Public ports: capacity investment decisions under congestion and uncertainty

Matteo Balliauw*[1], Peter Kort[2,3], Hilde Meersman[1], Eddy Van de Voorde[1], and Thierry Vanelslander[1]

[1]Department of Transport and Regional Economics, Faculty of Applied Economics, University of Antwerp, Prinsstraat 13, 2000 Antwerp, Belgium
[2]Tilburg School of Economics and Management Econometrics and Operations Research, Tilburg University, PO Box 90153, 5000 LE Tilburg, The Netherlands
[3]Department of Applied Economics, Faculty of Applied Economics, University of Antwerp, Prinsstraat 13, 2000 Antwerp, Belgium

Abstract

Port capacity investments involve large projects with high uncertainty and irreversibility. In a landlord port, the managing port authority (PA) is responsible for the investment in infrastructure on the one hand. On the other hand, the terminal operating company (TOC) that obtained a concession from the PA to handle the cargo, invests in the superstructure. Moreover, the PA is often partly or fully publicly owned, leading to the inclusion of social welfare among its objectives. Because port users are averse to congestion and the costs it involves, the investment decision is complexer in this service environment than in a production environment. In this paper, the optimal size and timing of a new capacity investment in a public landlord port is studied using a real options approach. Compared to the findings in a similar service port fully managed and operated by one single actor, it is found that the PA can follow the strategy of forcing the TOC to invest in the PA's individual optimum. If the destruction of aggregated welfare is to be avoided, the PA and TOC could agree to invest at the optimum of a service ports' single actor and redistribute the additional gains. As opposed to a common real options finding, higher public involvement leads to a larger investment that is also made earlier.

Keywords: port capacity, public ownership, landlord port, investment size and timing, real options.

1 Introduction

Port capacity is crucial for worldwide trade and maritime transportation. Maritime and hinterland access, infrastructure (e.g., a dock), superstructure and equipment (e.g., cranes) all need to be present in a port for the cargo to be handled efficiently (Meersman & Van de Voorde, 2014a; Verhoeven, 2015). Disposing of sufficient capacity in the port is crucial for its operations. In a port and in transportation in general, it is even more important than in a production environment to dispose of the right amount of capacity, since the transport service is not storable (de Weille & Ray, 1974). Capacity that is not used at the actual time period cannot be stored and used in the next, as opposed to warehoused goods. Undercapacity cannot be covered either by unused outputs from a previous period. Since the demand for cargo handling is uncertain and ports encounter additional sources of uncertainty (Balliauw et al., 2016), it might occur that moments

*Corresponding author

of empty berths are followed by moments in which ships are waiting to be serviced at a berth that is currently occupied. In this way, congestion and waiting time might start to build up. Congestion poses a problem to the shipping companies, as they are waiting time averse because of the cost it involves (Blauwens et al., 2016). As a result, without sufficient capacity, the port risks losing clients and profit. To avoid this, sufficient capacity should be foreseen by investing in it. However, installing too much capacity involves a downside as well, as money is invested in capacity that is never used and that hence does not generate revenues. Finding the optimal amount of capacity in which to invest under the present uncertainty, is crucial (Blauwens et al., 2016; de Weille & Ray, 1974). In a port, this capacity investment decision is often taken by different actors and often involves public money. The objective of this paper is to analyse how the optimal investment decision under congestion and uncertainty is influenced by these two specific port characteristics. To this end, a new real options (RO) model is developed.

The structure of this paper is as follows: the next section introduces the economic background and model incorporating the distinction between the different actors in a port and the involvement of public money. Section 3 explains how the values for the model parameters are set. The subsequent section shows how the RO model and calculations are influenced by introducing a cooperative game between the different actors in the port. Section 5 discusses the results, followed by a sensitivity analysis in Section 6. The conclusions and ways for future research are given in Section 7.

2 Economic setting and methodology

The port capacity investment decision has received a lot of attention in literature. Some authors take congestion (Balliauw, 2017; Xiao et al., 2012) or uncertainty (Balliauw, 2017; Chen & Liu, 2016) into account. These studies are however situated in a port entirely operated by a single actor. In such a *service port*, the port operator owns the infrastructure and superstructure and is responsible for providing cargo handling services (Trujillo & Nombela, 2000; Slack & Frémont, 2005). In the majority of ports worldwide, the port product is realised by a combination of actors under the *landlord* model (Suykens & Van de Voorde, 1998). The infrastructure is owned by the port authority (PA), the actor who manages the port, while the terminal operating company (TOC) owns the superstructure and is allowed by a concession agreement with the PA to handle the cargo. Another aspect typical for large infrastructure projects such as port infrastructure is the involvement of public money (Brooks & Cullinane, 2007). In this light, Xiao et al. (2012) studied the influence of multiple port owners on capacity investment, showing that private ports tend to invest less in capacity than publicly owned ports. A port with public involvement exhibits a faster expansion path, since profit maximisation is not its only objective (Asteris et al., 2012). They also want to maximise social welfare and/or employment, which is often linked to the amount of throughput. This explains why so many ports try to maximise their throughput (Tsamboulas & Ballis, 2014). This observation was also confirmed by Jiang et al. (2017). A similar study of Zhang & Zhang (2003) for airports unveiled that publicly owned airports invest sooner in capacity than private airports. However, all of these papers allowing for different forms of ownership do not consider uncertainty. As Balliauw (2017) and Chen & Liu (2016) already demonstrated, uncertainty alters the investment decision a lot and needs to be included in the port capacity investment analysis. Also congestion has an impact on the optimal capacity investment decision and the operation of a port, as Xiao et al. (2012) illustrated.

In the considered ports here, the PA and TOC invest in complementary elements of port capacity to realise their individual activities and responsibilities and earn in return different revenues. The sources of these revenues and the investment outlays of both actors are displayed in Figure 1. Other TOC income sources than the terminal tariff (e.g., storage) are ignored, as they account for maximum 15% of the TOC's revenue and do not apply for every unit of throughput handled (Jenné, 2017). Demand originates from a receiver buying goods from the shipper, who ships them through a shipping line, with or without consulting intermediating parties such as forwarders or agents (Coppens et al., 2007). The goods, the pricing base of the TOC who handles them, are carried by ships, on which the pricing structure of the PA is mainly based. As the focus is on the supply side with the PA and TOC, the complexity of the demand side needs simplification. The number of ships or throughput can therefore be expressed in terms of the other variable through a conversion factor. As welfare is often linked to throughput, ships are converted to throughput in Section 2.1. In this way, demand depends on one single variable, which reduces mathematical complexity.

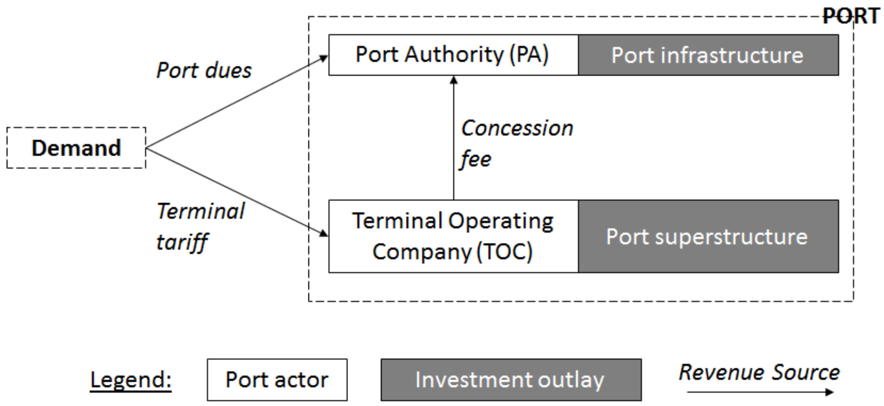

Figure 1: Revenue sources and investment outlays of the PA and TOC.
Source: Own composition.

