on the goods transported, the aversion to waiting is different for each shipping line (Blauwens et al., 2016; De Borger et al., 2008). As a result, ports tend to avoid congestion in order to be competitive with respect to non-congested ports nearby.

In order to avoid congestion, ports can charge a higher price, leading to a demand reduction (Xiao et al., 2013), or accommodate the demand by investing in additional cargo-handling capacity (Meersman & Van de Voorde, 2014a; Xiao et al., 2012). Chang et al. (2012) used an economic approach to balance all elements of capacity in a port, given the objectives of the port owners, explicitly taking waiting time costs into account. The capacity investment decision is complicated by a trade-off. Overinvestment wastes money on unused capacity. Oppositely, when insufficient capacity is installed in the port, the user incurring congestion costs may move to a nearby port (Alderton, 2008). An additional consideration is that a congestion-reducing capacity investment in one port increases its own demand, but reduces the demand in the other port (Wan et al., 2013). In this light, the port's investment decision also depends on the decision of the competitor who serves (a part of) the same hinterland. In this way, competition has an impact on the capacity investment decision of ports (Huisman & Kort, 2015; Xiao et al., 2012). Therefore, the port needs to endogenise the other port's investment decision to avoid investing in capacity that is not used due to the other port's capacity serving part of the demand (Huberts et al., 2015).

The capacity decision is even more complicated by the fact that the demand faced by the port is very uncertain (Vilko & Hallikas, 2012; Huisman & Kort, 2015). Many different sources of this uncertainty have been identified by Balliauw et al. (2019), including not only the impact of the financial crisis on global trade and the uncertain decisions of many actors in the logistics chain, but also technological, environmental and regulatory changes. To correctly account for the value of different sorts of managerial flexibility in capacity investment decisions under uncertainty in a competitive environment, real options models have been widely explored in the literature (Dixit & Pindyck, 1994; Bar-Ilan & Strange, 1996; Dangl, 1999; Aguerrevere, 2003; Hagspiel et al., 2016), in combination with game-theoretic modelling (Azevedo & Paxson, 2014). More specifically, Herder et al. (2011) highlighted the importance of considering the value of flexibility in port investments to react to uncertainty. Hence, real options are needed, as traditional discounted cash flow methods like the net present value rule cannot account for this option value (Trigeorgis, 1996). The options considered in this paper are a flexible one-shot investment size and timing and a flexible throughput level. The present paper extends the real options literature by determining the investment timing and capacity choice in a continuous-time framework that simultaneously deals with competition and volume flexibility.

The objective of this paper is to analyse how a port's capacity investment is influenced by a number of factors in the context of port competition and demand uncertainty. To this end, the research question consists of a number of sub-questions: How is a port's capacity investment influenced by an increase in: 1) competition, 2) public money involvement, 3) congestion costs, 4) uncertainty, 5) expected growth, and 6) the cost advantage of one port? In order to accurately study the capacity investment decisions of the competing ports, a game-theoretic model including congestion and uncertainty is developed. In this sense, we extend the state-of-the-art in the field of industrial organisation with a port-specific application, wherein congestion plays an important role (De Borger & Van Dender, 2006; De Borger et al., 2008). This role of congestion was illustrated by Xiao et al. (2012), who however omitted uncertainty from the analysis. Chen & Liu (2016) did include this uncertainty in the analysis with endogenous capacity decisions, but used a uniform distribution to model it.

We extend the literature of port capacity investment decisions under uncertainty by modelling uncertainty using a stochastic process that allows analysing the impact of the expected growth and uncertainty (variability) separately. Hence, we are able to better account for small growth after an economic crisis, in combination with high uncertainty. Subsequently, next to the size, also the timing of the investment decision matters. As opposed to the majority of the literature, we include the timing decision and moreover allow for heterogeneous ports in a game where the ports do not necessarily invest at the same time. In this way, our model accounts for entry deterrence and preemption as additional strategies to the often solely considered accommodation strategy. Luo et al. (2012) modelled the preemptive prices by the dominant port, but did not consider uncertainty and congestion.[1] In order to study a port context, we extend the real options model of Huisman & Kort (2015) in three ways, to account for the cost of port congestion, differentiated services offered by different ports (Bichou & Gray, 2005) and mixed ownership by both private and public actors (Xiao et al., 2012). This allows deriving three new results (1, 2 and 3), demonstrating each specific element's impact on port capacity investment decisions.

As a result of our methodological additions, we are able to account for the frequently observed phenomenon that port investments in two competing ports do not necessarily take place at the same time, notwithstanding that simultaneous investment is also possible. In this setting, we find that higher growth, uncertainty and port customers' aversion to waiting lead to a larger project installed at a later moment. However, if competition intensifies, the option value of waiting is reduced, leading to earlier investment, but also in less capacity. Finally, we confirm in this setting that an increase of public money involvement leads to an earlier and larger investment.

The paper is structured as follows. The next section describes the basic model for our two-port setting and each port's investment decision making objectives. Subsequently in Section 3, the methodology and analysis are described. Since no closed-form solutions can be derived, the numerical results with respect to the impact of competition combined with different government ownership structures are give in Section 4. Sensitivity analysis in Section 5 identifies the impact of other factors on the investment decision in a competitive setting. The final section presents conclusions and avenues for future research.

2 The basic model

We consider two private or public service ports that compete to handle a flexible amount of throughput, but offer differentiated services (Bichou & Gray, 2005). The next subsection deals with the individual situation in, and the relevant information for each port. This is followed by a discussion of the type of competition between both ports and the related game-theoretic modelling. The model equations are summarised in Table 1.

2.1 Individual port situations

The fact that ports offer differentiated services is mainly the result of the different geographic locations of the ports, implying different distances to the hinterland. Moreover, each port being organised differently adds to this service differentiation. Also their service levels as expressed by their occupancy rates, with an impact on their prices, may differ (De Borger & Van Dender, 2006). The product market's heterogeneity is expressed through differentiation parameter δ in the inverse

[1] Ishii et al. (2013) also examine port competition and stochastic demand with the size and timing of capacity investment. However, they did not consider the endogenous timing issue and the issue of entry deterrence or preemption.

demand function, giving rise to the full price, or gross willingness to pay, ρ_i for port i at time t (Vives, 1999; Xiao et al., 2012; Kamoto & Okawa, 2014):

$$\rho_i(t) = X(t) - Bq_i(t) - \delta Bq_j(t), \tag{1}$$

with X being the demand shift parameter, q_i the throughput of port i and q_j the throughput of port j ($j \neq i$). As a result of port services being differentiated products leading to different prices in different ports, we do not make use of a single market demand function.

Depending on the location and services of the ports, parameter δ can vary between zero and one. In the case of an isolated port not experiencing competition from another port, e.g., a sole port on an island, δ would equal 0 and the model would simplify to a monopoly model. For two ports at the same location and offering the same services, δ would equal 1. We do not dispose of empirically estimated values for δ. However, to show its impact on the investment decision, we study three different instances. Initially, δ is set to 0.6 to take the different characteristics of two competing ports in a close range into account (e.g., Antwerp and Rotterdam in the Hamburg-Le Havre range). This value is altered in the sensitivity analysis to 0.9, to account for ports situated back to back but offering slightly different services, (e.g. Los Angeles (LA) and Long Beach in California, Seattle and Tacoma in Washington, Vancouver and Prince Rupert in British Columbia, or Gdynia and Gdansk in Poland), and to 0.3 to account for two ports that are situated further from each other, possibly at different coast lines and with only partly overlapping hinterlands (e.g. LA/Long Beach and New York/New Jersey in America, or Hamburg-Le Havre and Trieste/Koper in Europe (De Langen, 2007)).

In order to model demand evolution and its uncertainty, intercept X follows a geometric Brownian motion (GBM) with an independent parameter for the drift (economic growth, μ) and the variability (uncertainty, σ):

$$\mathrm{d}X(t) = \mu X(t)\mathrm{d}t + \sigma X(t)\mathrm{d}Z(t), \tag{2}$$

with dZ the increment of a standard Wiener process.[2] Additionally, the slope of the demand function (B) will be normalised and set to 1. For the sake of readability, denoting the functional dependence on time will be omitted in the remainder of the paper.

The full price involves not only the price paid in port i, p_i, but also a cost incurred because of congestion and resulting waiting times at high occupancy rates (Zhang & Zhang, 2006; Xiao et al., 2012). Price p_i can hence be written as

$$p_i = X - Bq_i - \delta Bq_j - AXq_i/K_i^2, \tag{3}$$

with AXq_i/K_i^2 being the congestion unit cost term.[3] Total congestion cost for port i then equals $AX(q_i/K_i)^2$, which is increasing in the occupancy rate (De Borger & Van Dender, 2006; De Borger & De Bruyne, 2011; De Borger et al., 2005, 2007). The square of the occupancy rate, q_i/K_i is used as a proxy for the amount of waiting time. Queuing theory proves that waiting times start to grow after 50 percent occupancy of the theoretical design capacity (K_i in port i) and increase more than linearly beyond 80 percent (Blauwens et al., 2016). A is a monetary scaling factor to convert delays to costs and is port-user and good-type dependent. Here A is set to 5 (see discussion below in Section 3). The height of the congestion cost is also related to the uncertain price level. To this end, we multiply with X. An important difference from the economic model of Dangl (1999) is

[2] Marathe & Ryan (2005) empirically show that the GBM is a good process to model demand for established services such as the number of passengers in airline transportation. Moreover, Lindsey & De Palma (2014) highlight the frequent use of a GBM in different papers in a transportation context. Finally, the example evolution in Figure 2 appears realistic when compared to the data of Vlaamse Havencommissie (2016). Important to note hereby is that, although throughput in a particular seaport can diverge substantially from a GBM process for a substantial period of time, this does not invalidate the general validity of the process to model evolutions in the market for container throughput.

