The case of public and private ports with two actors : capacity investment decisions under congestion and uncertainty

The case of public and private ports with two actors: capacity investment decisions under congestion and uncertainty

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Abstract

Since port capacity investments involve expensive large projects with high uncertainty and irreversibility, we use real options calculations to study the optimal size and timing of the investment decision in new port capacity. This paper focuses on cases where 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 containers, invests in the superstructure. Moreover, the PA is often partly or fully publicly owned, leading to the consideration of social welfare among its objectives. Examples of such container ports include Gioia Tauro in Italy when it was developed, and the port of Luanda in Angola. In the type of ports considered, the PA's strategy could be to urge the TOC to invest in the PA's individual optimum. When a share of the PA is owned publicly, social welfare is to be maximised. In this light, the PA and the TOC could agree to invest at the service ports' single actor optimum and redistribute the additional aggregate gains. Higher public involvement leads to a larger investment that is also made earlier, augmenting benefits generated by the port. This relationship between investment size and timing is exceptional in the real options literature. Moreover, the investment decision is complicated by the fact that port users are averse to congestion and the costs it involves. When this cost or uncertainty are higher, it is found that more capacity will be installed, but at a later moment.

Highlights:

- The port capacity investment decisions of two actors are studied under uncertainty: a terminal operator and a port authority, which can be (partly or fully) publicly owned.
- Higher uncertainty and congestion costs lead to postponing the investment, which will be larger.
- More public money involvement leads to larger and earlier investment.
- The concession fee allows the port authority to urge the terminal operator to follow the same investment strategy.
- The joint investment decision could also result from negotiation.

Keywords: port capacity; two port actors and public ownership; real options for flexible investment decisions.

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1 Introduction

Port activities drive worldwide trade, maritime transportation, economic activity and development of a region. Maritime and hinterland access, infrastructure (e.g., docks), superstructure and equipment (e.g., cranes) are important interrelated elements determining port capacity (Verhoeven, 2015; Vanelslander, 2014). Compared to a production environment, capacity has an even more important role in a port, 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. UNCTAD (2015); De Langen et al. (2018) emphasize that the demand for cargo handling is uncertain but growing, especially the container trade segment. Hence, it might occur that moments 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. Congestion and insufficient capacity may also lead to a slowdown of the economy, decreased GDP and increased trade distances and freight delays. To avoid such negative effects, sufficient capacity should be provided by investing in it (Kauppila et al., 2016). Such investments moreover lead to increased employment. De Langen et al. (2018) indicate that in the period 2018-2027, 50 billion euro of port investments are needed in Europe, of which about 70% involve capacity expansion projects. This type of projects is deemed crucial by the majority of port authorities. The question however remains when the investment should be made, and how large it should be, given the growth and uncertainty that are present.

Oppositely, installing too much capacity involves a downside as well, as money is invested in capacity that might never be used and that might hence 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 (i) is often taken by different actors and (ii) often involves public money, because ports create value beyond the border of a port. The objective of this paper is to analyse how the optimal investment decision in new port capacity under congestion and uncertainty is influenced by these two specific port characteristics. To this end, a real options (RO) model is developed and applied to a port with two actors: a port authority (PA) who manages the port and a terminal operating company (TOC) who handles the containers under a concession agreement with the PA. Among the shareholders of the PA, a public government is included. Examples of such container ports include the port of Gioia Tauro in Italy during its development (CSIL, 2012, p. 10) and the port of Luanda in Angola (Porto de Luanda, 2018). Kauppila et al. (2016) indicate that the largest capacity needs exist in Africa and Asia. As the number of container ports is low in such developing countries, these ports experience almost no competition from nearby ports yet.

The structure of this paper is as follows: the next section introduces the economic background through a literature study and the economic 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. Section 4 presents the RO model and calculations. Section 5 discusses the results, followed by a sensitivity analysis in Section 6. The conclusions and avenues for future research are given in Section 7.

2 Economic environment of the case study

The port capacity investment decision has received a lot of attention in literature. Some authors take congestion (Xiao et al., 2012) and uncertainty (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 and land are owned by the PA, the actor who manages the port, while the TOC owns the superstructure and handles the cargo under a concession agreement with the PA. The involvement of public money is another typical aspect of large infrastructure projects such as port infrastructure (Brooks & Cullinane, 2007). In this light, Xiao et al. (2012) studied the influence of multiple port owners on capacity, 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, value added, and/or employment, which is often linked to the amount of throughput. This offers an explanation for a large number of ports trying to maximise their throughput (Tsamboulas & Ballis, 2014; 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, these papers allowing for different types of ownership do not consider uncertainty.

As Balliauw et al. (2017) already demonstrated for lumpy port capacity investments in a service port, the combination of congestion and uncertainty alters the investment decision a lot. This paper adds to the literature by studying the impact of congestion and uncertainty in (i) a landlord port with two actors, where (ii) public ownership is possible. To this end, a real options model is constructed, which allows answering the following research question: "How are the investment decisions of the PA and the TOC in new port capacity influenced by each other's decisions and public PA ownership under congestion and uncertainty in the absence of competition?"