The objectives of the PA and the TOC often diverge, because of their different activities and type of ownership (Heaver et al., 2000; Meersman et al., 2015; Xiao et al., 2012). As a result, two major model expansions are elaborated on a private service port. First, the distribution of all cash flows among the different actors needs to be thoroughly discussed and included. Secondly, public ownership is accounted for through an expansion of the PA objective function with social welfare.

Every model is a simplification of reality, hence some assumptions are made here to be able to extend the model of a private service port of Balliauw (2017) and to compare the findings. Relaxing these assumptions offers viable ways for future research. First of all, expansion, time to build and phased investment are omitted from the analysis. This implies that only new projects are considered, where the full project is installed at once and without lead time. The omission of phased investment and lead time leads to the fact that the timing and size decision of both the PA and TOC need to be equal. A detailed elaboration on this assumption is given in Section 2.2. Additionally, the investment decision in only one port is studied, so that inter-port competition is beyond the scope of this paper too. It is however possible to extend the model with a second port. Subsequently, the assumption is made that the PA has full information of the TOC's price and cost decisions. This is a strong assumption, since in reality, the PA only has full information about the throughput of the TOC. The PA will be bound to make decent predictions of prices and costs of an efficient TOC, based on the limited available information about the terminal operators already active in the port. These predictions allow the PA to ex-ante calculate its expected part of the income from terminal operations, charged to the TOC through the concession fee. This income makes up for a considerable part of the port's profit and its correct inclusion in the objective function is unmissable when deciding about the optimal size and timing of the infrastructure investment.

2.1 Differentiating between TOC and PA

The port customer faces a total price, which depends on throughput q. It is expressed by the inverse demand function

$$p(q) = X - Bq. \tag{1}$$

This price consists of the port dues $p_{\text{PA}}(q) = (1 - \alpha_1) \cdot p(q)$ for the PA and the terminal tariff $p_{\text{TOC}}(q) = \alpha_1 \cdot p(q)$ for the TOC, so that $p_{\text{PA}} + p_{\text{TOC}} = p$. In this model, it is assumed that the PA and TOC independently set their respective prices for servicing ships and handling cargo, before the new capacity is operated for the first time. The chosen relative prices determine α_1, the average share of the terminal tariff in the total price, which is then assumed fixed over time. Subsequently, both the port dues and terminal tariff follow the evolution of the market. It is determined by X following a geometric Brownian motion (GBM) with μ the drift parameter and σ^2 the drift variance expressing uncertainty. A growth of X leads to a higher total price, as expressed by the inverse demand function $p(q)$. This growth, with its uncertainty, is distributed accordingly over the PA and TOC. Given its resulting individual demand function, the TOC sets the optimal q maximising its profits, as the TOC is responsible for loading and unloading the ships. It however needs to satisfy $q < K$, to indicate that throughput cannot exceed total design capacity K, on which both the PA and TOC have an impact.

A similar reasoning holds for the operational costs of the TOC and PA. It is assumed that the shares of the TOC and the PA in the total operating cost cq are α_2 and $1 - \alpha_2$ respectively. These shares, like the other parameters, are assumed to be constant over time. The operational cost for the TOC encompasses for example labour and electricity, whereas the cost of the PA encompasses amongst others administration of the ships arriving (Lacoste & Douet, 2013). Also the total investment cost $I(K)$, a fourth order function of capacity to indicate fixed investment costs (FC_I), economies of scale in investment size and a boundary of maximum investment size, and capital holding cost $c_h K$ are divided between the TOC and PA. For the investment cost, the shares α_3 and $1-\alpha_3$ are used, whereas for the capital holding cost, it are α_4 and $1-\alpha_4$. These both express the cost structure differences between infrastructure and superstructure investments. The most difficult cost to split over the two actors is the total congestion cost. Since this is a non-cash cost, the exact shares are difficult to observe. Nevertheless, the congestion cost is expressed as

$$A f(X) q^2 / K^2, \tag{2}$$

with A a monetary scaling factor and $f(X) = X/B$, the maximum demand (Xiao et al., 2012). Because of this link with total demand, the congestion cost is assumed to be distributed by the same shares as the demand function, being α_1 and $1 - \alpha_1$ respectively.[1]

The last element that needs to be modelled to account for the different actors involved, is the concession fee. The PA grants a TOC the right to exploit a certain area of the port to handle the cargo. In return, the PA receives a concession fee from the TOC. Many different ways of determining the concession fee exist, like a lump sum, an annual fee, a quantity-dependent fee, a percentage of the revenue or a combination of these elements (Saeed & Larsen, 2010). The impact of the different forms of concession agreements is beyond the scope of this paper. Hence and in order to avoid setting an arbitrary value for the concession fee, it is modelled as the TOC paying a share α_5 of its annual operational profit to the PA.[2] In this way, the modelled concession fee takes the full economic reality into account. This would not be the case with revenue, since the PA creaming off a too high percentage of the TOC's revenue would leave the TOC losing money and being discouraged to invest. Setting an arbitrary percentage can be avoided by ex-ante calculating the concession fee as a share of the TOC's operational profit, taking both revenues and costs into account. In this way, if the TOC is profitable, it will always remain so after paying the concession fee, since only a share of this profit is to be paid. In case the TOC cannot be profitable from operations, it will decide to suspend operations. Hence, operational profit will always be greater than or equal to zero. This is a prerequisite for a meaningful calculation of the concession fee.[3]

[1] Note that α_1, α_2, α_3 and α_4 not need to be equal, as they encompass different elements of the project cash flows.

[2] A consequence is that the capacity holding cost does not influence the concession fee payment, as it is a fixed cost related to capacity and not to throughput.

[3] This explains why it is crucial to focus on operational profit and leave $c_h K$ out. The capacity holding cost is a sunk cost once the investment is made and has no influence on the optimal level of output. As a result, the TOC could decide to operate if operational profit is positive, but total profit is negative, as long as a part of the sunk cost $c_h K$ is recovered. Because total profit could become negative, calculating the concession fee as a percentage of

As it is assumed that the PA has full information about the TOC, the PA can ex-ante calculate the discounted cash flows resulting from the percentage *times* the expected TOC's profits over the project life time. This value can subsequently be converted to one of the commonly applied concession fee systems, e.g., a lump sum, annual, throughput or revenue based fee (Pallis et al., 2008).

Because the concession fee has an impact on the cash flows of both the PA and TOC and is set by the PA, the latter can influence its own profit and optimal investment decision as well as the TOC's decision. This makes the concession fee an important decision variable for the PA to obtain desired behaviour of the TOC, without resorting to penalties that are in reality difficult to enforce. In fact, such penalties involve negative consequences for both parties. When the concession agreement terminates prematurely, the port foregoes future throughput and income from this site. For the TOC, it involves the loss of the residual value (future cash flows) from the irreversible investment in the superstructure, such as pavement, warehouses or specific equipment (e.g., cranes) that is very costly to transport. As a consequence of the TOC fulfilling the negotiated concession agreement conditions to the extent that the economic situation and demand allow it, a renewed agreement is assumed (Wang & Pallis, 2014).