[3] Although congestion costs are modelled here on the demand side, a mathematically equivalent approach could have been to model congestion at the supply side (i.e. to include it in the port's costs), since congestion can impose costs on both suppliers and customers of port capacity.

that in this paper, design capacity K_i is not a hard constraint for the maximal throughput.[4] This adaptation is necessary to avoid unnecessary mathematical complexity. Realism is not to be lost if A, the monetary scaling factor in the congestion cost, is sufficiently high. In that case, the price would become too low to profitably operate if $q_i > K_i$. This will be avoided as much as possible, but in some emergency cases, the port has no other choice than to handle the additional cargo. To have a realistic setting, A is set to 5. This results in a congestion cost height that discourages full occupancy in most situations, but that does not prevent it de facto and that allows in some exceptional cases for exceeding design capacity, at a high cost. Since in most cases, ports like to avoid these high costs and because a nearby port with free capacity offers an alternative, such high levels of occupancy are hardly encountered in reality as well as in our numerical simulations of the described ports.

Since not only situations with two private ports are considered, but also with two public ports, it is not sufficient to only consider annual profit ($\pi_i = (p_i - c) \cdot q_i - c_h K_i$, with c the marginal operational cost and c_h the capital holding cost) maximisation, which is the objective of a private port. Governments also consider positive externalities or local spillover benefits per unit of throughput handled (e.g. employment and local industry growth), and consumer surplus in their social welfare (SW_i) maximisation (Xiao et al., 2012; Jiang et al., 2017). Social welfare generated by port i is calculated as the sum of the profit of port i, the spillover benefits $\lambda \cdot q_i$ and a share s_{CS} of consumer surplus generated by port i (CS_i), since some governments only consider the part that is relevant for the region they govern.[5] To account for the fact that the two ports are owned by a different, independent government, consumer surplus in port i is calculated as follows (Xiao et al., 2012):

$$\begin{aligned} CS_i(q_i, q_j) = CS_i(q_i) &= \int_0^{q_i} \rho_i(y, q_j)\mathrm{d}y - \rho_i(q_i, q_j)q_i \\ &= \int_0^{q_i} (X - By - \delta B q_j)\mathrm{d}y - (X - Bq_i - \delta B q_j)q_i \\ &= \frac{Bq_i^2}{2}. \end{aligned} \tag{4}$$

This calculation reflects that the difference between the gross willingness to pay for each unit of throughput in port i and the actual full price in port i is not affected by the throughput realised by port j. In the case of two independent governments owning only shares of port i and j respectively, q_j is considered exogenous by port i.

The aggregated operational objective function Π_i of port i is then the weighted sum of the individual owner's objectives, with the shares of ownership used as the weights. If the government owns a share s_G, and the private party hence $1 - s_G$, of the port, the weighted operational objective function of port i is composed as follows:

$$\begin{aligned} \Pi_i(X, K_i, q_i, q_j) &= (1 - s_G) \cdot \pi_i(X, K_i, q_i, q_j) + s_G \cdot SW(X, K_i, q_i, q_j) \\ &= \pi_i(X, K_i, q_i, q_j) + s_G \cdot \lambda q_i + s_G s_{CS} \cdot Bq_i^2/2. \end{aligned} \tag{5}$$

Based on the information provided by Coppens et al. (2007) and Benacchio & Musso (2001), the average spillover benefits per unit of throughput, λ, is set to 40% of the marginal operational cost, to account for the port's spillover effects in the entire country. To analyse the impact of the share

[4] The impact of this change on the results in a monopoly setting is negligible. The disadvantage of the constraint $q_i \leqslant K_i$ in a two-port setting is that more regions for q_i^{opt} arise (e.g., one of the two ports at full capacity, both at full capacity, etc.) and that the relative order of these regions is endogenous and capacity dependent. It could be added to the model, but only complexity would increase and tractability would be reduced.

[5] The Antwerp city council, shareholder of the Port of Antwerp's port authority, might only be interested in local spillover benefits next to port profit, which in turn differs from the objectives of Rotterdam's council. Similarly, the Canadian government, shareholder of the Port of Vancouver, might or might not consider the CS of Chinese shipping lines, having an influence on parameter s_{CS}. To compare with a full social planner in each country, state or city, we include instances with s_{CS} set to 1. In Section 5, we also consider the case where one government may own shares of both ports, giving rise to a different CS_i calculation.

of ownership on the investment decision, s_G, is varied between 0 and 1 in our numerical simulations. Hence, we consider a range of market structures, but in every case the two governments own the same share of their respective ports, and attach the same weight to consumer surplus.[6] Nonetheless, as higher s_G and s_{CS} lead to social welfare being taken more into account by the ports, two public ports fully considering consumer surplus will generate the highest social welfare.

In this paper, we do not restrict our analysis just to ports that are homogeneous in costs, as is often done in game-theoretic approaches. Here, the ports may differ in costs. The investment cost of the project, I_i, and more specifically the fixed investment cost $FC_{I,i}$ is chosen to reflect the cost difference of a similar project.[7] This is illustrated by the example of Antwerp and Rotterdam. In Antwerp, the Deurganckdok has been dug, whereas the Maasvlakte 2 in Rotterdam has been constructed in open water through rainbowing sand, resulting in an $FC_{I,2}$ that is 20 million euro higher for this second project. These considerations give rise to a Stackelberg leader-follower game, with the possibility of simultaneous investment under an entry accommodation strategy. It is however impossible for the port with a cost disadvantage to become the leader. It will be the follower, unless it chooses to invest simultaneously (Pawlina & Kort, 2006).[8] Hence in this paper, the difference in investment timing of both ports is endogenous, allowing for simultaneous investment as well.

The investment cost functions of one single capacity project of respectively the port with a cost advantage (project 1) and with a cost disadvantage (project 2) are graphed in Figure 1. These functions are fourth order polynomials with a negative second order term. The parameters are determined to reflect investment costs that are in line with Port of Antwerp (2016), Vanelslander (2014), and Zuidgeest (2009). The concave-convex functions model the economies of scale in investment size over the first part of the domain, and the boundary beyond which further expansion is extremely costly because houses and extra land need to be expropriated. By expressing capacity K in million TEU per year, $I_i(K)$ is in million euro.

[6] We have not considered instances where the weights differ to ensure tractability of the calculations. Considering competing ports that differ in ownership shares and objectives in asymmetric cases (e.g., a mixed duopoly) would however be an interesting extension for future research.

[7] Fixed investment costs determine the intercept of the investment function. Capacity is determined by a number of interrelated elements, such as quay length, berth size, number of cranes, terminal area, width, depth of the dock, etc. (De Langen et al., 2018). By slightly adapting the amount of each element, costs and capacity will incrementally increase, giving rise to a continuous investment cost function (Novaes et al., 2012).

[8] Only if the port with the cost disadvantage would have a higher number of shares owned by the government, this result would not necessarily hold. Such cases are however not considered in our paper.

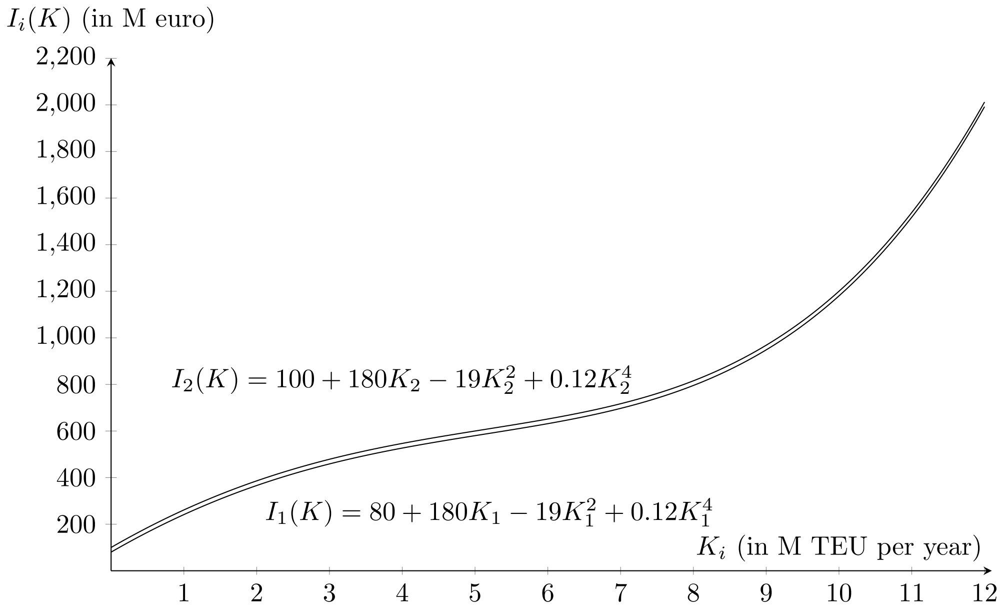

Figure 1: Total investment cost functions for the two projects.

In Table 1, the full economic model is summarised. The price is expressed in euro per TEU. The height of the marginal operational cost $c(= 1)$ and the capital holding cost $c_h(= 0.5)$ are expressed in euro per TEU as well, and are based on Vergauwen (2010), Meersman & Van de Voorde (2014b), and Wiegmans & Behdani (2017). The drift ($\mu = 0.015$) and the drift variability ($\sigma = 0.1$) are estimated applying regression analysis with an exponential growth model on the annual container throughput in the ports of Antwerp and Rotterdam from 2010 to 2015 (Vlaamse Havencommissie, 2016). The growth rate observed is between 1.5 and 2% and is significant at the 5% level, respectively being the base case and sensitivity analysis alteration. The root of the squared error of the regression results in a standard deviation of 15%, justifying the 10% for σ, and its increase to 15% in the sensitivity analysis. The discount rate is set to 0.06 (Aguerrevere, 2003).

Table 1: Model overview.