In the type of ports considered here, the PA and the TOC invest in complementary elements of port capacity 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 here, as they do not apply for every unit of throughput handled or they are negligible, depending on the trade and period of time considered (Jenné, 2017). Demand originates from a receiver buying goods from the shipper, who ships them through a shipping line (Coppens et al., 2007). This paper focuses on containerised goods. Containers, the pricing base of the TOC that handles them, are carried by shipping lines on their ships, which is the pricing base of the PA. As the focus is on the supply side with the PA and the 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 throughput generates welfare (Xiao et al., 2012), the number of ships is converted to throughput in Section 3 (see footnote 10). In this way, demand depends on one single variable, which reduces mathematical complexity.

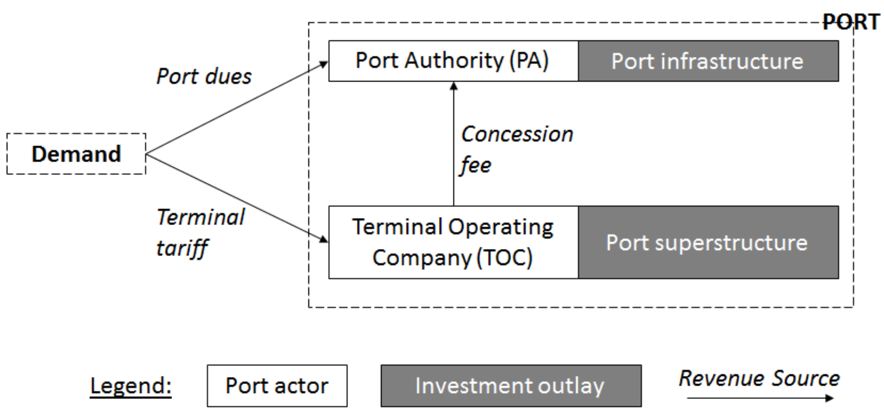

Figure 1: Revenue sources and investment outlays of the PA and the TOC.
Source: Own composition.

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, our model presents two expansions compared to the available literature on port capacity investments and real options. First, the distribution of revenues and costs over the different actors is included in the model. Second, public ownership is accounted for through an extension of the PA's operational objective function with social welfare. Before discussing and quantifying both elements, the assumptions regarding the economic environment and the behaviour of the port are discussed.

2.1 Assumptions

This paper looks at the development of new ports, where the dock and terminal are installed at once and without time to build, by respectively one PA and one TOC. Since we look at ports experiencing little or no competition, the investment decision in only one port is studied.

Next to these assumptions related to the economic environment, some behavioural assumptions are made in relation to the described cases. the PA and the TOC have the option to make a once and for all investment decision, of which the size and timing are flexible. Moreover, the assumption is made that the PA has full information on the TOC's price and cost decisions. In reality, the PA often only has full information about the realised throughput of the TOC. The PA could however make decent predictions of prices and costs of an efficient TOC, based on the limited available information about terminal operators already active in other ports and the expected demand. These predictions allow the PA to ex-ante calculate its expected part of the income from terminal operations, charged to the TOC through a concession fee. This income constitutes a considerable part of the port's profit and its correct inclusion in the calculations is required to correctly decide about the optimal size and timing of the infrastructure investment. In reality, also the price is little transparent for the customers, since it is set by a number of actors (Meersman et al., 2015). Here however, price transparency is assumed to give rise to the demand function specified in the next subsection. The specific assumptions regarding the concession agreement and the mathematical model are included in the next subsections.

2.2 Differentiating between TOC and PA

This subsection describes how the distinction between the PA and the TOC is made in the economic model. The division of revenues and costs is described in Section 2.2.1. The modelling of the concession fee and the related assumption of a renewal of the concession agreement are discussed in Section 2.2.2. Additionally, our model does not consider the time to build a project. Since the project is installed at once, Section 2.2.3 explains why it follows that the PA and the TOC are assumed to install the same capacity at the same time.

2.2.1 The distribution of revenues and costs between both actors

The port customer faces a full price ρ, which depends on throughput q at time t as follows:

$$\rho(t) = X(t) - Bq(t), \tag{1}$$

with $X(t)$ a random demand shift parameter and B the slope of the inverse demand function. $X(t)$ follows a Geometric Brownian Motion (GBM):

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

specified by parameters μ (expected drift, expressing growth) and σ (drift variability, expressing uncertainty) and with $Z(t)$ a standard Wiener process. In what follows, the time dependencies will be omitted for the sake of readability.

Since the full price ρ consists of p (the sum of the terminal tariff and port dues) *plus* a congestion cost, p can be derived as follows:

$$p = X - Bq - AX\frac{q}{K^2}, \tag{3}$$

with the latter term expressing unit congestion costs (Xiao et al., 2012). Total congestion costs then equal $AX(q/K)^2$. They increase with a higher occupancy rate, q/K (De Borger & Van Dender, 2006; De Borger & De Bruyne, 2011).[1] The square of the occupancy rate is used as a proxy for the amount of waiting time to express the non-linear relation with occupancy (Blauwens et al., 2016). The monetary scaling factor A converts delays to costs and is port-user and good-type dependent. The height of the congestion cost is also related to the uncertain price level through the multiplication with X.