The profit and investment cost functions resulting from this subsection are given for the TOC:

$$\pi_{\mathrm{TOC}}(X,K,q) = (1-\alpha_5)\cdot\left\{\alpha_1\cdot\left[p(q)\cdot q - A\frac{X}{B}\left(\frac{q}{K}\right)^2\right] - \alpha_2\cdot cq\right\} - \alpha_4\cdot c_h K, \tag{3}$$

$$I_{\mathrm{TOC}}(K) = \alpha_3\cdot\left(FC_I+\gamma_1 K+\gamma_2 K^2+\gamma_3 K^3+\gamma_4 K^4\right), \tag{4}$$

and the PA:

$$\begin{aligned}\pi_{\mathrm{PA}}(X,K,q) &= [(1-\alpha_1)+(\alpha_1\alpha_5)]\cdot\left[p(q)\cdot q - A\frac{X}{B}\left(\frac{q}{K}\right)^2\right]\\ &\quad -[(1-\alpha_2)+(\alpha_2\alpha_5)]\cdot cq-(1-\alpha_4)\cdot c_h K, \qquad (5)\\ I_{\mathrm{PA}}(K) &= (1-\alpha_3)\cdot\left(FC_I+\gamma_1 K+\gamma_2 K^2+\gamma_3 K^3+\gamma_4 K^4\right). \qquad (6)\end{aligned}$$

Note that the sum of the profit functions on the one hand and the investment functions on the other hand both result in the profit and investment function of a private service port.

2.2 Possible concession fee strategies for the PA

In the described port, the optimal timing (expressed as a threshold X_T for X) and size (K) of the investment decision of the PA and the TOC may differ, because they have different objective functions to optimise. In the framework of Xiao et al. (2015) studying port infrastructure investments preventing disasters, different investments of the PA and TOC are possible. In this case however, the investment size and timing of both actors are the same, as they are the outcome of a cooperative game. In a landlord port, the PA and TOC need each other's efforts to maximise their objectives through throughput generation. The PA's infrastructure investment facilitates the TOC servicing the ships and handling the goods. In this cooperative game, it would be disadvantageous for both parties or even impossible to invest at a different moment or in a different size. Infrastructure needs to be installed before superstructure can be installed and the capacity of the infrastructure poses a limit to the capacity of the superstructure. When phased investment is not an option and construction lead times are omitted from the analysis, it would not make sense for a PA to invest in more capacity than the TOC's capacity investment under the concession agreement, as this only causes a loss of money in (temporary) unused capacity. The same holds for the PA investing before the TOC, which would result in a period without cash flows, as the infrastructure would not yet be operated. As a result, the PA would not invest before the moment the TOC is willing to invest too. Hence, when optimal timing and size differ for both individual

this could lead to the unrealistic case of a negative concession fee. This would be equivalent to the port subsidising a TOC.

actors, their optima form an interval from which the unique final investment decision needs to be determined. (Meersman & Van de Voorde, 2014a)

Two possible strategies are discerned in this setting, depending on the negotiation power the PA possesses during the concession negotiations. Both are numerically illustrated in Section 5. A first strategy involves both the TOC and PA giving in from their individual optima to invest at the aggregated optimum of a service port, which is comprised in the decision interval. When the PA invests in a size at a threshold deviating from its optimum, it can force the TOC to deviate as well through the concession negotiation or auction following the concession tender. If the TOC is not willing to deviate, it will not be granted the concession. Under this strategy, the concession fee can be interpreted as a redistribution of the project value after the deduction of investment costs ($V - I$) from one party to another. The concession fee should always be below a critical value that ascertains that the TOC's $V - I$ is sufficient to be willing to invest. It should be positive and exceed the opportunity cost of investing in a different port with a higher $V - I$. In this way, the concession fee height is market- and competition-dependent. These conditions set, a port wondering what the best concession fee is, could pursue different objectives of the concession fee:

- Reaching an equal distribution of $V - I$ over both actors,
- Reaching a distribution of $V - I$ according to the share in operational cost, investment cost or a weighted sum of both,
- Reaching a distribution according to other objectives based on the port strategy, e.g., the relative effort made for marketing and attracting port customers,
- A concession fee equalling the amount of discounted $V - I$ given up by each party to deviate from the individual optimum to the agreed decision.

An important consideration when following this strategy is that incentives for the TOC to cheat should be avoided or at least minimised. Such a situation could occur when the optimal size and/or threshold of the TOC are respectively below and/or above the optima of the PA.

A second strategy for the PA to deal with such a situation could be to force the TOC to invest at the same time and in the same capacity through economic incentives. When the PA would invest later or in a smaller amount than the TOC's optimum, the TOC is forced to adapt its strategy by taking this limiting investment decision variable as given for its own investment decision. The remaining decision variable can then be optimised conditional on the already fixed variable. With a carefully selected concession fee, the TOC's conditional optimal value for this remaining decision variable will equal the PA's optimum. This strategy hence leads to the TOC and PA investing in the same amount of capacity at the same market threshold. The downside of this strategy however is that less profit is realised at port level, aggregated over TOC and PA, as it differs from the global optimum in a service port.

2.3 Allowing for both public and private ownership of the PA

In reality, very often, public money is involved in a landlord port with a (partly) publicly owned PA (Suykens & Van de Voorde, 1998). When a government is involved, the PA would not maximise profit, but social welfare (SW), as infrastructure involves a benefit for society as a whole (Jenné, 2017). Social welfare is the sum of profit, spillover benefits for the local economy generated by the throughput handled in the port and consumer surplus (CS). Spillover benefits are included in the objective function as λq, with λ the spillover benefit per unit q. Consumer surplus (CS) is in this case calculated as $Bq^2/2$. Some governments however only tend to consider the CS relevant for the region they govern. To account for this in the objective function, s_{CS} is the share of total CS considered by the government. (Xiao et al., 2012)

The previous reasoning results in the following expression for social welfare:

$$SW(X, K, q) = \pi_{\text{PA}}(X, K, q) + \lambda q + s_{CS} \cdot Bq^2/2. \tag{7}$$

It might also be the case that the port is owned by a combination of public and private entities. Let s_G be the relative amount of PA shares owned by the government. Then the private parties together own a share of $1 - s_G$ of the PA, as the sum of the shares equals 1. The aggregated objective function (Π) of the PA now becomes the weighted sum of the individual owners' objective functions. The shares of ownership are used as the weights:

$$\begin{aligned} \Pi_{\mathrm{PA}}(X, K, q) &= (1 - s_G) \cdot \pi_{\mathrm{PA}}(X, K, q) + s_G \cdot SW(X, K, q) \\ &= \pi_{\mathrm{PA}}(X, K, q) + s_G \cdot \lambda q + s_G s_{CS} \cdot Bq^2/2. \end{aligned} \tag{8}$$

An overview of the full model is given in Table 1. It contains a short explanation of all the variables, equations and parameters, together with the values as determined in the next section for the numerical examples.

3 Calibration of the model parameters

In this paper, a hypothetical example of a new container terminal of about 8 to 14 million TEU is used to illustrate the theoretical analysis. This is in line with projects such as Deurganckdok or Saeftinghedok in the port of Antwerp (Port of Antwerp, 2016; Vanelslander, 2014) and Maasvlakte II in the port of Rotterdam (Zuidgeest, 2009). The investment cost function lies between one to three billion euro, depending on the construction technologies applied. Therefore, q and K are expressed in million TEU, while p, $c(= 1)$ and $c_h(= 0.5)$ are in euro per TEU (Vergauwen, 2010; Meersman & Van de Voorde, 2014b; Wiegmans & Behdani, 2017). In this way, it is reflected that the operational variable cost (c) in infrastructure projects is relatively low (Wiegmans & Behdani, 2017). The slope of the demand function is set to 1. The values for the drift ($\mu = 0.015$) and the drift variability ($\sigma = 0.1$) can be empirically validated in the port context (Vlaamse Havencommissie, 2016). A discount rate of 6% is a good choice in a transportation context (Blauwens, 1988; Centraal Planbureau, 2001). The monetary scaling factor of congestion, A, is set to 5 (Balliauw, 2017).