Variables		
p_i	$=$	price in port i
q_i	$=$	throughput in port i
K_i	$=$	capacity in port i
Inverse demand function ($\forall i$)**:** $p_i = X - Bq_i - \delta Bq_j - AX\frac{q_i}{K_i^2}$		
$B(=1)$	$=$	slope
$\delta(=0.6)$	$=$	product differentiation parameter
$A(=5)$	$=$	monetary scaling factor of congestion cost
Demand shift parameter X**:** $\mathrm{d}X(t) = \mu X(t)\mathrm{d}t + \sigma X(t)\mathrm{d}Z(t)$		
t(=annual)	$=$	time horizon
Z	$=$	standard Wiener process
$\mu(=0.015)$	$=$	drift of Z
$\sigma(=0.1)$	$=$	drift variability of Z
Total cost ($\forall i$) $TC_i = cq_i + c_h K_i$		
$c(=1)$	$=$	constant marginal operational cost
$c_h(=0.5)$	$=$	cost to hold one unit of capital in place
Investment cost ($\forall i$) $I_i = FC_{I,i} + \gamma_1 K_i - \gamma_2 K_i^2 + \gamma_3 K_i^3 + \gamma_4 K_i^4$		
$FC_{I,i}(=80,100)$	$=$	fixed investment cost of port 1 and 2 respectively
$\gamma_1(=180)$	$=$	first order coefficient
$\gamma_2(=19)$	$=$	coefficient reflecting investment economies of scale
$\gamma_3(=0)$	$=$	omitted third order coefficient
$\gamma_4(=0.12)$	$=$	coefficient reflecting boundary of project size
Operational objective function ($\forall i$) $\Pi_i = \pi_i + s_G \cdot \lambda q_i + s_G s_{CS} \cdot CS_i$		
π_i	$=$	annual profit of port i $=p_i q_i - TC_i$
$\lambda(=0.4)$	$=$	spillover benefit per unit q_i
CS_i	$=$	consumer surplus in port i, i.e. $Bq_i^2/2$
$s_G(\in[0;1])$	$=$	share of port owned by the government
$s_{CS}(\in[0;1])$	$=$	share of total CS_i taken into account by the government

2.2 Game-theoretic modelling of competition

The leader could opt for an entry deterrence or accommodation strategy. Under each strategy, the game structure is slightly different, as we explain in this subsection. The occurrence of each strategy is discussed in Subsections 3.3 and 3.4.

As opposed to the majority of the literature, we do not limit the analysis to both ports investing simultaneously. When the leader invests in sufficient capacity at the moment the market is not large enough to accommodate two ports, the leader is deterring the entry of the follower to a later moment. In this way, we discern a four-stage game in case of entry deterrence (Huberts et al., 2015). In the first stage, the leader invests in a capacity K^{L} as soon as its relevant investment threshold X_T^{L} is reached for the first time from below at time T^{L}; see Figure 2. In line with the terminology of Huberts et al. (2015), the first port to enter the market, i.e. the leader, becomes the incumbent after investment. If this initial investment is sufficiently large, it will be entry-deterring, to delay the follower's investment. If the leader's initial investment were relatively small, it would be entry-accommodating to allow simultaneous follower investment. This is described below in a three-stage game. In the second stage of the four-stage game, immediately after the first stage, the incumbent starts to operate under a temporary monopoly at its optimal throughput level, $q(X, K^{\mathrm{L}}, 0)$. This throughput level is flexible, and depends on $X(t)$. In the third stage, when the market has grown sufficiently until X_T^{F} is reached at time T^{F}, the follower will invest in K^{F}. This size is not only dependent on the timing of the follower's investment, but also conditional on the investment size of the leader. Once the follower invests, the incumbent loses its monopoly. Both ports will now operate at their optimal throughput level, given the level of the other port, their capacity investment size and the state of the market X. In this light, both ports compete in quantities, leading to a Cournot equilibrium.

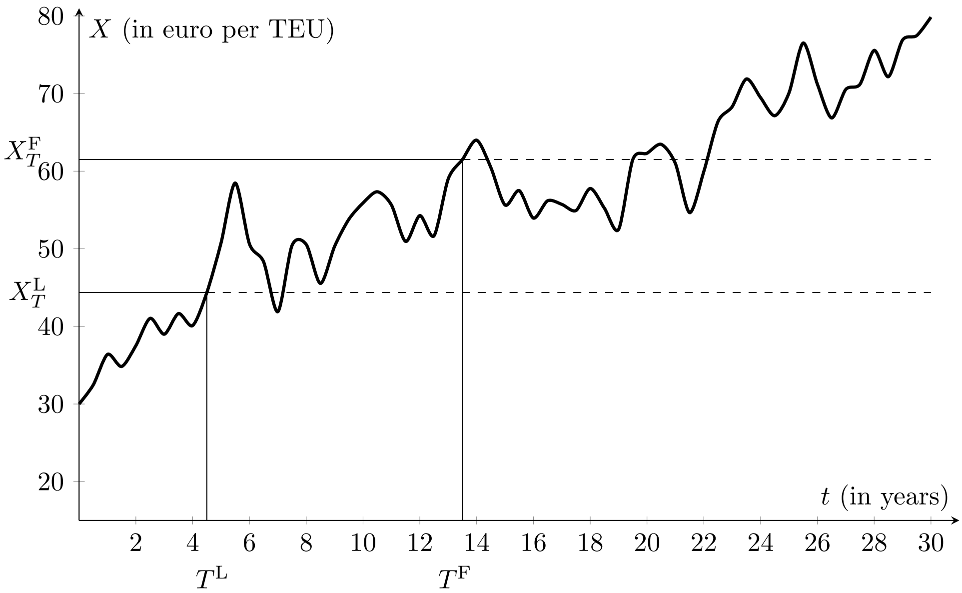

Figure 2: Exemplary evolution of demand shift parameter X (following a GBM with $X(t = 0) = 30$, $\mu = 0.015$ and $\sigma = 0.1$) over time, showing the relationship between optimal timing (T^L and T^F) and the threshold for X (X_T^L and X_T^F) of the leader and the follower port.

Following Wan & Zhang (2013), we consider ports to compete on quantity (i.e., Cournot competition). In general, which model of competition is applicable to a particular industry depends largely on its production technology. In Cournot competition, firms commit to quantities, and prices are then adjusted to clear the market (i.e., the committed quantities) implying the industry is flexible in price adjustments, even in the short run. On the other hand, in Bertrand (price) competition, capacity is unlimited or easily adjusted in the short run. There are some good reasons to believe that quantity competition may be more realistic than price competition in the case of ports. For instance, Quinet & Vickerman (2004, p. 263) remarked:

> "The general idea which emerges from the theoretical analysis is that when transport capacities are high, or can be enlarged through the transfer of capacity from other locations, and the services provided are not differentiated, then competition is likely to be of a Bertrand type, based on price. [...] If, on the other hand, capacity is difficult to increase, then competition is likely to be of a Cournot type, based on quantities. This is the case found, for example, in rail, maritime or inland waterway transport."

The main reason for why port capacity is difficult to change (relative to the ease and rapidity with which prices can be adjusted) is that port capacity investment is lumpy, time-consuming and irreversible, which is consistent with our present set-up described above. Moreover, it involves high investment costs, including high fixed costs of designing, scheduling and implementing investments.[9] Indeed, with capacity constraints Van Reeven (2010) assumes quantity competition between port terminal operators based on Kreps & Scheinkman (1983)'s argument of capacity-constrained price competition yielding quantity competition. Furthermore, Menezes et al. (2007) empirically estimated the market "conduct parameters" with respect to port charges of the three largest, competing Australian seaports. Our calculation based on their results indicates that at

[9]Here, we make abstraction of the fact that ports can increase capacity to a limited extent in the short run, e.g. by increasing productivity or extending working hours. This approach is plausible when studying the investment of market entrants.

the 0.1 level of statistical significance, the hypothesis of price competition among the ports is rejected.[10] As a result of Cournot competition, Wan & Zhang (2013) find that investment increases the own port's profit, which is not necessarily true under Bertrand competition (De Borger et al., 2008). Additionally, we note that the use of quantity as a decision variable has been observed for firms in the production of goods as well as for firms in the production of service (e.g., competition among airlines or airports; see Zhang & Czerny (2012) for a recent survey of the literature).

As a final remark to the described game, note that it is slightly, but not substantially, different in case the leader invests when the market is large enough to accommodate two ports. We now have a three-stage game, as stage 2 is omitted. In this situation, leader investment (stage 1) is immediately followed by the follower's investment (stage 3). Right after this investment, both ports set again their optimal throughput levels under Cournot competition in stage 4.

3 Optimal investment strategies

With two heterogeneous competing ports making a decision to invest in new capacity, of which the size and the timing are not ex-ante defined, the optimisation problem is solved backwardly using dynamic programming. First, the decision of the follower is optimised, *given* the decision of the leader. Subsequently, the optimal entry-deterring or entry-accommodating decision of the leader is explicated, taking the information of the resulting follower's optimal decision into account as expressed by its reaction function.

3.1 A port's throughput decision

First, port i's optimal throughput quantity, once its investment is made, needs to be determined. Differentiating the operational objective function $\Pi_i(X, K_i, q_i, q_j)$ w.r.t. q_i leads to

$$q_i^{opt}(X, K_i, q_j) = \begin{cases} 0, & X < c - s_G\lambda, \\ \dfrac{X + s_G\lambda - c - \delta B q_j}{2\dfrac{AX}{K_i^2} + (2 - s_G s_{CS})B}, & X \geqslant c - s_G\lambda. \end{cases} \tag{6}$$

Through the boundary value ensuring $q_i^{opt} \geqslant 0$ in Eqs. (6) and (7), two regions for X are identified for both ports: $R_1 = [0, c - s_G\lambda)$ where throughput is zero and $R_2 = [c - s_G\lambda, \infty)$ where throughput equals the optimal throughput. In this R_2, throughput could exceed the design capacity, but only at a substantial congestion cost. Hence, as opposed to Yang & Zhang (2012), we do not consider just the interior solutions; rather we also allow corner solutions. By substituting $q_j^{opt}(X, K_j, q_i)$ into $q_i^{opt}(X, K_i, q_j)$, q_i^{opt} can be expressed in terms of X, K_i and K_j. The advantage of the latter is that this value is dependent only on X once both investments are made, as opposed to also being dependent on the continuously changing q_j. This leads to

$$q_i^{opt}(X, K_i, K_j) = \begin{cases} 0, & X \in R_1, \\ \dfrac{(X + s_G\lambda - c)(2\dfrac{AX}{K_j^2} + (2 - s_G s_{CS})B)}{(2\dfrac{AX}{K_i^2} + (2 - s_G s_{CS})B)(2\dfrac{AX}{K_j^2} + (2 - s_G s_{CS})B) - \delta^2 B^2}, & X \in R_2. \end{cases} \tag{7}$$

For each region R_k, with $k = \{1, 2\}$, the resulting optimum of port i's operational objective function can be calculated as $\Pi_i(X, K_i, q_i^{opt}(X, K_i, K_j), q_j^{opt}(X, K_j, K_i))$. This is rewritten as $\overline{\Pi}_i(X, K_i, K_j)$.