Since p is the sum of the terminal tariff $p_{\text{TOC}} = \alpha_1 \cdot p$, paid by the shipping company to the TOC, and port dues $p_{\text{PA}} = (1 - \alpha_1) \cdot p$, paid by the shipping company to the PA; it holds that $p = p_{\text{TOC}} + p_{\text{PA}}$. In this paper, the TOC and the PA independently set their respective prices for servicing ships and handling cargo, before the capacity is operated. The chosen relative prices determine α_1, the average share of the terminal tariff in the total price. The calculation of α_1 in practice, using real data and average port occupancy, is illustrated in Section 3. This share then remains fixed over time, as both the port dues and terminal tariff subsequently follow the evolutions of the demand shift parameter X, which determines the evolution of the market.[2] A growth of X leads to a higher total price p. This market growth, with its uncertainty as expressed by the GBM, is distributed accordingly over the TOC and the PA by shares α_1 and $1 - \alpha_1$. As a result, the customers' reduced willingness to pay due to congestion is also distributed by the same shares α_1 and $1 - \alpha_1$ respectively.

A similar reasoning holds for the operational costs of the TOC and the PA. The shares of the TOC and the PA in the total operating cost cq, with c the constant marginal operational cost, are α_2 and $1 - \alpha_2$ respectively. These shares, like the other division parameters, are constant over time. The operational cost for the TOC encompasses for example labour and electricity, whereas the cost of the PA encompasses among other things administration (Lacoste & Douet, 2013). Also the total investment cost and the capital holding cost $c_h K$ are divided between the TOC and the PA. The investment cost is a fourth order function of capacity:

$$I(K) = FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_4 K^4, \tag{4}$$

to indicate fixed investment costs (FC_I), economies of scale in investment size (negative second order term) and a boundary of maximum investment size (positive fourth order term). For the division of the investment cost, the shares α_3 and $1 - \alpha_3$ are used, whereas for the capital holding cost, they are α_4 and $1 - \alpha_4$ respectively. These express the cost structure differences between superstructure and infrastructure investments.[3]

2.2.2 Modelling the concession fee

An additional 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 this paper, one TOC handles all the containers in the port. In return, the PA receives a concession fee from the TOC. Many different concession fee schemes exist, such as a lump sum, an annual fee, a quantity-dependent fee, a percentage of the revenue or a combination of these elements (Saeed & Larsen, 2010). 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.[4] In this way, the modelled concession fee values are endogenous and more realistic. This would not be the case if the concession fee had been based on revenue, since the PA creaming off a too high percentage of the TOC's revenue would leave the TOC with losses and being discouraged to

[1] It should be noted that throughput q (determined by the TOC, as will be explained later) cannot exceed total capacity, denoted by K.

[2] In reality however, it might happen that the PA and the TOC alter their prices separately over time, e.g. when an actor applies peak-load pricing.

[3] Note that α_1, α_2, α_3 and α_4 do not need to be equal, as they encompass different elements of the project cash flows (i.e. revenues and costs).

[4] 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.

invest. Setting an arbitrary percentage of the revenue can only be avoided by ex-ante calculating the concession fee as a share of the TOC's operational profit, taking in this way both revenues and costs into account. If operating is profitable for the TOC, it will 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 could decide to suspend operations, especially if losses are persistent in the long run. Hence, operational profit will always remain greater than or equal to zero after deducting the concession fee. This is a prerequisite for a meaningful calculation of the concession fee.[5]

As it is assumed that the PA has full information about the TOC, the PA can *a priori* estimate the discounted profit of the TOC over time. With this information, the PA can decide on model parameter α_5, the percentage of this TOC profit to be creamed off, resulting in a discounted income stream from the concession fee. This can subsequently be converted into one of the in reality commonly applied concession fee systems with an equal net present value, e.g., a lump sum, annual, throughput or revenue based fee (Pallis et al., 2008). This conversion is required to be able to implement the outcome of the ex-ante calculations and outcomes from the model in reality.

Because the concession fee has an impact on the returns of both the TOC and the PA and is set by the PA, the latter can influence its own profit and optimal investment decision as well as those of the TOC. 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 profits) 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, future renewals of the agreement are assumed (Wang & Pallis, 2014). This leads to an infinite project life time.

2.2.3 Possible investment and concession strategies for the PA

In the described port, the optimal timing (expressed as a threshold X_T, triggering investment as soon as demand shift parameter X reaches the threshold for the first time from below)[6] and size (K) of the investment decision of the PA and the TOC may differ, because they have different operational objective functions to optimise. In the framework of Xiao et al. (2015) studying port infrastructure investments preventing disasters, different investments of the PA and the TOC are possible. In our paper however, the chosen investment size and timing of both actors need to be the same, as they are the outcome of a cooperative game. Also Xiao et al. (2015) take the contract of cooperation between the PA and the TOC into account. As a public party considers aggregated social welfare rather than individual profits, cooperation can be justified. However, results in this paper are compared to the (non-cooperative) individual optima as well.