Next to these parameters that are common with a private service port, additional parameters are introduced to account for public ownership and the landlord port model. Spillover effects within the port perimeter are estimated at 20 to 30 percent of the cost c to process one TEU (Coppens et al., 2007). However, depending on the method used, a wide variety is observed (Benacchio & Musso, 2001). Depending on the level of aggregation of the local government's jurisdiction, the spillover effects could even amount to 60 percent of c. This would leave λ in the range of 0.2 to 0.6. Here it is set to 0.4, to account for a port's spillover effects in an entire country. Two other parameters that result from allowing multiple owners are the share of ownership of the government and the share of the CS taken into account by this government, respectively s_G and $s_{CS} \in [0; 1]$. The shares are not fixed in advance, as they will be varied to study different types of port ownership.

As a result of differentiating between a TOC and a PA, five alphas are introduced. $\alpha_5 (\in [0; 1])$ is a variable that can be set by the PA to determine the height of the concession fee. The share of the superstructure cost in the total investment cost is expressed by α_3. Based on Vanelslander (2005), Jacob (2013) and Jenné (2017), it is set to 0.35.[4] The share of superstructure holding cost in the total capacity holding cost $c_h K$, i.e. α_4, varies a lot depending on the specific project considered and the related dredging contract. As an average, it is set here to 0.5, but it is varied in the sensitivity analysis (Zheng, 2015; Jan De Nul, 2012; Jenné, 2017; Keskinen et al., 2017; Luck, 2017; Vanelslander, 2005; UNCTAD, 2014). Next, α_2 expresses the relative share of the TOC's operational cost in the total operational cost of the cargo handling services. To load and unload ships, the TOC encounters the cost of labour and electricity, which is the major part. The PA's marginal operational cost is negligible and mainly incurred by administration. By consequence, α_2 is set to 0.95.

[4]For a project with a capacity of 10 million TEU, the infrastructure would cost about 1 billion euro and the superstructure about 550 million euro, including cranes, straddle carriers, warehouses and gates.

Table 1: Model overview.

Variables		
p	=	price
q	=	throughput
K	=	capacity
α_5	=	concession fee calculation parameter: share of TOC's annual operational profit paid to PA
Aggregated inverse demand function: $p = X - Bq$		
$B(=1)$	=	slope
Demand shift parameter X**:** $dX(t) = \mu X(t)dt + \sigma X(t)dZ(t)$		
t(=annual)	=	time horizon
$\mu(=0.015)$	=	drift
$\sigma(=0.1)$	=	drift variability
Aggregated total cost $TC = cq + A\frac{X}{B}\left(\frac{q}{K}\right)^2 + c_h K$		
$c(=1)$	=	constant marginal production cost
$c_h(=0.5)$	=	cost to hold one unit of capital in place
$A(=5)$	=	monetary scaling factor of congestion cost
TOC investment cost $I_{\text{TOC}} = \alpha_3 \cdot \left(FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_3 K^3 + \gamma_4 K^4\right)$		
PA investment cost $I_{\text{PA}} = (1-\alpha_3) \cdot \left(FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_3 K^3 + \gamma_4 K^4\right)$		
$\alpha_3(=0.35)$	=	share of total investment cost I incurred by TOC
$FC_I(=80)$	=	fixed investment cost
$\gamma_1(=180)$	=	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
TOC profit = objective function $\pi_{\text{TOC}} = (1-\alpha_5) \cdot \left\{\alpha_1 \cdot \left[p(q) \cdot q - A\frac{X}{B}\left(\frac{q}{K}\right)^2\right] - \alpha_2 \cdot cq\right\} - \alpha_4 \cdot c_h K$		
PA profit $\pi_{\text{PA}} = [(1-\alpha_1) + (\alpha_1\alpha_5)] \cdot \left[p(q) \cdot q - A\frac{X}{B}\left(\frac{q}{K}\right)^2\right] - [(1-\alpha_2) + (\alpha_2\alpha_5)] \cdot cq - (1-\alpha_4) \cdot c_h K$		
$\alpha_1(=0.9)$	=	share of terminal tariff in total price p
$\alpha_2(=0.95)$	=	share of c incurred by TOC
$\alpha_4(=0.5)$	=	share of capital holding cost incurred by TOC
PA objective function $\Pi_{\text{PA}} = \pi_{\text{PA}} + s_G \cdot \lambda q + s_G s_{CS} \cdot CS$		
$\lambda(=0.4)$	=	spillover benefit per unit q
CS	=	consumer surplus, i.c. $Bq^2/2$
$s_G(\in [0;1])$	=	share of PA owned by the government
$s_{CS}(\in [0;1])$	=	share of total CS taken into account by the government

Finally, α_1, the share of the terminal tariff in the total price needs to be set. The share of the port dues is then $1 - \alpha_1$. This is the most difficult parameter to set. Port dues depend on many different factors like ship size and the number of locks that need to be passed, they are not only throughput dependent (Meersman et al., 2015). It are amongst others the ship and the location in the port that determine the port dues, and only partly the amount of goods loaded and unloaded. Hence, a conversion is required to find an expression for the average amount of port dues per TEU. This conversion has an influence on α_1, which is in reality not fixed, but is the result of the demand function taking into account the ship size, location in the port and the relative ship capacity loaded and unloaded. The difference in price calculation method per port and the limited transparency complicate the calculation of α_1 even more. As a result, α_1 is calculated here as an average ratio over a full year and based on data from the Port of Antwerp (2017a,b) to come to a value of 0.9.[5]

4 Solving for the optimal investment strategy in a landlord port

With the objective functions of the port actors deciding on capacity at hand, the optimal investment decision in a landlord port can be calculated. In reality, a port first decides at which moment it would invest in infrastructure and how much capacity it would foresee. Once this investment is made, it poses two boundaries to the superstructure investment of the TOC that obtained a concession agreement through negotiations or an auction following a tender. Since the TOC is responsible for the operation of the terminal, it sets the optimal throughput maximising its own profit: q^{opt}_{TOC}. Moreover, the assumption of full ex-ante information for the PA and the interactions with the TOC proceeding a concession agreement lead to the assumption that the PA and TOC select the same size and timing of the investment. The decision will always be somewhere between the extrema of both actors' optima, which form the decision interval as described in Section 2.2. If the TOC would deviate from the PA's decision, the PA will not grant the concession and the TOC cannot invest in and operate the terminal.

In this paper, the dynamic programming methodology from Dixit & Pindyck (1994) and Dangl (1999), is adapted to backwardly solve the real options problem including congestion and multiple actors in a port. The way congestion is modelled gives rise to hypergeometric functions (${}_2F_1$) in the value functions $V(X, K) = \mathbb{E}\int_0^\infty \max_q\{\pi(t+\tau)\}\mathrm{e}^{-r\tau}\mathrm{d}\tau$ of both actors (Balliauw, 2017). An important difference when compared to a service port however is that the optimisation is to be executed for two actors, but that only one actor handles the goods. To start, the TOC determines q^{opt}_{TOC} through the first and second order conditions for π_{TOC} in Eq. (3). This results in

$$q^{opt}_{\text{TOC}} = \begin{cases} 0, & X < \dfrac{\alpha_2 c}{\alpha_1}, \\ \dfrac{(\alpha_1 X - \alpha_2 c)BK^2}{2\alpha_1(AX + B^2K^2)}, & \dfrac{\alpha_2 c}{\alpha_1} \leqslant X < \dfrac{(2\alpha_1 BK + \alpha_2 c)BK}{\alpha_1 BK - 2\alpha_1 A}, \\ K, & X \geqslant \dfrac{(2\alpha_1 BK + \alpha_2 c)BK}{\alpha_1 BK - 2\alpha_1 A}. \end{cases} \tag{9}$$

Because it should hold that $0 \leqslant q^{opt}_{\text{TOC}} \leqslant K$, q^{opt}_{TOC} is divided into three regions, defined by boundaries for X. Plugging q^{opt}_{TOC} into π_{TOC} leads to π^{opt}_{TOC}, defined in the same three regions.