[10] For studies using conduct parameters to assess the empirical relevance of certain oligopoly models to a particular market, see, e.g., Bresnahan (1989), and Brander & Zhang (1990).

3.2 The follower's investment decision

To determine the follower's optimal investment decision, an approach in line with the one of Hagspiel et al. (2016) is adopted, with specific port-economic adaptations. $\overline{\Pi}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)$ at the time port i invests after port j's investment in K^{L}_j, forms the input to calculate $V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)$, the value of the investment project for port i for which it pays $I_i(K^{\mathrm{F}}_i)$ when it invests at threshold $X^{\mathrm{F}}_{T,i}$ at time T^{F} in capacity K^{F}_i, given that the other port has invested in K^{L}_j. The differential equation for $V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)$ in a two-port setting is found by applying Bellman Equation and Itô's Lemma to

$$V^{\mathrm{F}}_i = \mathbb{E}\int_0^\infty \max_{q_i}\{\Pi_i(T^{\mathrm{F}}+\tau)\}\mathrm{e}^{-r\tau}\mathrm{d}\tau. \tag{8}$$

This results in

$$\frac{\sigma^2}{2}(X^{\mathrm{F}}_{T,i})^2\frac{\partial^2 V^{\mathrm{F}}_i}{\partial(X^{\mathrm{F}}_{T,i})^2}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) + \mu X^{\mathrm{F}}_{T,i}\frac{\partial V^{\mathrm{F}}_i}{\partial X^{\mathrm{F}}_{T,i}}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)$$
$$-rV^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) + \overline{\Pi}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) = 0, \tag{9}$$

with r the discount rate (Dixit & Pindyck, 1994).

The solution for each region R_k is given by

$$\begin{aligned} V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)|_{X^{\mathrm{F}}_{T,i}\in R_k} &= V^{\mathrm{F}}_{i,k}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) \\ &= G^{\mathrm{F}}_{i,(k,1)}(K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)\cdot(X^{\mathrm{F}}_{T,i})^{\beta_1} + G^{\mathrm{F}}_{i,(k,2)}(K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)\cdot(X^{\mathrm{F}}_{T,i})^{\beta_2} \\ &\quad + \overline{V}^{\mathrm{F}}_{i,k}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j), \end{aligned} \tag{10}$$

with $\overline{V}^{\mathrm{F}}_{i,k}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)$ the particular solution of differential equation (9) and $\overline{\Pi}_i = \overline{\Pi}_{i,k}$ in each region R_k. The roots β_1 and β_2 are equal to

$$\beta_1 = \frac{\frac{\sigma^2}{2} - \mu + \sqrt{(\frac{\sigma^2}{2}-\mu)^2 + 2r\sigma^2}}{\sigma^2} > 1, \qquad \beta_2 = \frac{\frac{\sigma^2}{2} - \mu - \sqrt{(\frac{\sigma^2}{2}-\mu)^2 + 2r\sigma^2}}{\sigma^2} < 0, \tag{11}$$

whereas the boundary conditions are given by

$$\begin{cases} V^{\mathrm{F}}_i(0, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) = \mathbb{E}\int_0^\infty -c_h K^{\mathrm{F}}_i \mathrm{e}^{-rt}\mathrm{d}t = \dfrac{-c_h K^{\mathrm{F}}_i}{r} \\ \lim\limits_{X^{\mathrm{F}}_{T,i}\to+\infty}\Big(V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) - \overline{V}^{\mathrm{F}}_{i,2}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)\Big) = 0 \\ \lim\limits_{X^{\mathrm{F}}_{T,i}\overset{<}{\to}c-s_G\lambda} V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) = \lim\limits_{X^{\mathrm{F}}_{T,i}\overset{>}{\to}c-s_G\lambda} V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) \\ \lim\limits_{X^{\mathrm{F}}_{T,i}\overset{<}{\to}c-s_G\lambda} \frac{\partial V^{\mathrm{F}}_i}{\partial X^{\mathrm{F}}_{T,i}}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) = \lim\limits_{X^{\mathrm{F}}_{T,i}\overset{>}{\to}c-s_G\lambda} \frac{\partial V^{\mathrm{F}}_i}{\partial X^{\mathrm{F}}_{T,i}}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j). \end{cases} \tag{12}$$

The first two conditions are required since the term in β_2 does not exist in region R_1 because it does not converge in $X = 0$ and the term in β_1 does not exist in region R_2 because it does not take speculative bubbles into account (Dixit & Pindyck, 1994). These conditions lead to $G^{\mathrm{F}}_{i,(1,2)}$ and $G^{\mathrm{F}}_{i,(2,1)}$ being equal to 0. The remaining two G^{F}_i stand for the value of the option to switch to the other region R_k, i.e. to start or stop operations (Dixit & Pindyck, 1994).

The follower's investment problem objective function

$$\max_{T^{\mathrm{F}}_i\geqslant 0, K^{\mathrm{F}}_i\geqslant 0}\left\{\left[V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) - I_i(K^{\mathrm{F}}_i)\right]\mathrm{e}^{-rT^{\mathrm{F}}_i}|X(t=0) = X\right\}, \tag{13}$$

gives rise to the following option value maximisation

$$F^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}) = \max\{\mathrm{e}^{-r\mathrm{d}t}\mathbb{E}(F^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i})) + \mathrm{d}F^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i})), \max_{K^{\mathrm{F}}_i}\left[V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) - I_i(K^{\mathrm{F}}_i)\right]\}, \tag{14}$$

which allows determining the optimal timing and size. The inner maximisation of Eq. (14) considers the project's net present value as $V_i^{\mathrm{F}}(X_{T,i}^{\mathrm{F}}, K_i^{\mathrm{F}}, K_j^{\mathrm{L}})$ minus $I_i(K_i^{\mathrm{F}})$ in order to determine the optimal capacity of the follower $(K_i^{*,\mathrm{F}})$ in terms of its timing threshold $(X_{T,i}^{\mathrm{F}})$ and the capacity already installed by the other port (K_j^{L}). This optimal capacity needs to satisfy

$$\frac{\partial V_i^{\mathrm{F}}}{\partial K_i^{\mathrm{F}}}(X_{T,i}^{\mathrm{F}}, K_i^{*,\mathrm{F}}, K_j^{\mathrm{L}}) = \frac{\partial I_i}{\partial K_i^{\mathrm{F}}}(K_i^{*,\mathrm{F}}), \tag{15}$$

stating that capacity is added up to the point where the marginal added value of extra capacity equals the marginal cost of extra capacity. Using the relevant smooth pasting and value matching conditions on the outer maximisation of Eq. (14), the optimal follower's timing threshold $(X_{T,i}^{*,\mathrm{F}})$ can be determined in terms of its own installed capacity (K_i^{F}) and the capacity already installed by the other port (K_j^{L}) (Dangl, 1999; Huisman & Kort, 2015; Hagspiel et al., 2016).

Solving the system

$$\begin{cases} X_{T,i}^{**,\mathrm{F}}(K_j^{\mathrm{L}}) = X_{T,i}^{*,\mathrm{F}}(K_i^{**,\mathrm{F}}(K_j^{\mathrm{L}}), K_j^{\mathrm{L}}) \\ K_i^{**,\mathrm{F}}(K_j^{\mathrm{L}}) = K_i^{*,\mathrm{F}}(X_{T,i}^{**,\mathrm{F}}(K_j^{\mathrm{L}}), K_j^{\mathrm{L}}) \end{cases} \tag{16}$$

results in the investment decision optimal in both timing and size of the follower, only dependent on K_j^{L} of the leader. It is written as $(X_{T,i}^{**,\mathrm{F}}(K_j^{\mathrm{L}}), K_i^{**,\mathrm{F}}(K_j^{\mathrm{L}}))$. It is worth highlighting that the timing of the leader has no impact on the follower's decision, as opposed to the leader's investment size. Concerning timing, it only matters that the leader has invested (Huisman & Kort, 2015). As a result, it could be that $X_{T,i}^{**,\mathrm{F}}(K_j^{\mathrm{L}}) < X_{T,i}^{\mathrm{L}}$ in case the leader plays an entry accommodating strategy (see the next section). The investment strategy of the follower will then be $X_{T,i}^{\mathrm{L}}, K_i^{*,\mathrm{F}}(X_{T,i}^{\mathrm{L}})$.

3.3 The leader's investment decision

The leader port with the cost advantage needs to decide on its own optimal timing and capacity, taking the calculated reaction function of the follower into account. There are three investment alternatives for the leader. First, if the market is initially large, the leader could invest in an entry accommodating capacity, which is low enough so that the follower can profitably invest at the same time and serve a part of the market as well (Huisman & Kort, 2015). If the market is initially smaller and the leader has a large cost advantage, it is also possible to invest in a capacity that is higher, so that the entire market is served at the moment of investment, the unrestricted entry deterrence threshold. In this case, entry of the follower is deterred to a later moment, when the market will have grown and it will have become also for this port profitable to invest. If the cost differences are rather small however, both ports could strive to be the first to invest. The leader's investment then occurs at the preemption point of the port with the cost disadvantage, where its follower value, $V_2^{\mathrm{F}} - I$, equals its leader value $V_2^{\mathrm{L}} - I$. This is called the preemption equilibrium. All of these strategies are calculated and discussed in greater detail in the following subsections.