In a landlord port, the PA and the 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 our cooperative game considering a lumpy once and for all investment without time to build, it would be disadvantageous for both actors 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. In this way, the decision of the PA can limit the TOC's investment options. If phased investment is not an option and construction lead times are omitted from the analysis,

[5] This explains why it is crucial to focus on operational profit and leave the capacity holding cost 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. Since total profit could become negative, calculating the concession fee as a percentage of this could lead to the unrealistic case of a negative concession fee. This would be equivalent to the port subsidising a TOC and the TOC would be discouraged to invest.

[6] The higher the threshold, the later investment takes place.

it does not make sense for a PA to invest in more capacity than the TOC's capacity investment under the concession agreement, as it causes in this case only a loss of money because of unused capacity. The same holds for the PA investing before the TOC, which would result in a period without profits, as the infrastructure would not yet be operated. As a result, the PA would not invest in the infrastructure before the moment the TOC is willing to install the superstructure. Hence, if optimal timing and size differ for both individual actors, their optima constitute an interval from which the unique final investment decision needs to be determined. (Meersman & Van de Voorde, 2014)

Two possible investment 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. Because of the previous considerations and the model disregarding time to build, the concession negotiations, as compared to reality, are in the model anticipated to a moment before the project is installed.

A first investment strategy involves both the TOC and the PA giving in from their individual optima to invest at the aggregated optimum of a service port, which is often comprised in the decision interval. If the PA invests in a size at a threshold deviating from its optimum, it can urge 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 could be denied the concession. In that case, the PA of course needs to search for a new concessionaire. Under the described strategy, the concession fee can be interpreted as a redistribution of the project value after the deduction of investment costs ($V - I$) from one actor 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 when determining its concession fee:

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

An important consideration when following this first investment strategy is that incentives for the TOC to deviate from the concession agreement should be avoided or at least minimised. Such incentives are present if the optimal size and/or threshold of the TOC are respectively below and/or above the optima of the PA.

A second investment strategy for the PA to deal with deviating optima in the described scenario could be to urge the TOC to decide at the same time to invest in the same amount of capacity through economic incentives.[7] If the PA invests later or in a smaller amount than the TOC's optimum, the TOC is urged 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 the 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.

[7] In this light, it is crucial to recall that time to build and phased investment are disregarded in the RO model.

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; Bichou & Gray, 2005). If a government is involved, the PA will 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 operational objective function as λq, with λ the spillover benefit per unit q. Consumer surplus 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 operational objective function, s_{CS} is the share of total consumer surplus considered by the government. (Xiao et al., 2012)

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

$$SW(X, K, q) = \pi_{\mathrm{PA}}(X, K, q) + \lambda q + s_{CS} \cdot Bq^2/2, \tag{5}$$

with $\pi_{\mathrm{PA}}(X, K, q)$ the instantaneous annual profit of the PA, given the instantaneous value for X, the size of the port K and the instantaneous annual throughput q. 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 number 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 operational objective function (Π) of the PA now becomes the weighted sum of the individual owners' operational objective functions. The shares of ownership are used as the weights:

$$\begin{aligned} \Pi_{\mathrm{PA}}(X, K, q) &= (1 - s_G) \cdot \pi_{\mathrm{PA}}(X, K, q) + s_G \cdot SW(X, K, q) \\ &= \pi_{\mathrm{PA}}(X, K, q) + s_G \cdot \lambda q + s_G s_{CS} \cdot Bq^2/2. \end{aligned} \tag{6}$$

2.4 Model summary

To summarise, the profit and investment cost functions resulting from the division of revenues and costs between the two actors are given. For the TOC, this results in:

$$\pi_{\mathrm{TOC}}(X, K, q) = (1 - \alpha_5) \cdot \{\alpha_1 \cdot [p(q) \cdot q] - \alpha_2 \cdot cq\} - \alpha_4 \cdot c_h K, \tag{7}$$

$$I_{\mathrm{TOC}}(K) = \alpha_3 \cdot \left(FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_4 K^4\right), \tag{8}$$

whereas for the PA, it results in:

$$\begin{aligned} \pi_{\mathrm{PA}}(X, K, q) &= [(1 - \alpha_1) + (\alpha_1 \alpha_5)] \cdot [p(q) \cdot q] \\ &\quad - [(1 - \alpha_2) + (\alpha_2 \alpha_5)] \cdot cq - (1 - \alpha_4) \cdot c_h K, \end{aligned} \tag{9}$$

$$I_{\mathrm{PA}}(K) = (1 - \alpha_3) \cdot \left(FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_4 K^4\right). \tag{10}$$

The profits and costs of both actors are determined by the same drivers. However, these drivers are distributed differently over the TOC and the PA. It is hereby interesting to 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 with one single actor. In this way, the presented model can be used to calculate the private service port optimum as well. Because a (partly) publicly owned PA also considers social welfare, the operational objective function of the PA has been extended in Eq. (6) with spillover benefits and consumer surplus, weighted by the share of public ownership.

Table 1 gives an overview of the entire economic model. It contains a short explanation of all the variables, equations and parameters, together with the values for the numerical examples as determined in the next section.

Table 1: Model overview.