[5] 4500 container ships called the Port of Antwerp (2017b) in 2016, with an average GT of 55000 BT. Moreover, about 10 million TEU was handled in the same year. The tariffs of Port of Antwerp (2017a) show that the port dues per BT are 0.2 euro, when the ship is operated by a container line, without reductions included. The container supplement is 0.2 euro per ton and the Port of Antwerp (2017b) assumes 12 ton per TEU on average, so that the additional port dues for handling one TEU are 2.4 euro. The terminal tariff is 69 euro per TEU, as handling a container, involving two moves, costs about 110 euro and the average container is 1.59 TEU (Port of Antwerp, 2017b; Saeed & Larsen, 2010; Port of Felixtowe, 2017; Chennai International Terminals, 2012; Wiegmans & Behdani, 2017).

Secondly, through differential equation

$$\frac{\sigma^2}{2}X_T^2\frac{\partial^2 V_{\text{TOC}}}{\partial X_T^2}(X_T,K)+\mu X_T\frac{\partial V_{\text{TOC}}}{\partial X_T}(X_T,K)-rV_{\text{TOC}}(X_T,K)+\pi_{\text{TOC}}(X_T,K)=0, \tag{10}$$

V_{TOC}, the value of the project for which the TOC pays I_{TOC}, is derived. Thirdly,

$$F_{\text{TOC}}(X_T)=\max\{\mathrm{e}^{-r\mathrm{d}t}\mathbb{E}(F_{\text{TOC}}(X_T)+\mathrm{d}F_{\text{TOC}}(X_T)),\max_K[V_{\text{TOC}}(X_T,K)-I_{\text{TOC}}(K)]\} \tag{11}$$

gives the option value in order to find the optimal size and timing of the TOC's investment $(X^{**}_{T,\text{TOC}},K^{**}_{\text{TOC}})$. Fourthly, the objective function of the PA, Π^{opt}_{PA}, is determined by plugging q^{opt}_{TOC} into Π_{PA} from Eq. (8), as it is the TOC who sets the throughput quantity. Using q^{opt}_{TOC} results in the same three regions for the PA's profit as found for the TOC's profit. Fifthly, differential equation

$$\frac{\sigma^2}{2}X_T^2\frac{\partial^2 V_{\text{PA}}}{\partial X_T^2}(X_T,K)+\mu X_T\frac{\partial V_{\text{PA}}}{\partial X_T}(X_T,K)-rV_{\text{PA}}(X_T,K)+\Pi_{\text{PA}}(X_T,K)=0, \tag{12}$$

allows deriving V_{PA}. Finally, option value

$$F_{\text{PA}}(X_T)=\max\{\mathrm{e}^{-r\mathrm{d}t}\mathbb{E}(F_{\text{PA}}(X_T)+\mathrm{d}F_{\text{PA}}(X_T)),\max_K[V_{\text{PA}}(X_T,K)-I_{\text{PA}}(K)]\} \tag{13}$$

results in the optimal investment size and timing for the PA $(X^{**}_{T,\text{PA}},K^{**}_{\text{PA}})$. Both $(X^{**}_{T,\text{TOC}},K^{**}_{\text{TOC}})$ and $(X^{**}_{T,\text{PA}},K^{**}_{\text{PA}})$ together form the decision interval wherein the final investment decision is situated. (Balliauw, 2017; Dangl, 1999)

5 Results and discussion

In this section, numerical solutions for different port types are calculated using the previously described methodology. The investment decisions are compared to the optimal decision for a private service port with the same values for the common parameters. This optimum is calculated as $X^{**}_T=37.63$ and $K^{**}=11.17$. In this section, the impact on the investment decision of the division between the PA and the TOC and the height of the concession fee in a private landlord port is firstly studied separately from the impact of government involvement as PA shareholders in a public service port. Afterwards, both are combined in a public landlord port setting (Tsamboulas & Ballis, 2014).

5.1 Division between PA and TOC

When the distinction between the PA and TOC in a private landlord port (no government involvement, or s_G set to zero) is made according to the model in Table 1, a new individual optimal investment threshold can be calculated for both the PA and TOC. Numerical solutions prove that an α_5 leading to the same optimal investment size (α_5^K) and an α_5 leading to the same optimal timing (α_5^X) for both parties exist for different values of α_1, α_2, α_3 and α_4 (see Table 8). Moreover, this optimal value common for both parties, is almost equal to the optimum of the private service port where the port is directed and operated by one single party. The other decision variable determining the optimal investment strategy differs per actor. This leads to the already explained decision interval. In this interval, the other determinant's optimum value from the private service port is comprised.

Table 2: Optimal $X_T^*(K)$, $K^*(X_T)$ and (X_T^{**}, K^{**}) under different α_5 in a private landlord port.

α_5	**Actor**	$\boldsymbol{X_T^*(K = 11.17)}$	$\boldsymbol{K^*(X_T = 37.63)}$	$\boldsymbol{(X_T^{**}, K^{**})}$
0.4	PA	47.12	10.21	(47.30, 11.21)
	TOC	28.97	12.45	(28.85, 11.14)
0.469	PA	43.18	10.56	(43.18, **11.17**)
	TOC	31.30	12.07	(31.30, **11.17**)
0.5	PA	41.69	10.71	(41.63, 11.16)
	TOC	32.53	11.89	(32.59, 11.19)
0.59475	PA	37.86	11.12	(**37.63**, 11.12)
	TOC	37.31	11.26	(**37.63**, 11.26)
0.6	PA	37.67	11.14	(37.44, 11.11)
	TOC	37.62	11.22	(37.97, 11.26)

Parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, \alpha_1 = 0.9, \alpha_2 = 0.95, \alpha_3 = 0.35, \alpha_4 = 0.5$.

Source: Own calculations.

The previous reasoning is illustrated with the numerical example in Table 2. When α_5 is set to 0.59475, $X_{T,\text{TOC}}^{**} = X_{T,\text{PA}}^{**} = 37.63$, which is nearly the same X_T^{**} as found in a private service port.[6] In that case, $K_{\text{PA}}^{**} = 11.12$ and $K_{\text{TOC}}^{**} = 11.26$. Indeed, $K^{**} = 11.17$ from a similar private service port is comprised in this decision interval. With α_5 set to 0.469 however, the optimal size of the investment is equal for both the PA and TOC, almost equalling the $K^{**} = 11.17$ from a private service port. The optimal thresholds are then $X_{T,\text{PA}}^{**} = 43.18$ and $X_{T,\text{TOC}}^{**} = 31.30$. Through mutual concessions, the optimal $X_T^{**} = 37.63$ from a private service port is attainable. It is also possible for other α_5's to select the global optimum from the decision interval. This is because the optimal throughput of the TOC in Eq. (9) is independent of the concession fee.[7]

Table 2 also shows how the optimal investment decisions of both the PA and TOC depend on the concession fee. For example, when the TOC is required to pay a higher share of its operational profit, the TOC would want to invest later, or it would invest in less capacity ceteris paribus. This is opposed to the investment becoming more attractive for the PA, as expressed by a lower threshold for X or a higher investment size. It is confirmed that a parameter change increasing X_T^*, reduces K^*. When looking at the final optimal investment decision combining timing and size however, a similar logic as in the private service port setting holds (Balliauw, 2017). X_T^{**} will always be close to X_T^*, which does not hold for K^{**} and K^*. A higher X_T^{**} coincides with a higher K^{**}, because the effect of the positive $K^*(X_T)$ and $X_T^*(K)$-functions dominate the opposite shifts of the functions K^* to X^* following a change in α_5.

It is also interesting to highlight that the optimum of a private service port can be calculated by this private landlord port model. The model is reduced to the one of the private service port when all income and costs are concentrated in one party (the PA and TOC then coincide in one entity). It is however also possible to find exactly the same optimum for TOC and PA with the distinction between these two actors. When $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4$, all revenues and costs of both parties remain proportional to one another as compared to the private service port. Hence, no compensating concession fee from TOC to PA ($\alpha_5 = 0$) is required to make $X_{T,\text{PA}}^{**} = X_{T,\text{TOC}}^{**} = 37.63$ and $K_{\text{PA}}^{**} = K_{\text{TOC}}^{**} = 11.17$.