3.3.1 Entry deterrence

To derive the optimal investment decision of the leader, we first determine the value of this port after its investment $V_i^{\mathrm{L}}(X_i^{\mathrm{L}}, K_i^{\mathrm{L}})$. If the leader chooses the entry deterring strategy by investing in such a high capacity that it (temporarily) serves the entire market, this value is made up of two parts. Since leader investment can only be optimal in region R_2, the investment value is given by:

$$\begin{aligned} V_{i,2}^{\mathrm{L_{det}}}(X_i^{\mathrm{L}}, K_i^{\mathrm{L}}) &= V_{i,2}^{\mathrm{M}}(X_i^{\mathrm{L}}, K_i^{\mathrm{L}}) - \left(\frac{X_{T,i}^{\mathrm{L}}}{X_{T,j}^{**,\mathrm{F}}(K_i^{\mathrm{L}})}\right)^{\beta_1} \cdot \\ & \left(V_{i,2}^{\mathrm{M}}(X_{T,j}^{**,\mathrm{F}}(K_i^{\mathrm{L}}), K_i^{\mathrm{L}}) - V_{i,2}^{\mathrm{F}}(X_{T,j}^{**,\mathrm{F}}(K_i^{\mathrm{L}}), K_i^{\mathrm{L}}, K_j^{**,\mathrm{F}}(K_i^{\mathrm{L}}))\right), \end{aligned} \tag{17}$$

for $X^{\mathrm{L}}_{T,i} \in R_2$. As demonstrated by Huisman & Kort (2015), the monopoly value $V^{\mathrm{M}}(X^{\mathrm{L}}_i, K^{\mathrm{L}}_i)$ is corrected for the reduced profit stream once the follower invests. This follower investment will always take place in region R_2 as well, since this is the only region wherein it is optimal for the follower to invest. Eq. (17) indicates that the leader has an incentive to invest in more capacity, which leads to further delaying the follower's entry. In that way, the leader can take advantage, because it earns the higher monopoly profit for a longer time. The monopoly value $V^{\mathrm{M}}_{i,k}(X^{\mathrm{L}}_i, K^{\mathrm{L}}_i)$ in region R_2 can be calculated like in Dangl (1999), with the exception that here only two regions are retained and that hence $G_{2,1}$ in R_2 is set to zero.

The correction to the monopoly value is calculated as the discounted future reductions of the profit flows due to the investment of the follower.[11] The same stochastic discount factor as Huisman & Kort (2015),

$$\left(\frac{X^{\mathrm{L}}_{T,i}}{X^{**,\mathrm{F}}_{T,j}(K^{\mathrm{L}}_i)}\right)^{\beta_1}, \tag{18}$$

is used here. However, the discounted future reductions of the profit flows are more complicated to explicate than in the case of Huisman & Kort (2015), because of output flexibility and the two resulting regions for $\overline{\Pi}_i$. In that light, we consider the correction as a reduction of the residual value of the project after the follower's investment. As a result, we calculate it as the difference in value V for the leader between being the sole active port and the duopoly situation at the moment the follower invests. The value at the moment that both ports have invested is calculated using Eq. (10) with port i being the leader and port j the follower. The solution takes into account that the follower invests in its own optimal size based on the capacity installed by the leader.[12]

It is interesting to note that each V in Eq. (17) contains a term of the form $G^{\mathrm{S}}_{i,(k,l)}X^{\beta_l}$, with S the role (L or F) of port i, k the region and $l = \{1, 2\}$ to account for the possibility of X crossing the boundary between R_1 and R_2. The value matching and smooth pasting conditions automatically hold for $V^{\mathrm{L_{det}}}_i$. This is because these conditions need to be imposed for $V^{\mathrm{M}}_{i,1}(X^{\mathrm{L}}_i, K^{\mathrm{L}}_i)$ and $V^{\mathrm{M}}_{i,2}(X^{\mathrm{L}}_i, K^{\mathrm{L}}_i)$ (see Hagspiel et al. (2016)) and because the correction terms are the same for each region. The latter is because the follower will always invest only in the profitable region 2, giving rise to a sequential problem.[13]

Analogous to the previous section, $V^{\mathrm{L_{det}}}_i(X^{\mathrm{L}}_i, K^{\mathrm{L}}_i)$ and $I_i(K^{\mathrm{L}}_i)$ together allow calculating the optimal capacity $K^{*,\mathrm{L_{det}}}_i$ for a given timing $(X^{\mathrm{L}}_{T,i})$, whereas the relevant value matching and smooth pasting conditions for $F^{\mathrm{L_{det}}}_i(X^{\mathrm{L}}_{T,i}, K^{\mathrm{L}}_i)$ lead to the optimal unrestricted timing $X^{*,\mathrm{L_{det}}}_{T,i}$ as a function of installed capacity (K^{L}_i). Combining both leads to $(X^{**,\mathrm{L_{det}}}_{T,i}, K^{**,\mathrm{L_{det}}}_i)$, the investment decision optimal in both timing and size for the leader playing the entry deterrence strategy.[14] According to Huisman & Kort (2015) however, the leader can only play the deterrence strategy when $X \in [X^{\mathrm{det}}_{T,1}, X^{\mathrm{det}}_{T,2}]$. $X^{\mathrm{det}}_{T,1}$ on the one hand is calculated as the lowest X wherefore an optimal $K^{*,\mathrm{L_{det}}}_i$ exists. On the other hand, $X^{\mathrm{det}}_{T,2}$ is defined as $X^{*,\mathrm{F}}_{T,j}(K^{*,\mathrm{L_{det}}}_i(X^{\mathrm{det}}_{T,2})) = X^{\mathrm{det}}_{T,2}$.

In this light, it should always be verified that $X^{**,\mathrm{L_{det}}}_{T,i} \in [X^{\mathrm{det}}_{T,1}, X^{\mathrm{det}}_{T,2}]$ to make sure that this optimal entry deterrence strategy is feasible and indeed deters the follower. In the case of sufficiently large cost differences, the leader will wait to invest until the optimal deterrence threshold is reached if $X(t = 0) < X^{**,\mathrm{L_{det}}}_{T,i}$, whereas the port will invest right away if $X(t = 0) > X^{**,\mathrm{L_{det}}}_{T,i}$

[11] Alternatively, the correction term could be written as $+\left(\frac{X^{\mathrm{L}}_{T,i}}{X^{**,\mathrm{F}}_{T,j}(K^{\mathrm{L}}_i)}\right)^{\beta_1} \cdot \left(V^{\mathrm{F}}_{i,2}(X^{**,\mathrm{F}}_{T,j}(K^{\mathrm{L}}_i), K^{\mathrm{L}}_i, K^{**,\mathrm{F}}_j(K^{\mathrm{L}}_i)) - V^{\mathrm{M}}_{i,2}(X^{**,\mathrm{F}}_{T,j}(K^{\mathrm{L}}_i), K^{\mathrm{L}}_i)\right)$, as $V^{\mathrm{F}}_{i,2}$ replaces $V^{\mathrm{M}}_{i,2}$ after the follower's investment.

[12] This reasoning is analogous to $V^{\mathrm{M}}_1(X_T, K) = \overline{V}^{\mathrm{M}}_1 + (X_T/X_{T,\mathrm{boundary}})^{\beta_1} \cdot \left(V^{\mathrm{M}}_2(X_{T,\mathrm{boundary}}, K) - \overline{V}^{\mathrm{M}}_1(X_{T,\mathrm{boundary}}, K)\right)$, where the correction expresses the possibility of X crossing $X_{T,\mathrm{boundary}}$ to enter a different region R_k.

[13] $X_{T,\mathrm{boundary}} < X^{**,\mathrm{F}}_{T,j}$.

[14] This is the outcome of the joint optimisation of $X^{*,\mathrm{L_{det}}}_{T,i}$ and $K^{*,\mathrm{L_{det}}}_i$, without timing nor size being dependent on K_i and X respectively.

3.3.2 Entry accommodation

It may occur that entry deterrence is not the optimal strategy for the port to follow. This is the case when the market is initially large enough to accommodate two operating ports. Then the leader does not have the incentive to overinvest in order to delay the follower's investment, since it would be too costly to do so. Consequently, it is better for the leader port to invest in less capacity than what would be optimal under entry deterrence.

Under entry accommodation, the value function of the leader is different than under entry deterrence, because the follower invests right away and there is no V^{M}-term. It is however similar to Eq. (10), as the two ports invest at the same time (Huisman & Kort, 2015). The difference is that the capacity of the other port, i.e. the follower, is now endogenous, since it depends on the capacity of the leader and the given threshold, which is by definition equal to the timing of the leader. The value of the leader now becomes:

$$V_i^{\mathrm{L_{acc}}}(X_{T,i}^{\mathrm{L}}, K_i^{\mathrm{L}}) = V_i^{\mathrm{F}}(X_{T,i}^{\mathrm{L}}, K_i^{\mathrm{L}}, K_j^{*,\mathrm{F}}(X_{T,i}^{\mathrm{L}}, K_i^{\mathrm{L}})) \tag{19}$$

The accommodation strategy can only be played when the market is large enough such that $X \in [X_{T,1}^{\mathrm{acc}}, \infty)$, with $X_{T,1}^{\mathrm{acc}} \leqslant X_{T,2}^{\mathrm{det}}$ and $X_{T,1}^{\mathrm{acc}}$ defined as $X_{T,j}^{*,\mathrm{F}}(K_i^{*,\mathrm{L_{acc}}}(X_{T,1}^{\mathrm{acc}})) = X_{T,1}^{\mathrm{acc}}$ (Huisman & Kort, 2015).