Variables		
p	$=$	price
q	$=$	throughput
K	$=$	capacity
α_5	$=$	concession fee parameter: share of TOC's annual operational profit paid to PA
Aggregated inverse demand function: $p = X - Bq - AX\frac{q}{K^2}$		
$B(=1)$	$=$	slope
$A(=5)$	$=$	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
Aggregated total cost $TC = cq + c_h K$		
$c(=1)$	$=$	constant marginal operational cost
$c_h(=0.5)$	$=$	cost to hold one unit of capital in place
TOC investment cost $I_{\mathrm{TOC}} = \alpha_3 \cdot \left(FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_3 K^3 + \gamma_4 K^4\right)$		
PA investment cost $I_{\mathrm{PA}} = (1-\alpha_3) \cdot \left(FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_3 K^3 + \gamma_4 K^4\right)$		
$\alpha_3(=0.35)$	$=$	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 = operational objective function $\pi_{\mathrm{TOC}} = (1-\alpha_5) \cdot \{\alpha_1 \cdot [p(q) \cdot q] - \alpha_2 \cdot cq\} - \alpha_4 \cdot c_h K$		
PA profit $\pi_{\mathrm{PA}} = [(1-\alpha_1) + (\alpha_1\alpha_5)] \cdot [p(q) \cdot q] - [(1-\alpha_2) + (\alpha_2\alpha_5)] \cdot cq - (1-\alpha_4) \cdot c_h K$		
$\alpha_1(=0.9)$	$=$	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 operational objective function $\Pi_{\mathrm{PA}} = \pi_{\mathrm{PA}} + s_G \cdot \lambda q + s_G s_{CS} \cdot CS$		
$\lambda(=0.4)$	$=$	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

3 Case study description and parameter calibrations

The current analysis concentrates on the investment decision in a new port such as Gioia Tauro (in its development phase) or Luanda, with one PA and one TOC and without competition from nearby ports. The case calculations rely on numerical simulations of the RO model, as described in the next section, since analytical solutions cannot be calculated. Proxies for the parameters are calculated using real data from a number of sources (Port of Antwerp, 2016; Vanelslander, 2014; Zuidgeest, 2009). The investment cost lies between one and three billion euro, depending on the construction size (between 8 and 14 million TEU) and technologies applied. Therefore, q and K are expressed in million TEU, while p and $c(= 1)$ are in euro per TEU and $c_h(= 0.5)$ in euro per TEU per year. In this way, it is reflected that the operational variable cost (c) in infrastructure projects is relatively low (Wiegmans & Behdani, 2018). As a simplification, the slope of the demand function is normalised to 1. The values for the drift ($\mu = 0.015$) and the drift variability ($\sigma = 0.1$) are estimated in the port context, using data of the port of Antwerp and Rotterdam from 2010 to 2015 Vlaamse Havencommissie (2016).[8] The discount rate r of 6%, used by Aguerrevere (2003) in his real options analysis, lies between the 4 (Blauwens, 1988) and 8% (Centraal Planbureau, 2001) often used in a transportation context. The monetary scaling factor of congestion, A, is the most difficult parameter to estimate. Here, it is set to 5, to model a sufficiently high impact of congestion on the investment decision and yield realistic results for the price. Yet, A is altered in the sensitivity analysis.

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 euro per TEU. Here it is set to 0.4 euro per TEU, 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 the TOC and the 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.[9] 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; Keskinen et al., 2017; Luck, 2017). 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.

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 determine. 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). Among other things the ship characteristics and the location in the port determine the port dues. Hence, the amount of goods loaded and unloaded only partly influence the heigth of these port dues. As a result, a conversion is required to find an expression for the average amount of port dues per TEU. Conversions have an influence on α_1, which is in reality not fixed, but is the result of the demand function taking into account the

[8] The growth rate is approximated by the significant coefficient of an estimated exponential growth model. The root of the squared error is used to approximate σ.

[9] 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.

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 of operations using data from the Port of Antwerp (2017a,b), to come to a value of 0.9.[10] Since detailed data on the ports of Gioia Tauro and Luanda has proven difficult to obtain, proxies have been determined based on data from other ports. To study the impact of the determined values and changes in these values, they will be altered in the sensitivity analysis in Section 6.

4 Methodology to solve for the optimal investment strategy in a landlord port

With the operational objective functions of the port actors deciding on capacity and the numerical values for the parameters at hand, the optimal investment decision in a landlord port can be calculated. In reality, the PA first decides at which moment it would invest in infrastructure and how much capacity it would provide. 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_{TOC}^{opt}. This needs to be below K, because throughput cannot exceed total design capacity K. Moreover, the assumption of full ex-ante information for the PA and the interactions with the TOC preceding a concession agreement lead to the consequence that the PA and the TOC select the same size and timing of the investment. The decision will often be somewhere between the extrema of both actors' optima, which constitute the decision interval as described in Section 2.2.3. If the TOC deviates 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 of Dixit & Pindyck (1994) and Dangl (1999) is adapted to backwardly solve the real options problem including congestion and multiple actors (a: TOC and PA) in a port. The way congestion is modelled gives rise to hypergeometric functions (${}_2F_1$) in the expressions of the project value functions (after investment at time T_a) of the TOC:

$$V_{\text{TOC}} = \mathbf{E} \int_0^\infty \max_{q_{\text{TOC}}} \{\pi_{\text{TOC}}(T_{\text{TOC}} + \tau)\} \mathrm{e}^{-r\tau} \mathrm{d}\tau \tag{11}$$