[6] Only the rounded numbers are slightly different. Because $X_T >> c$ and the chosen α_1 and α_2 do not differ by much, combined they have in this numerical example a very limited impact on q_{TOC}^{opt} in Eq. (9) and the optimal investment strategy.

[7] The TOC maximises its profit w.r.t. q. The capacity holding cost does not depend on q but on K, so its derivative w.r.t. q is 0. What remains is the derivative of the operational profit, of which a share is paid to the PA. By its definition, the height of this share has no impact on the q maximising this profit. Or mathematically: $\partial(\alpha_5 \pi(q, X, K))/\partial q = 0 \Leftrightarrow \partial(\pi(q, X, K))/\partial q = 0$.

5.2 Quantifying the impact of the PA's concession fee strategies

Additional numerical calculations illustrate the previously described strategy of selecting the private service port optimum, with a total project value minus investment costs $V-I$ of 1760 million euro. If the PA and TOC in a private landlord port invest both at this optimum, their aggregated $V-I$ also equals 1760 million euro, independent of the height of the concession fee. This concession fee only has an impact on the distribution of the cash flows among both parties. This is illustrated in Table 3. The table shows that $\alpha_5 = 0.5204$ leads to an equal $V-I$ for both actors, and that $\alpha_5 = 0.6058$ equals the share each actor has in $V-I$ and in I, which is 65% for the PA and 35% for the TOC.

Table 3: $V-I$ of PA and TOC under different concession fees, if both invest at the optimum of a private service port.

α_5	$(V-I)_{\text{PA}}$	$(V-I)_{\text{TOC}}$	$\Sigma_i(V-I)_i$
0.4	508	1252	1760
0.469	721	1039	1760
0.5	817	943	1760
0.5204	880	880	1760
0.59475	1110	650	1760
0.6	1126	634	1760
0.6058	1144	616	1760

Parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, \alpha_1 = 0.9, \alpha_2 = 0.95, \alpha_3 = 0.35, \alpha_4 = 0.5$.

Source: Own calculations.

The case of $\alpha_5 = 0.59475$ allows easily calculating each actor's impact of diversion from its own optimum. Because it is optimal with this concession fee for both actors to invest at the same time, $V-I$ of both can be compared at the moment of investment. No additional discounting is required.[8] The situation is quantified in Table 4 for different investment strategies based on Table 2.

Table 4: $V-I$ of PA and TOC with $\alpha_5 = 0.59475$ under possible investment strategies, equally followed by both actors.

Common investment strategy: (X_T, K)	$(V-I)_{\text{PA}}$	$(V-I)_{\text{TOC}}$	$\Sigma_i(V-I)_i$
PA individual optimum: $(37.63, 11.12)$	1110.0	649.8	1759.8
Private service port optimum: $(37.63, 11.17)$	1109.8	650.1	1759.9
TOC individual optimum: $(37.63, 11.26)$	1109.0	650.3	1759.3

Parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, \alpha_1 = 0.9, \alpha_2 = 0.95, \alpha_3 = 0.35, \alpha_4 = 0.5, \alpha_5 = 0.59475$.

Source: Own calculations.

The results show that the PA investing in more capacity than its own optimum leads to a decrease in $V-I$ for itself of 0.2 million euro. This allows the TOC to make a bigger investment, which is already closer to its own optimum. Because the TOC can now invest in $K = 11.17$ in stead of 11.12, the TOC's $V-I$ increases with 0.3 million euro. This leads to an aggregated gain of 0.1 million euro. Deviating from this optimum hence leads to a destruction of aggregated profit. Both actors investing at the TOC's optimum would make the TOC win an additional 0.2 million euro, but the PA would lose 0.8 million euro, destroying 0.6 million euro of aggregated profit. As

[8] With a GBM, the stochastic discount factor at t where $X(t) = X$, is equal to $(X/X_T)^{\beta_1}$, with $\beta_1 = \dfrac{\frac{\sigma^2}{2} - \mu + \sqrt{(\frac{\sigma^2}{2} - \mu)^2 + 2r\sigma^2}}{\sigma^2}$ (Huisman & Kort, 2015).

argued before, the extra aggregated profit can be distributed among the PA and TOC through the adaptation of the concession fee. The height of the concession fee set by the PA is part of its strategy as discussed in Section 2.2.

The results in Table 2 also bear worthy information for a PA searching for a good concession fee. For any value of α_5 between 0.469 and 0.59475, the PA poses a limit to both the size and timing of the TOC's optimal investment decision. In this range for the concession fee, the optimal timing of the TOC is earlier than the timing of the PA and the optimal capacity of the TOC would exceed that of the PA. In such a case, the PA knows that as soon as it invests in the negotiated capacity, the TOC will be willing to invest too in the same amount of capacity, as long as this still is a profitable strategy. This is important from a game-theoretic point of view, as the TOC does not have any incentive to cheat by breaking the contract.

This first strategy displayed in Table 3 and Table 4 however do might include an incentive for the TOC to deviate from the PA's optimum for some other values of α_5. When α_5 is below 0.469, the TOC may be willing to invest in less capacity than what is decided on, whereas any α_5 above 0.59475 could lead to the TOC investing later than the moment agreed upon. Nevertheless, even in these latter two cases, the PA still has some negotiation power that could turn out to be sufficient. In the first case, the PA could install the project at its own optimal threshold, which is higher than what is optimal for the TOC. This is a limiting factor and the TOC will internalise this higher threshold. Subsequently the TOC's optimal size is determined as $K^*_{\text{TOC}}(X^{**}_{T,\text{PA}})$, which might come closer to or even equal or exceed the optimal size of the PA. In this way, the PA retains a strong position. In the second case, a smaller project than what is optimal for the TOC could be installed. In that case, the TOC takes the size as given and determines its remaining investment decision degree of freedom, its optimal threshold, conditional on the size of the PA. This $X^*_{T,\text{TOC}}(K^{**}_{\text{PA}})$ might come closer to or even equal or be below the optimal threshold of the PA. An illustration is given in Table 5 for the unique α_5, given the other parameters, wherein the PA can force the TOC to invest exactly at the PA's optimum.

Table 5: Illustration of PA's concession fee strategy forcing the TOC to take the same investment decision.

Actor	Optimal investment strategy		Conditioned investment strategy
PA	(**37.43**, *11.11*)		=
TOC	(**38.00**, ~~*11.26*~~)	→	$(X^*_{T,\text{TOC}}(11.11), 11.11) = (\mathbf{37.43}, 11.11)$

Parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, \alpha_1 = 0.9, \alpha_2 = 0.95, \alpha_3 = 0.35, \alpha_4 = 0.5, \alpha_5 = 0.60035$.

Source: Own calculations.

If $\alpha_5 = 0.60035$, the optimal decision for the TOC is later and in more capacity than what is installed by the PA. Hence, the TOC knows that it has to reduce its investment size accordingly to the 11.11 million TEU of the PA. Taking this into account, the TOC calculates its conditional optimal threshold $X^*_{T,\text{TOC}}(11.11) = 37.43$, which is equal to the threshold of the PA. The impact on the individual and aggregated discounted $V - I$ is limited and is given in Appendix A. For any other α_5, $X^*_{T,\text{TOC}}(K^{**}_{\text{PA}})$ will be either higher than the $X^{**}_{T,\text{PA}}$, meaning that the TOC is even more forced to deviate from its conditional optimum, or below $X^{**}_{T,\text{PA}}$, still implying an incentive for the TOC to invest below the PA's optimal capacity. In the presented numerical calculations, in the other situation where the optimal timing of the PA is later than the optimal timing of the TOC, the resulting optimal size of the TOC will still exceed the PA's size. So there the TOC has to deviate even more from its optimum. There is no concession fee leading to an $X^{**}_{T,\text{PA}} > X^{**}_{T,\text{TOC}}$ coinciding with $K^*_{\text{TOC}}(X^{**}_{T,\text{PA}}) = K^{**}_{\text{PA}}$.