It is moreover possible to determine whether it is optimal to play the deterrence or accommodation strategy if $X \in [X_{T,1}^{\mathrm{acc}}, X_{T,2}^{\mathrm{det}}]$. In case $X_{T,1}^{\mathrm{acc}} < X_{T,2}^{\mathrm{det}}$, there exists an $\hat{X}_T \in [X_{T,1}^{\mathrm{acc}}, X_{T,2}^{\mathrm{det}}]$ for which it holds that for $X < \hat{X}_T$, it is optimal for the leader to play the entry deterrence strategy, while for $X > \hat{X}_T$ the entry accommodation strategy is optimal.[15] $\hat{X}_T$ satisfies $V_i^{\mathrm{L_{det}}}(\hat{X}_T, K_i^{*,\mathrm{L_{det}}}(\hat{X}_T)) - I(K_i^{*,\mathrm{L_{det}}}(\hat{X}_T) = V_i^{\mathrm{L_{acc}}}(\hat{X}_T, K_i^{*,\mathrm{L_{acc}}}(\hat{X}_T)) - I(K_i^{*,\mathrm{L_{acc}}}(\hat{X}_T))$.

3.3.3 Preemption

In the case of a small cost asymmetry between the ports, both ports have an incentive to be the first investor (Corchón & Marini, 2018). At the optimal investment threshold $X_{T,i}^{*,\mathrm{L_{det}}}$ of the first port with the cost advantage, the project value $V_1^{\mathrm{L}} - I_1$ of being the leader for this port is higher than the discounted value of being the follower $V_1^{\mathrm{F}} - I_1$. If the same holds for the second port, this follower would then prefer to become the leader. The second port could achieve this by investing at an X that is infinitesimally smaller than $X_{T,i}^{*,\mathrm{L_{det}}}$: $X_{T,i}^{*,\mathrm{L_{det}}} - \varepsilon$, with ε an infinitesimal small positive number. The first port would then invest at $X_{T,i}^{*,\mathrm{L_{det}}} - 2\varepsilon$ to remain the leader. This process of epsilon preemption as described by Huisman & Kort (2015) would continue until the preemption threshold X_T^{P} for which it holds that

$$\begin{aligned} V_2^{\mathrm{L}}(X_T^{\mathrm{P}}, K_2^{*,\mathrm{L}}(X_T^{\mathrm{P}})) - I_2(K_2^{*,\mathrm{L}}(X_T^{\mathrm{P}})) = &\left(\frac{X_T^{\mathrm{P}}}{X_{T,2}^{**,\mathrm{F}}(K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}}))}\right)^{\beta_1} \cdot \\ &\Big[V_2^{\mathrm{F}}(X_{T,2}^{**,\mathrm{F}}(K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}})), K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}})), K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}})) - I_2(K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}})))\Big]. \end{aligned} \tag{20}$$

At this point, the port with the cost disadvantage is indifferent between the role of the leader and that of the follower. The cost advantage for the other port leads to its leader value at this point still being higher than its discounted follower value. Hence, at this point no further preemption will take place, and port 1 will act as the leader and invest at X_T^{P} in $K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}})$ to preempt port 2, whose investment will be deterred. However, if $X < X_{T,i}^{**,\mathrm{L_{det}}} < X_T^{\mathrm{P}}$, the port with the cost advantage would invest at its deterrence-optimum and the preemption point would be insignificant.

3.4 A synthesis of the leader's and follower's strategies

As the previous subsections illustrated, the leader port can choose from three different investment strategies. The choice it will make, depends on the initial state of the market as expressed by X. In this subsection, we discuss these possible strategies using a number line for X in Figure 3.

[15] In case $X_{T,1}^{\mathrm{acc}} = X_{T,2}^{\mathrm{det}}$, $\hat{X}_T = X_{T,1}^{\mathrm{acc}} = X_{T,2}^{\mathrm{det}}$.

Assuming that X is initially very small, i.e. below $X_{T,1}^{\mathrm{det}}$, no profitable investment is possible for any port at the beginning. As soon as $X > X_{T,1}^{\mathrm{det}}$, the leader could profitably invest in an entry-deterring quantity. However, it will not decide to do so, since waiting is an even more valuable strategy. As soon as $X = X_T^{\mathrm{P}}$ and assuming that $X_T^{\mathrm{P}} < X_{T,i}^{**,\mathrm{L_{det}}}$ due to relatively small cost differences between the ports, the port with the cost advantage will decide to invest in the optimal entry-deterring quantity $K_1^{*,\mathrm{L_{det}}}(X_T^{\mathrm{P}})$. If it would not do so, the other port would invest first to preempt the port with the cost advantage, who would then become the follower. This would for the cost-advantaged firm imply a lower value than if it would be the leader. However, if the preemption point would be higher than the optimal investment threshold of the leader due to a larger cost advantage, the leader could wait longer until X reaches $X_{T,i}^{**,\mathrm{L_{det}}} \in [X_{T,1}^{\mathrm{det}}, X_{T,1}^{\mathrm{det}}]$. At that point, the port with the cost advantage can invest at its unrestricted leader threshold, i.e. entry deterrence with $K_i^{**,\mathrm{L_{det}}}$ being the amount of capacity.

If X would initially exceed $\min\{X_T^{\mathrm{P}}, X_{T,i}^{**,\mathrm{L_{det}}}\}$, the leader would invest right away. The investment strategy and related capacity are dependent on the actual value of X. As long as $X < X_{T,1}^{\mathrm{acc}} \leqslant X_{T,2}^{\mathrm{det}}$, the optimal instantaneous investment for the leader would be the deterrence strategy, which is at the same time the only feasible strategy. If $X > X_{T,2}^{\mathrm{det}} \geqslant X_{T,1}^{\mathrm{acc}}$, it would be optimal for the leader to invest right away in an entry-accommodating strategy, which is in this situation, again, the only feasible strategy. If $X \in [X_{T,1}^{\mathrm{acc}} \leqslant X_{T,2}^{\mathrm{det}}]$, both the deterrence and accommodation strategies are feasible. If $X < \hat{X}_T$, the deterrence strategy is more profitable, while if $X > \hat{X}_T$, accommodation is the most profitable strategy to play. As a result, a higher $\hat{X}_T$ decreases the probability that the leader will invest in an entry-accommodating capacity level.

The decision of the follower is easier to determine. If the leader invests in an entry deterring capacity, the follower would wait with investment until X reaches its optimal threshold, which is $X_{T,i}^{**,\mathrm{F}}$. At that point, it would invest in the corresponding optimal capacity $K_i^{**,\mathrm{F}}$. Both depend on the capacity of the leader, as described in Section 3.2. If the leader would invest in an entry-accommodating quantity, the follower would invest at the same time in its corresponding optimal capacity $K_i^{*,\mathrm{F}}(X_{T,j}^{\mathrm{L_{acc}}})$ as calculated before.

4 Impact of competition and ownership on investment decisions

In this section, the previously described methodology is applied to a two-port setting specified by the parameters in Table 1. We calculate the specific $X_{T,i}$ and K_i from Figure 3 that are required to describe the full domain of possible decisions for both the leader and the follower port. In order to examine the impact of competition intensity and answer research sub-question 1), we vary the product differentiation parameter δ from 0.6 to 0.9 for intensified competition and to 0.3 for less competition with more diversified port services. For each δ, the analysis is carried out under three different ownership structures: a private port, a public port taking full consumer surplus into account and a port that is 50% owned publicly by a government taking 50% of port i's generated consumer surplus into account. This allows answering research sub-question 2). The resulting investment decisions for port 1 (the leader) and port 2 (the follower) are given in Tables 2 - 4.

The first threshold to be discussed is the preemption point X_T^{P}. In the numerical simulations, with a sufficiently low cost advantage for port 1, the preemption point is always below the unrestricted investment threshold for the leader. This implies that when X is initially below the preemption point, the port with the cost advantage will wait until X reaches X_T^{P} to invest in an entry deterring capacity, in order to preempt the follower. If government involvement is higher in both ports, the preemption threshold will be lower too, since more accounting for social welfare increases the projects' attractiveness. The willingness to invest of each port increases. As a result, epsilon preemption will continue further to lead to a lower preemption threshold. In order to preempt port 2, port 1 needs to invest earlier. The impact of intensified competition (through a lower product diversification) on the timing of the preemption point is as expected, namely a lower X_T^{P}-threshold. Since port 2's incentive to become the leader is larger, following a

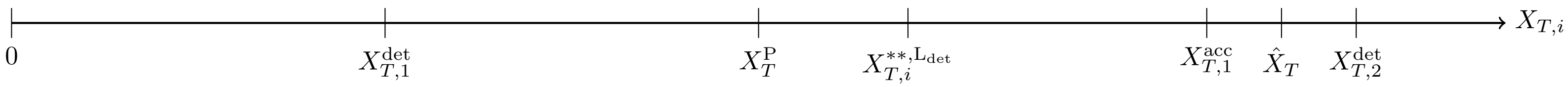

Figure 3: Number line with the leader's critical investment thresholds.

Table 2: Investment strategies of the leader (port 1: $X_{T,1}, K_1^{*,\mathrm{L_{det/acc}}}(X_{T,1})$) and follower (port 2: $(X_{T,2}^{**,\mathrm{F}}(K_1^{*,\mathrm{L_{det/acc}}}(X_{T,1})), K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L_{det/acc}}}(X_{T,1}))))$ for each characteristic $X_{T,i}$ in Figure 3.

s_G, s_{CS}	**Port role**	$X_{T,1}^{\mathrm{det}}$	X_T^{P}	$X_{T,i}^{**,\mathrm{L_{det}}}$	$X_{T,1}^{\mathrm{acc}}$	$\hat{X}_T$ (acc)	$\hat{X}_T$ (det)	$X_{T,2}^{\mathrm{det}}$
0, 0	*Leader (1)*	10.65, 5.14	32.75, 10.35	(36.24, 10.79)	48.72, 12.02	48.84, 12.04	48.84, 12.19	48.91, 12.20
	$\longrightarrow$ *Follower (2)*	(41.16, 11.50)	(46.89, 11.91)	(47.38, 11.94)	(48.72, 12.02)	48.84, 12.04	(48.90, 12.03)	(48.91, 12.03)
0.5, 0.5	*Leader (1)*	10.08, 5.14	30.97, 10.34	(34.68, 10.83)	47.89, 12.15	48.06, 12.17	48.06, 12.36	48.16, 12.38
	$\longrightarrow$ *Follower (2)*	(39.57, 11.54)	(45.67, 12.00)	(46.28, 12.05)	(47.89, 12.15)	48.06, 12.17	(48.15, 12.17)	(48.16, 12.17)
1, 1	*Leader (1)*	8.56, 5.14	25.93, 10.39	(30.49, 11.10)	47.75, 12.90	48.48, 12.99	48.48, 13.46	48.96, 13.52
	$\longrightarrow$ *Follower (2)*	(35.22, 11.83)	(43.06, 12.53)	(44.34, 12.64)	(47.75, 12.90)	48.48, 12.99	(48.85, 12.99)	(48.96, 13.00)

Parameter values: $A = 5, B = 1, \delta = 0.6, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_{I,1} = 80, FC_{I,2} = 100, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12.$

Source: Own calculations.