and the PA:

$$V_{\text{PA}} = \mathbf{E} \int_0^\infty \Pi_{\text{PA}}(q_{\text{TOC}}, T_{\text{PA}} + \tau) \mathrm{e}^{-r\tau} \mathrm{d}\tau, \tag{12}$$

after applying Bellman Equation and Itô's Lemma to this equation (Dixit & Pindyck, 1994). These equations highlight the important difference compared to a service port that the optimisation is to be executed for the two actors separately, but that only one actor handles the goods. In order to find the optimal investment decision of each actor, each actor maximises his expected future discounted profit stream minus the investment outlay of his project, with respect to timing T_a when $X(t = T_a) \underset{\nearrow}{=} X_{T,\text{a}}$, and capacity K_a (Huisman & Kort, 2015). If $X(t = 0) < X_{T,\text{a}}$ so that it is not optimal to invest from the beginning, this gives rise to each actor's investment problem

[10] 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 prices of Port of Antwerp (2017a) show that the port dues per BT are 0.2 euro, if 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. As a result, the average total port dues equal 7.35 euro per TEU. 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; Wiegmans & Behdani, 2018).

objective function:

$$\max_{T_{\mathrm{a}}\geqslant 0, K_{\mathrm{a}}\geqslant 0} \mathbf{E}\left\{\left[V_{\mathrm{a}}(X_{T,\mathrm{a}}, K_{\mathrm{a}}) - I_{\mathrm{a}}(K_{\mathrm{a}})\right]\mathrm{e}^{-rT_{\mathrm{a}}} | X(t=0) = X\right\}. \tag{13}$$

Because each actor has the option to postpone the investment, this investment decision contains an option value $F_{\mathrm{a}}(X)$, based on the economic equations in Section 2. The optimisation with respect to timing comes down to finding the critical threshold value $X_{T,\mathrm{a}}$ for which it is better to invest rather than to wait. Investment will take place as soon as this threshold is reached for the first time from below. If however $X(t=0)$ exceeds $X_{T,\mathrm{a}}$, investment takes place right away. As long as $X < X_{T,\mathrm{a}}$, actor a will postpone the investment and $F_{\mathrm{a}}(X)$ equals the value of waiting:

$$F_{\mathrm{a}}(X|X < X_{T,\mathrm{a}}) = \mathrm{e}^{-r\mathrm{d}t}\,\mathbf{E}\left[F_{\mathrm{a}}(X) + \mathrm{d}F_{\mathrm{a}}(X)\right]. \tag{14}$$

As soon as the $X \geqslant X_{T,\mathrm{a}}$, actor a invests in K_{a} and the option value equals the expected return of the investment, dependent on the value of X at the moment of investment and the installed capacity which maximises this return:

$$F_{\mathrm{a}}(X|X \geqslant X_{T,\mathrm{a}}) = \max_{K_{\mathrm{a}}}[V_{\mathrm{a}}(X, K_{\mathrm{a}}) - I_{\mathrm{a}}(K_{\mathrm{a}})]. \tag{15}$$

In order to solve this RO problem and optimise the investment decisions of both actors, the first step of the methodology determines the TOC's optimal throughput $q_{\mathrm{TOC}}^{opt}(X, K)$ through the first and second order conditions for the $\pi_{\mathrm{TOC}}(q, X, K)$ of Eq. (7). This results in

$$q_{\mathrm{TOC}}^{opt}(X,K) = \begin{cases} 0, & X < \dfrac{\alpha_2}{\alpha_1}c, \\ \dfrac{(\alpha_1 X - \alpha_2 c)K^2}{2\alpha_1(AX + BK^2)}, & \dfrac{\alpha_2}{\alpha_1}c \leqslant X < \dfrac{(2\alpha_1 BK + \alpha_2 c)K}{\alpha_1(K - 2A)}, \\ K, & X \geqslant \dfrac{(2\alpha_1 BK + \alpha_2 c)K}{\alpha_1(K - 2A)}, \end{cases} \tag{16}$$

given the size of the port K and the instantaneous value for X. Because it should hold that $0 \leqslant q_{\mathrm{TOC}}^{opt} \leqslant K$, q_{TOC}^{opt} is divided into three mathematical regions, defined by boundaries for X. Plugging q_{TOC}^{opt} into $\pi_{\mathrm{TOC}}(q, X, K)$ leads to $\overline{\pi}_{\mathrm{TOC}}(X, K)$, defined in the same three regions.