5.3 Government involvement

Next to a private owner maximising profit, also a social welfare-maximising government is now considered in the analysis as port shareholders. As was explained, the government owns a share

s_G of the public service port. The private partner has then the remaining share $1 - s_G$. The share of total CS taken into account by the government is given by s_{CS}. Some possible scenarios are given in Table 6.

Table 6: Optimal $X_T^*(K)$, $K^*(X_T)$ and (X_T^{**}, K^{**}) under different s_G and s_{CS} in a public service port.

s_G	s_{CS}	$X_T^*(K = 11.17)$	$K^*(X_T = 37.63)$	(X_T^{**}, K^{**})
0	N/A	37.63	11.17	(37.63, 11.17)
1/2	1/2	35.89	11.40	(35.98, 11.19)
1/2	1	34.39	11.64	(34.74, 11.27)
1	1/2	34.05	11.66	(34.25, 11.22)
1	1	30.70	12.22	(31.40, 11.38)

Parameter values:
$A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, \lambda = 0.4.$
Source: Own calculations.

The first line in Table 6 reflects the situation with a privately owned single port actor in a private service port. When the share of the government or the considered share of CS increases, the considered project benefits become higher, as the local benefits and CS are taken more into account in the port's objective function Π. This is translated into a lower threshold for $X_T^*(K)$, which goes again hand in hand with a higher investment size $K^*(X)$. The analysis confirms the finding that public entities tend to invest sooner or in more capacity than private entities (Asteris et al., 2012). The optimal investment strategy (X_T^{**}, K^{**}) changes accordingly. When the share of a central government or the considered share of CS increases, the project is valued a lot higher because social welfare is taken more into account. As a result, the individual effects of earlier and larger investment dominate the positive relation between size and timing, to result in a larger project that is also installed earlier. This finding is opposite to the common real options (RO) finding, where more capacity leads to a later timing or vice versa due to the dominating effect of the positive $K^*(X_T)$ and $X_T^*(K)$-functions.

5.4 Public landlord port

The previous subsections illustrated separately the impact of the landlord port model and public ownership on the port capacity investment decision. In this subsection, both are combined. The analysis is made for a landlord port in which the PA's shares are equally divided among the private parties and the government, who in turn takes 50% of total CS into account.

Table 7: Optimal $X_T^*(K)$, $K^*(X_T)$ and (X_T^{**}, K^{**}) under different α_5 in a public landlord port.

α_5	Actor	$X_T^*(K = 11.17)$	$K^*(X_T = 37.63)$	(X_T^{**}, K^{**})
0.4	PA	43.19	10.61	(43.57, 11.26)
	TOC	28.97	12.45	(28.85, 11.14)
0.504	PA	38.45	11.09	(38.54, **11.20**)
	TOC	32.70	11.86	(32.77, **11.20**)
0.55	PA	36.77	11.28	(36.76, 11.17)
	TOC	34.82	11.57	(35.01, 11.23)
0.5693	PA	36.12	11.35	(**36.08**, 11.16)
	TOC	35.84	11.44	(**36.08**, 11.24)
0.6	PA	35.16	11.47	(35.06, 11.15)
	TOC	37.62	11.22	(37.97, 11.26)

Parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, \alpha_1 = 0.9, \alpha_2 = 0.95, \alpha_3 = 0.35, \alpha_4 = 0.5, s_G = 1/2, s_{CS} = 1/2, \lambda = 0.4.$
Source: Own calculations.

The results are similar to the outcomes in Table 2 for a private landlord port. The table shows that the inclusion of mixed ownership with governments involved does not have an impact on the TOC's decision, as this remains a private party with the same cash flows and objective function as before. For the same concession fee, the optimal decision remains unchanged. Public involvement in the model only has an impact on the PA's optimal decision. The TOC's objective function considering π remains unchanged. As a result, the α_5's matching the timing or size of the project will alter.

In both Table 2 and Table 7, it is interesting to note that with a higher concession fee, the project will become less attractive for the TOC, as they retain a lower share of their profit. Unexpectedly however, the TOC would invest in more capacity. This counter-intuitive result is explained by the fact that the TOC makes the investment later, when the market is bigger. At the same time, the investment becomes more attractive for the PA, resulting in an earlier investment, which is however smaller.

The combination of mixed ownership of the PA and a landlord port model leads to two alterations. First, the optimum with the same $s_G = s_{CS} = 1/2$ as for the equivalent service port in Table 6 lies in some cases further outside the decision interval than in the case of a private port. At α_5^X, $X^{**}_{T,\text{PA}} = X^{**}_{T,\text{TOC}} = 36.08$, which is higher than the $X^{**}_T (= 35.98)$ in Table 6. This is caused by the fact that the TOC, deciding about optimal throughput q in the present scenario, does not take social welfare into account. As a private party, it only considers profit in its objective function.[9] Secondly, as was also apparent from Table 6, an increased share of public involvement leads to the PA investing earlier and in more capacity, because welfare effects other than profit are included in the analysis too.

In the present scenario, the two described strategies remain possible. Firstly, the PA could aggregate the objective functions of itself and the TOC and invest at the optimum of a public service port. Through the concession agreement, the PA can force the TOC to handle at least a certain minimal throughput. The height of the concession fee could be an optimal incentive for this. Secondly, if $\alpha_5 = 0.57252$, the optimal investment decision for the PA would be (35.96, 11.16), and the TOC would be forced to reduce its optimal investment of (36.27, 11.24) to a size of $K_{\text{TOC}} = 11.16$. The corresponding $X^*_{T,\text{TOC}}(11.16)$ would then be 35.96, which equals $X^{**}_{T,\text{PA}}$.

6 Investment decision sensitivity to an altered economic situation

In this section, the sensitivity of the results with respect to changes in other parameters is discussed. Table 8 shows how the investment decisions of the different parties alter with each parameter change. To this end, the decisions at respectively α_5^X and α_5^K are given for each situation, as this information allows understanding the direction of change of the optimal investment decision caused by different concession fees.

With the monetary scaling factor of congestion $A = 4$ instead of 5, the equalled investment threshold and installed capacity for the PA and TOC are lower. Also, α_5^K and α_5^X are lower than in the base case. With a lower A, congestion poses less a problem to the port users, so that relatively more throughput is allowed at the same infrastructure. When uncertainty is higher, the investment is made at a later moment, but the installed capacity will also be higher. These conclusions can also be found in a private service port setting. Additionally, the increase of σ leads to another interesting observation. In this case, α_5^X is below α_5^K. This inversion of α_5's has an important consequence on the negotiation power of the PA. Below $\alpha_5 = 0.5624$, the port still has negotiation power through timing the project at a higher threshold than what is optimal for the TOC. Above $\alpha_5 = 0.829$, the power of the PA also still lies in foreseeing less capacity than what would be optimal for the TOC. However, between α_5^X and α_5^K, the TOC has a bigger incentive

[9] Because a private TOC is a profit and not a SW maximiser, the q^{opt}_{TOC}, set by the TOC in a public landlord port will differ from the q^{opt} set by the single public actor in a public service port. This in turn influences the objective function and investment decision of both parties too.

Table 8: Changes of the PA and TOC's optimal investment decision (X_T^{**}, K^{**}) under different parameter changes in a public landlord port.