Table 3: Investment strategies of the leader (port 1: $X_{T,1}, K_1^{*,\mathrm{L_{det/acc}}}(X_{T,1})$) and follower (port 2: $(X_{T,2}^{**,\mathrm{F}}(K_1^{*,\mathrm{L_{det/acc}}}(X_{T,1})), K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L_{det/acc}}}(X_{T,1}))))$ for each characteristic $X_{T,i}$ in Figure 3 under higher product diversification.

s_G, s_{CS}	**Port role**	$X_{T,1}^{\mathrm{det}}$	X_T^{P}	$X_{T,i}^{**,\mathrm{L_{det}}}$	$X_{T,1}^{\mathrm{acc}}$	$\hat{X}_T$ (acc)	$\hat{X}_T$ (det)	$X_{T,2}^{\mathrm{det}}$
0, 0	*Leader (1)*	10.58, 5.14	35.12, 10.71	(36.57, 10.89)	43.19, 11.61	43.20, 11.61	43.20, 11.65	43.20, 11.65
	$\longrightarrow$ *Follower (2)*	(39.79, 11.38)	(42.75, 11.59)	(42.84, 11.59)	(43.19, 11.61)	43.20, 11.61	(43.20, 11.61)	(43.20, 11.61)
0.5, 0.5	*Leader (1)*	10.01, 5.14	33.31, 10.69	(34.93, 10.90)	41.88, 11.68	41.89, 11.69	41.89, 11.73	41.90, 11.74
	$\longrightarrow$ *Follower (2)*	(38.18, 11.42)	(41.34, 11.65)	(41.46, 11.66)	(41.88, 11.68)	41.89, 11.69	(41.90, 11.69)	(41.90, 11.69)
1, 1	*Leader (1)*	8.50, 5.14	28.12, 10.74	(30.45, 11.08)	39.04, 12.13	39.11, 12.13	39.11, 12.25	39.15, 12.26
	$\longrightarrow$ *Follower (2)*	(33.78, 11.68)	(37.91, 12.04)	(38.20, 12.06)	(39.04, 12.13)	39.11, 12.13	(39.15, 12.13)	(39.15, 12.13)

Parameter values: $A = 5, B = 1, \delta = 0.3, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_{I,1} = 80, FC_{I,2} = 100, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12.$

Source: Own calculations.

Table 4: Investment strategies of the leader (port 1: $X_{T,1}, K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X_{T,1})$) and follower (port 2: $(X_{T,2}^{**,\mathrm{F}}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X_{T,1})), K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X_{T,1}))))$ for each characteristic $X_{T,i}$ in Figure 3 under lower product diversification.

s_G, s_{CS}	**Port role**	$X_{T,1}^{\mathrm{det}}$	X_T^{P}	$X_{T,i}^{**,\mathrm{L}_{\mathrm{det}}}$	$X_{T,1}^{\mathrm{acc}}$	$\hat{X}_T$ (acc)	$\hat{X}_T$ (det)	$X_{T,2}^{\mathrm{det}}$
0, 0	*Leader (1)*	10.71, 5.14	31.15, 10.14	(36.28, 10.80)	55.27, 12.52	55.76, 12.57	55.76, 12.93	56.08, 12.96
	$\longrightarrow$ *Follower (2)*	(42.40, 11.61)	(50.87, 12.23)	(52.09, 12.32)	(55.27, 12.52)	55.76, 12.57	(56.02, 12.56)	(56.08, 12.57)
0.5, 0.5	*Leader (1)*	10.13, 5.14	29.43, 10.13	(34.79, 10.86)	55.20, 12.73	55.94, 12.80	55.94, 13.26	56.43, 13.31
	$\longrightarrow$ *Follower (2)*	(40.82, 11.66)	(49.81, 12.36)	(51.29, 12.46)	(55.20, 12.73)	55.94, 12.80	(56.33, 12.80)	(56.43, 12.80)
1, 1	*Leader (1)*	8.61, 5.14	24.64, 10.22	(30.90, 11.23)	60.33, 14.02	64.82, 14.46	64.82, 15.64	68.30, 16.03
	$\longrightarrow$ *Follower (2)*	(36.44, 11.97)	(47.88, 13.02)	(50.89, 13.27)	(60.33, 14.02)	64.82, 14.46	(66.66, 14.49)	(68.30, 14.61)

Parameter values: $A = 5, B = 1, \delta = 0.9, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_{I,1} = 80, FC_{I,2} = 100, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12.$

Source: Own calculations.

relative increase in the leader value as compared to the follower value, port 1 needs to advance its investment further to preempt port 2. The impact on the size of the investment is however remarkable. The earlier leader investment in order to preempt the follower implies investing at the moment that the market has a smaller size, which results in the leader installing less capacity. The optimal leader capacity investment size as a function of the timing increases however with the amount of competition. As a result of increased competition, the leader would invest in more capacity than what would be optimal under a monopoly setting in order to delay follower entry for a longer time, leading to a prolonged monopoly position (Huberts et al., 2014). This explains why follower investment is later and hence larger when there is more competition, notwithstanding the leader's earlier investment timing under the preemption strategy. The findings are summarised in the following results, which are derived numerically, since closed-form analytical results could not be obtained.

Result 1 *Intensified competition and resulting preemption not only leads to earlier investment of the leader, but also to less capacity installed. The follower however invests later and in more capacity.*

If there are large cost differences, the leader is able to invest at the unrestricted threshold $X_{T,i}^{**,\mathrm{L_{det}}}$. The impact of competition on this optimal timing threshold is ambiguous and limited. The impact of an increase of public money involvement however is clearer:

Result 2 *An increase of public money involvement leads to an earlier unrestricted investment in more capacity.*

Result 2 confirms the finding of Asteris et al. (2012), namely that public companies invest sooner and in more capacity than private companies. As soon as the initial X is high enough (above $\hat{X}_T$), the market is so profitable that the cost-disadvantaged port will also invest immediately. This implies that entry accommodation becomes the most profitable strategy for the leader. The leader will invest in less capacity than under entry deterrence, because then there is no incentive to prolong the monopoly period. The thresholds indicating the beginning of the accommodation region and the end of the deterrence region increase with a higher δ. As previously noted, if the competitive impact of the other port increases, the leader has a larger incentive to deter the follower from entry. This can be done through investing in more capacity to delay the follower's investment. The impact of public involvement on the two boundaries is ambiguous. Additionally, (increased) public money involvement and product diversification both widen the interval wherein both strategies (entry deterrence and accommodation) are possible. This is caused by a combination of effects. Due to public money involvement, investment becomes more beneficial for both ports. Since it is more profitable for the leader, deterrence is feasible over a longer time span, but because investment is also more profitable for the follower, at the same time it is more difficult to deter entry.

The follower's decision does not depend on the initial value of X and the different thresholds. It only depends on the capacity choice of the leader. If the leader has invested in more capacity, the follower will invest later, independent of the timing of the leader. The reason is that the leader has been able to capture a larger share of the market. Hence the follower needs to await more market growth in order to be able to invest profitably. Given the positive relationship between timing and size, the follower will not only invest later, but also invest in more capacity. If relatively more public money is involved, the follower will ceteris paribus invest earlier in more capacity. This observation is analogous to the leader's decision. If the port services are more homogeneous, leading to increased competition, the negative impact of the leader's activity on the follower's price is higher. As a result, the follower needs to wait longer in order to be able to invest profitably. Again, the installed capacity will be larger. The reason is that under more intense competition, investment by the leader has more effect on the follower's profitability. By consequence, it requires less effort of the leader to reduce profitability of the follower, thus making entry deterrence a relatively easier strategy to follow.

Table 5: Investment strategies of the leader (port 1: $X_{T,1}, K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X_{T,1})$) and follower (port 2: $(X_{T,2}^{**,\mathrm{F}}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X_{T,1})), K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X_{T,1})))$) for each characteristic $X_{T,i}$ in Figure 3 under different parameter changes.