Second, through differential equation

$$\frac{\sigma^2}{2}X^2\frac{\partial^2 V_{\mathrm{TOC}}}{\partial X^2}(X,K) + \mu X\frac{\partial V_{\mathrm{TOC}}}{\partial X}(X,K) - rV_{\mathrm{TOC}}(X,K) + \overline{\pi}_{\mathrm{TOC}}(X,K) = 0, \tag{17}$$

$V_{\mathrm{TOC}}(X, K)$, the value of the TOC's project of size K, installed at the moment that the demand shift parameter equals X and for which the TOC pays $I_{\mathrm{TOC}}(K)$, is derived. Here again, the same three mathematical regions apply. Third,

$$F_{\mathrm{TOC}}(X) = \max\{\mathrm{e}^{-r\mathrm{d}t}\,\mathbf{E}(F_{\mathrm{TOC}}(X) + \mathrm{d}F_{\mathrm{TOC}}(X)), \max_{K_{\mathrm{TOC}}}[V_{\mathrm{TOC}}(X, K_{\mathrm{TOC}}) - I_{\mathrm{TOC}}(K_{\mathrm{TOC}})]\} \tag{18}$$

gives the option value of investment postponement, which is maximised in order to find the optimal investment timing threshold and size of the TOC's investment $(X_{T,\mathrm{TOC}}^{**}, K_{\mathrm{TOC}}^{**})$. Fourth, the resulting operational objective function of the PA, $\overline{\Pi}_{\mathrm{PA}}(X, K)$, is determined by plugging q_{TOC}^{opt} into $\Pi_{\mathrm{PA}}(q, X, K)$ from Eq. (6), as it is the TOC that sets the throughput quantity. Using q_{TOC}^{opt} results in the same three regions for the PA's operational objective function as found for the TOC's profit. Fifth, the differential equation

$$\frac{\sigma^2}{2}X^2\frac{\partial^2 V_{\mathrm{PA}}}{\partial X^2}(X,K) + \mu X\frac{\partial V_{\mathrm{PA}}}{\partial X}(X,K) - rV_{\mathrm{PA}}(X,K) + \overline{\Pi}_{\mathrm{PA}}(X,K) = 0 \tag{19}$$

allows deriving $V_{\mathrm{PA}}(X, K)$, the value of the PA's project of size K, installed at the moment that the demand shift parameter equals X and for which the PA pays $I_{\mathrm{PA}}(K)$. Finally, the option value

$$F_{\mathrm{PA}}(X) = \max\{\mathrm{e}^{-r\mathrm{d}t}\,\mathbf{E}(F_{\mathrm{PA}}(X) + \mathrm{d}F_{\mathrm{PA}}(X)), \max_{K_{\mathrm{PA}}}[V_{\mathrm{PA}}(X, K_{\mathrm{PA}}) - I_{\mathrm{PA}}(K_{\mathrm{PA}})]\} \tag{20}$$

allows calculating the optimal investment timing threshold and size for the PA $(X^{**}_{T,\mathrm{PA}}, K^{**}_{\mathrm{PA}})$. Both $(X^{**}_{T,\mathrm{TOC}}, K^{**}_{\mathrm{TOC}})$ and $(X^{**}_{T,\mathrm{PA}}, K^{**}_{\mathrm{PA}})$ together constitute the decision interval from which the final investment decision is to be selected. The flowchart in Figure 2 summarises the steps of the RO methodology.

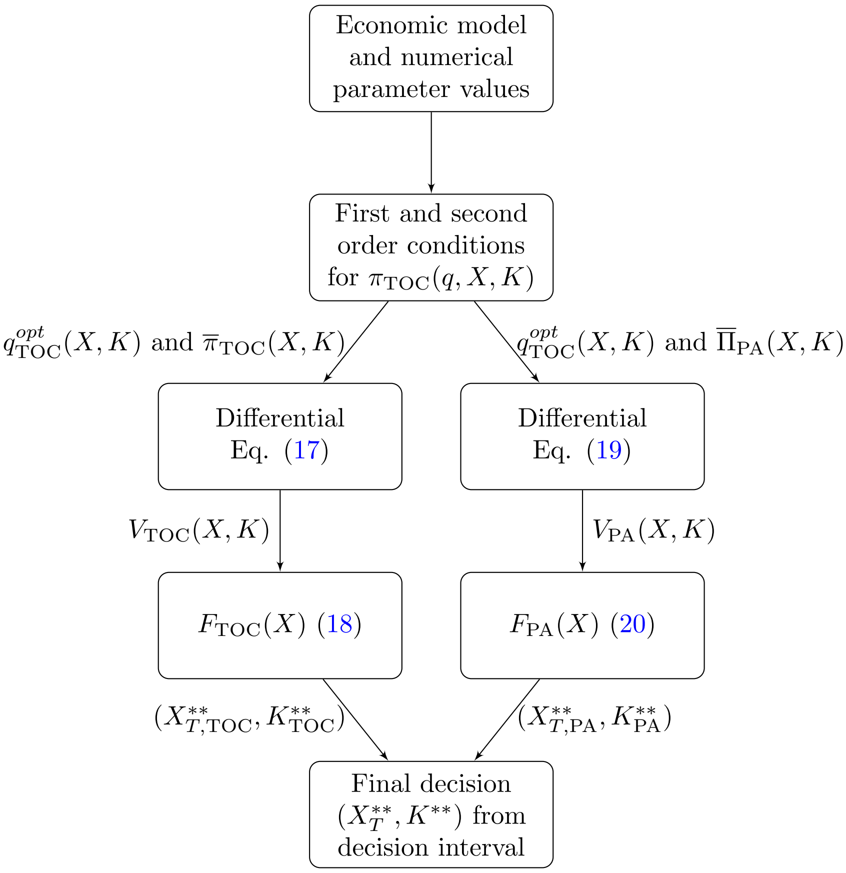

Figure 2: Summary of the RO cooperative game methodology.