Parameter alteration	α_5	**Actor**	$(\boldsymbol{X_T^{**}}, \boldsymbol{K^{**}})$
Base case	0.504	PA	(38.54, **11.20**)
		TOC	(32.77, **11.20**)
	0.5693	PA	(**36.08**, 11.16)
		TOC	(**36.08**, 11.24)
$A = 4$	0.472	PA	(35.09, **10.85**)
		TOC	(28.40, **10.85**)
	0.5643	PA	(**32.12**, 10.81)
		TOC	(**32.12**, 10.89)
$\sigma = 0.15$	0.5624	PA	(**49.88**, 12.74)
		TOC	(**49.88**, 13.02)
	0.829	PA	(41.04, **12.81**)
		TOC	(91.83, **12.81**)
$\lambda = 0.5$	0.491	PA	(38.89, **11.19**)
		TOC	(32.19, **11.19**)
	0.5673	PA	(**35.96**, 11.15)
		TOC	(**35.96**, 11.24)
$\alpha_1 = 0.95$	0.546	PA	(37.94, **11.19**)
		TOC	(33.41, **11.19**)
	0.594	PA	(**36.07**, 11.17)
		TOC	(**36.07**, 11.23)
$\alpha_2 = 0.9$	0.521	PA	(37.92, **11.19**)
		TOC	(33.43, **11.19**)
	0.5714	PA	(**36.07**, 11.17)
		TOC	(**36.07**, 11.23)
$\alpha_3 = 0.3$	0.5124	PA	(40.20, **11.20**)
		TOC	(30.29, **11.20**)
	0.6235	PA	(**36.08**, 11.15)
		TOC	(**36.08**, 11.28)
$\alpha_4 = 0.45$	0.5448	PA	(37.13, **11.19**)
		TOC	(34.45, **11.19**)
	0.57434	PA	(**36.08**, 11.18)
		TOC	(**36.08**, 11.21)

Base case parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, \alpha_1 = 0.9, \alpha_2 = 0.95, \alpha_3 = 0.35, \alpha_4 = 0.5, s_G = 1/2, s_{CS} = 1/2, \lambda = 0.4$.

Source: Own calculations.

to deviate from the PA's optimum, because it is optimal to install less capacity than what has already been foreseen by the PA and at a later timing. This contains a serious incentive for the TOC to cheat by handling less cargo than agreed under the concession agreement and should be avoided by the PA. For this, they could select the second strategy of forcing the TOC to follow the PA's optimal strategy by reducing the TOC's investment decision degrees of freedom.

The sensitivity of the results to changes in the parameters discerning a public landlord port from a private service port are also included in Table 8. When the average local benefits per TEU would be higher ($\lambda = 0.5$), the social welfare generated by the project would be higher too, making the project itself more attractive for the PA. As a result, the investment would be made slightly earlier, but it would also be smaller. Moreover, lower α_5's are required for the port to equal the size or timing of both actors' investment decision. As was already explained, local benefits and social welfare are not included in the private TOC's objective function (π_{TOC}) and hence do not influence the TOC's optimal investment decision. This is opposed to the PA, whose project's attractiveness is now higher. Hence, the PA requires less income from the concession since already more welfare has been generated. The last four blocks of Table 8 show the impact of the PA receiving less of the total port revenue or incurring a higher share of the port costs (represented respectively by an increase of α_1 and a decrease of α_2, α_3 or α_4). Qualitatively, the decision intervals remain similar. Additionally, almost identical optima as in the base case can be achieved, although through a higher value for α_5. In each of the altered cases, the PA has a lower share of total port profit. Hence, the PA requires a higher concession fee, expressed as a share of the TOC's profit, to obtain the same level of welfare as in the base case. This illustrates again how the concession fee can be calibrated to redistribute the profits in the port to approximate as much as possible an investment decision maximising aggregated social welfare.

7 Conclusions and future research

A private service port is the easiest setting to analyse port capacity investment decisions, since one single, profit maximising actor takes all decisions in the port. This paper presents two extensions to existing real options models to decide about the capacity investment in a port under congestion and uncertainty. Firstly, the PA's and TOC's different objectives in a landlord port lead to a decision interval with different optimal investment strategies for both actors. From this interval, a common investment decision is to be made. Through the concession agreement, the PA could persuade the TOC to invest in the strategy that is optimal for a service port in order to maximise the aggregate $V - I$. The concession fee can then be used as a redistribution mechanism of this $V - I$, which is influenced by the division of the cash flows among the PA and TOC through the α's in the model. Different objectives of a fair concession fee exist. Another possible strategy for the PA is to force the TOC to invest in the PA's optimal strategy. This can be achieved by setting a concession fee that limits one of the two investment decision degrees of freedom of the TOC. The other choice is then a conditional optimisation, and will equal the optimal value of the PA. Secondly, more PA shares held by the government leads to larger and earlier investments in port capacity. The same holds for a higher share of consumer surplus considered by this public PA, as social welfare is taken more into account. This is opposite to the common RO finding, where more capacity leads to a later timing or vice versa.

Additionally, it was observed that the optimum of a public service port is not always reachable by the public landlord port, since here the PA is publicly owned and the TOC privately. The TOC sets the optimal throughput without taking social welfare into account, leading to a higher deviation from the aggregated optimal throughput and hence the investment strategy in a public service port made by a single port actor. Finally, the model is proven to be robust, since it is confirmed that an increase in congestion costs and uncertainty lead to a port investing in more capacity, but at a later timing.

Considering the decision of one single port in this paper opens up some viable ways for future research. Many ports do not operate as monopolists. They experience competition from nearby ports, e.g. in the Hamburg-Le Havre range. Antwerp and Rotterdam are fierce competitors in their attempts to attract important loops of global shipping lines. The investment decision of a neighbouring port influences the own decision. This competition was left out of scope, but it forms the starting point of future research (Huisman & Kort, 2015). The impact of port expansion and time to build need to be considered as well (Aguerrevere, 2003). Another element that would alter the conclusions in this paper is the investment in the project in different phases so that the dock and the terminals are not to be installed all at once (Kort et al., 2010; Chronopoulos et al., 2015).

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A Discounted $V - I$ in a private service port where the PA can force the TOC to invest in the PA optimum.

Table 9 contains the discounted $V-I$ for both the PA and TOC under different possible strategies at the moment where $X(t) = 35$. These strategies are equally followed by both actors. This discounted $V - I$ is calculated as $(X/X_T)^{\beta_1} \cdot (V - I)$, with $(X/X_T)^{\beta_1}$ the stochastic discount factor at time t where $X(t) = X$ and with $\beta_1 = \frac{\frac{\sigma^2}{2} - \mu + \sqrt{(\frac{\sigma^2}{2} - \mu)^2 + 2r\sigma^2}}{\sigma^2\sigma^2}$ (Huisman & Kort, 2015). It is shown that the PA forcing the TOC to invest at its own optimum does in this case only imply small deviations in individual and aggregated discounted $V-I$ from the private service port optimum, or even from the optimal TOC's investment strategy.

Table 9: Discounted $V - I$ under under possible investment strategies equally followed by both actors in a private service port where the PA can force the TOC to invest in the PA optimum at time $t : X(t) = 35$.

Common investment strategy: (X_T, K)	**Discounted** $(V - I)_{\text{PA}}$	**Discounted** $(V - I)_{\text{TOC}}$	**Discounted** $\Sigma_i(V - I)_i$
PA individual optimum: $(37.43, 11.11)$	933.3	523.7	1457.0
Private service port optimum: $(37.63, 11.17)$	933.2	523.9	1457.1
TOC individual optimum: $(38.00, 11.26)$	932.9	524.0	1456.9

Parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, \alpha_1 = 0.9, \alpha_2 = 0.95, \alpha_3 = 0.35, \alpha_4 = 0.5, \alpha_5 = 0.60035, X = 35$.

Source: Own calculations.