Parameter change	**Port role**	$X_{T,1}^{\mathrm{det}}$	X_T^{P}	$X_{T,i}^{**,\mathrm{L}_{\mathrm{det}}}$	$X_{T,1}^{\mathrm{acc}}$	$\hat{X}_T$ (acc)	$\hat{X}_T$ (det)	$X_{T,2}^{\mathrm{det}}$
Base case	*Leader (1)*	10.08, 5.14	30.97, 10.34	(34.68, 10.83)	47.89, 12.15	48.06, 12.17	48.06, 12.36	48.16, 12.38
	$\longrightarrow$ *Follower (2)*	(39.57, 11.54)	(45.67, 12.00)	(46.28, 12.05)	(47.89, 12.15)	48.06, 12.17	(48.15, 12.17)	(48.16, 12.17)
$A = 4$	*Leader (1)*	9.41, 5.14	27.56, 10.07	(31.29, 10.61)	44.57, 12.05	44.75, 12.07	44.75, 12.30	44.86, 12.31
	$\longrightarrow$ *Follower (2)*	(36.36, 11.40)	(42.25, 11.89)	(42.90, 11.94)	(44.57, 12.05)	444.75, 12.07	(44.85, 12.07)	(44.86, 12.07)
$\sigma = 0.15$	*Leader (1)*	9.81, 5.14	41.32, 11.86	(49.36, 12.78)	N/A	N/A	N/A	N/A
	$\longrightarrow$ *Follower (2)*	(60.52, 14.06)	(80.77, 15.67)	(84.30, 15.93)	N/A	N/A	N/A	N/A
$\sigma = 0.14$	*Leader (1)*	9.88, 5.14	38.62, 11.48	(44.84, 12.21)	78.10, 15.18	78.70, 15.23	78.70, 15.51	79.12, 15.55
	$\longrightarrow$ *Follower (2)*	(53.93, 13.34)	(68.11, 14.47)	(70.02, 14.61)	(78.10, 15.18)	78.70, 15.23	(79.02, 15.25)	(79.12, 15.25)
$\mu = 0.02$	*Leader (1)*	8.89, 5.14	33.08, 11.23	(38.09, 11.90)	62.51, 14.42	62.89, 14.45	62.89, 14.70	63.15, 14.73
	$\longrightarrow$ *Follower (2)*	(45.38, 12.95)	(56.10, 13.91)	(57.44, 14.02)	(62.51, 14.42)	62.89, 14.45	(63.10, 14.46)	(63.15, 14.46)
$\mu = -0.01$	*Leader (1)*	15.59, 5.14	33.29, 8.89	(36.07, 9.20)	43.35, 9.60	43.54, 9.61	43.54, 9.93	43.69, 9.95
	$\longrightarrow$ *Follower (2)*	(39.22, 9.44)	(42.67, 9.57)	(42.97, 9.58)	(43.35, 9.60)	43.54, 9.61	(43.68, 9.61)	(43.69, 9.61)
$FC_{I,2} = 116.3$	*Leader (1)*	10.07, 5.14	(34.74, 10.84)	(34.74, 10.84)	51.33, 12.51	51.51, 12.53	51.51, 12.74	51.63, 12.75
	$\longrightarrow$ *Follower (2)*	(42.24, 11.87)	(49.20, 12.38)	(49.20, 12.38)	(51.33, 12.51)	51.51, 12.53	(51.61, 12.53)	(51.63, 12.53)
Single government	*Leader (1)*	10.06, 5.14	31.46, 10.41	(34.70, 10.83)	46.29, 12.03	46.40, 12.04	46.40, 12.19	46.46, 12.19
	$\longrightarrow$ *Follower (2)*	(39.24, 11.51)	(44.61, 11.92)	(45.06, 11.95)	(46.29, 12.03)	46.40, 12.04	(46.46, 12.04)	(46.46, 12.04)

Base case parameter values:
$A = 5, B = 1, \delta = 0.6, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_{I,1} = 80, FC_{I,2} = 100, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, s_G = 0.5, s_{CS} = 0.5.$

Source: Own calculations.

5 Impact of other parameters on investment decisions

In order to analyse the impact of the height of congestion costs (A), uncertainty (σ), growth (μ) and investment cost difference between the two ports (as expressed by $FC_{I,i}$) on the investment decision, each time we alter the respective parameter and compare it to the base case (where $\delta = 0.6$ and $s_G = s_{CS} = 0.5$). In this light, the outcomes in Table 5 allow answering research sub-questions 3) to 6).

If the port customers are more averse to waiting, the willingness to pay is lower for the same utilisation rate. As a reaction, the following result holds:

Result 3 *Both the leader and the follower port will invest in more capacity, but at a later moment if the customers are more averse to waiting.*

The reason is that in order to make up for the less profitable project, the port will delay its investment until the market is profitable enough to install the project. This goes hand in hand with a larger investment in order to reduce the occupancy rate. This allows at the same time taking better advantage of the investment size scale economies.

If the economic environment is more uncertain, both ports benefit from waiting longer to invest, in order to gain more information. This confirms the frequent real options observation:

Result 4 *Increased uncertainty not only leads to waiting longer before investment due to a higher option value of waiting, but also to more capacity installed.*

However, this effect is lower under competition, since competition has a negative impact on the option value of waiting. Next to the common real options result, uncertainty also has another effect. It might even be that due to high uncertainty, entry accommodation is no longer a feasible strategy. If uncertainty goes up, the value of waiting for the follower rises. This makes that for sufficiently high values of uncertainty, the follower always waits whenever the leader invests. This implies the absence of an accommodation region. Because higher uncertainty implies that the follower invests later, the leader is a monopolist for a longer time in the deterrence region. This makes deterrence more attractive for the leader, implying that $X_{T,1}^{\mathrm{det}}$ can be lower.

If average growth is higher, both ports need to install substantially more capacity, in order to be able to accommodate the future demand without too much congestion. However, a larger investment requires a larger market, implying later investment. This result is summarised as follows:

Result 5 *Increased growth leads to investing later, in more capacity.*

Additionally, the X_1^{det} threshold will be lower as well, since the project is more attractive, and the port will be willing to install the project earlier. However, also the impact of negative economic growth needs some attention:

Result 6 *If growth is negative, the port will need to wait for a higher threshold to be reached, in order to be able to install the project profitably. Due to the negative growth rate, reaching this threshold is much less probable. Moreover, the project will be much smaller, since future demand is expected to decrease.*

Since the leader's project will be much smaller, the follower speeds up investing, but, also due to declining market size, in a smaller capacity level.

The impact of a cost advantage increase for the leader, such that $FC_{I,2}$ increases, is that the leader can wait longer to invest in order to still deter or preempt the follower. The reason is that the follower needs to wait longer (as expressed through a higher X_T) in order to be able to profitably invest in capacity, due to its higher investment cost. This leads to both ports not only investing later, but also in more capacity. As a consequence, the following result holds:

Result 7 *When the cost advantage becomes large enough, preemption no longer takes place.*

In such a case, the role of each port is ex-ante determined. The first port (leader) can invest at its unrestricted leader threshold, while at this point the follower value of the second port is at least as high as its leader value. Additionally, it is observed that $X_{T,1}^{\text{det}}$ slightly decreases. The leader knows that it will benefit for a longer time of its monopoly position due to the FC-cost increase for port 2. As a result, investing in capacity becomes profitable earlier.

Throughout this paper, the analyses were made under the assumption that the public owner involved in port i differs from the public owner involved in port j. However, it is worthwhile to check the robustness of our analysis in case the same government would own a share of port i and j, which could be the case if those two ports are located in the same country or province. In such a case, the government would consider the consumer surplus of both ports, CS_{i+j}, which under product differentiation equals $CS_{i+j}(q_i, q_j) = B/2 \cdot (q_i^2 + 2\delta q_i q_j + q_j^2)$ (Singh & Vives, 1984). As a result, CS_i in Eq. (4) would no longer be valid, as it needs to be replaced by $B/2 \cdot (q_i^2 + \delta q_i q_j)$. The consumer surplus of the other port would equal $B/2 \cdot (q_j^2 + \delta q_i q_j)$, so that the sum of both equals $CS_{i+j}(q_i, q_j)$. Implementing this in our model yields the investment strategies in the last two lines of Table 5, indicated by 'single government'. The effect on the calculated investment decisions is limited and is qualitatively similar to the effect of a decreased impact of the other port's throughput quantity q_j on the own port's price p_i, mathematically expressed as a decrease of δ.

6 Conclusions and future research

Many examples of competing ports, operating in an uncertain environment, exist. Depending on the geographical situation and services offered, the amount of competition may however differ. In this paper, we have analysed how inter-port competition under uncertainty interacts with other typical port characteristics while influencing the port capacity investment decision. We not only allow for simultaneous investment when the leader invests in an entry-accommodating capacity, but also address the possibility for the leader to deter entry in a leader-follower timing game. Uncertainty is modelled by a GBM, which allows analysing the impact of growth and uncertainty independently.

We find that when competition is more intense, the option value of waiting is reduced because each port has a larger incentive to invest before the other port. As a result of this earlier investment, it will be smaller as well. The same effect on the timing is observed when government involvement increases. The consideration of social welfare in the operational objective function leads to a more attractive project. As a result, the port will invest earlier, and also in more capacity. If growth expectations are higher, it is beneficial to wait longer and benefit from the larger market and higher price. As a result, more capacity will be installed at this later timing. The same holds for more uncertainty, since the option value of waiting and gaining more information increases with uncertainty. Subsequently, we show that if the customers are less waiting-time averse, less capacity is needed, and because the project is more attractive due to higher full prices, the port will want to invest earlier. Finally, we show that if the cost advantage of the leader is small enough, both ports are seeking to preempt each other. If the cost difference is large enough however, the cost-advantaged port is guaranteed of its leader role, so that it can invest at its unrestricted leader threshold.

Some limitations are present in the model too, which allow additional model extensions in future research. The impact of intra-port competition on the investment decision is beyond the scope of this paper, but would be an interesting subject of a follow-up study. Additionally, it takes time to build the infrastructure, during which the market evolves in an uncertain way. As a result, the exposure to risk is larger in reality than accounted for in the presented model. Additionally, a difference in time to build between two ports, e.g., due to a different political and legal environment, may also impact competition. In this light, adapting the model of Aguerrevere (2003) to a port setting provides an interesting way for further research. Moreover, the current model neglects the option to expand. When the port is already active, it might want to mitigate the already present congestion, with its detrimental effect on the port customers' willingness to pay, in order to increase profitability of the port operations in the future. Another limitation of the model is the assumption of the project being built at once. Many port expansion projects are deployed in stages, each one at the time when the market has grown sufficiently. The modelling approach of Chronopoulos et al. (2017) is able to account for phased investment and needs to be considered in the next stage of this research. Finally, more differences between the two ports may be considered, such as different objectives and ownership shares. In line with Result 2, we expect the port with a higher public ownership share to invest earlier in more capacity, since the project is more attractive due to the fact that social welfare is taken more into account. Moreover, port investment decisions are influenced by the government's port development doctrine. Where this paper accounts for the properties of the Anglo-Saxon and European (Continental) doctrine with individual ports, respectively private and at least partly public ports, the results may well be different under the Asian doctrine (Bennathan & Waters, 1979; Lee & Flynn, 2011). Considering the centrally planned development of multiple ports, possibly encompassing cross-subsidisation may alter the findings. Hence, this would be an interesting extension of our paper to allow for comparison with Chen et al. (2017).

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