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 $X^{**}_T = 37.63$ euro per TEU and $K^{**} = 11.17$ million TEU per year.[11]. Note that each optimal X^{**}_T, given the optimal capacity, can be converted through each actor's inverse demand function into an optimal throughput quantity (in million TEU) that needs to be demanded at a certain price (in euro per TEU) before investment takes place. 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 first studied separately from the impact of government involvement as a PA shareholder in a service port, partly or fully owned by the government. Afterwards, both are combined in a landlord port setting with public money involvement.

[11]This is done by setting the α's, s_G and s_{CS} to 0 and calculating the PA's optimum.

5.1 Division between PA and TOC

If the distinction between the PA and the TOC in a private landlord port (no government involvement, or s_G set to zero) is made according to the model in Table 1, an individual optimal investment threshold can be calculated for both the PA and the TOC. Numerical simulations 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 for both actors (α_5^X) exist for different values of α_1, α_2, α_3 and α_4, leading to a different division of the revenues and costs between the PA and the TOC (see e.g. Table 8). Moreover, this optimal value common for both actors is almost equal to the optimum of the private service port where the port is directed and operated by one single actor. The other decision variable determining the optimal investment strategy then differs per actor, giving rise to a decision interval. This interval often comprises the optimum value from the private service port.

Table 2: Optimal $X^*_{T,\mathrm{a}}(K)$, $K^*_{\mathrm{a}}(X)$ and $(X^{**}_{T,\mathrm{a}}, K^{**}_{\mathrm{a}})$ under different α_5 in a private landlord port.

α_5	**Actor a**	**Timing** $\boldsymbol{X^*_{T,\mathrm{a}}(K_\mathrm{a} = 11.17)}$	**Size** $\boldsymbol{K^*_\mathrm{a}(X = 37.63)}$	**Decision** $\boldsymbol{(X^{**}_{T,\mathrm{a}}, K^{**}_\mathrm{a})}$
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. If the TOC needs to pay 59.48% of its operational profit as a concession fee to the PA, the optimal investment threshold $X^{**}_{T,\mathrm{TOC}} = X^{**}_{T,\mathrm{PA}} = 37.63$ euro per TEU will be the same for both actors, which is nearly the same investment threshold as found in a private service port.[12] In that case, the optimal capacity for the PA will equal 11.12 million TEU per yera, whereas for the TOC it will be optimal to invest in 11.26 million TEU per year. Indeed, the optimal capacity from a similar private service port (11.17 M TEU p.a.) is comprised in this decision interval. With a lower concession fee (α_5 set to 0.469) however, the optimal size of the investment is equal for both the PA and the TOC, almost equalling the optimal capacity $K^{**} = 11.17$ M TEU p.a. from a private service port. The optimal thresholds are then $X^{**}_{T,\mathrm{PA}} = 43.18$ euro per TEU and $X^{**}_{T,\mathrm{TOC}} = 31.30$ euro per TEU. Through mutual concessions, the same optimal threshold $X^{**}_T = 37.63$ euro per TEU from a private service port is attainable. It is also possible for other concession fees to select the global optimum from the decision interval.

Table 2 moreover illustrates the influence of the concession fee on the optimal investment decisions of both the PA and the TOC. If the TOC is required to pay a higher share of its operational profit, the TOC will invest later, or in less capacity ceteris paribus, because the project will be less attractive. This is opposed to the investment becoming more attractive for the PA, leading to an earlier investment or a larger investment size. Every parameter change increasing X^*_T, reduces K^* and vice versa. When looking at the final optimal investment decision

[12] Only the rounded numbers are slightly different. Since $X_T >> c$ and the chosen α_1 and α_2 do not differ by much in this numerical example, their impact on q^{opt}_{TOC} in Eq. (16) and the optimal investment strategy is limited. Note moreover that each optimal threshold, given the capacity available, can be translated into a quantity for which a certain price can be charged. This allows observing the threshold in reality through real indicators.

combining timing and size however, X_T^{**} will always be close to X_T^*, which does not hold for K^{**} and K^*. A later optimal timing coincides with a higher optimal design capacity K^{**}, because the effect of the positive $K^*(X)$ and $X_T^*(K)$-functions dominate the opposite shifts of these functions following a change in α_5.

Additional numerical calculations further illustrate the strategy of selecting the private service port optimum, which has a total project value minus investment costs $V - I$ of 1.76 billion euro. If the PA and the TOC in a private landlord port invest both at this optimum, their aggregated $(V - I)$ also equals 1.76 billion euro, independent of the height of the concession fee. This concession fee only has an impact on the distribution of the revenues and costs among both actors. The different concession fee strategies from Section 2.2.3 are 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 both $V - I$ and 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 actors 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: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, \alpha_1 = 0.9, \alpha_2 = 0.95, \alpha_3 = 0.35, \alpha_4 = 0.5, X_T = 37.63, K = 11.17$.

Source: Own calculations.

The case involving a TOC paying 59.475% of its operational profit to the PA as a concession fee allows easily calculating each actor's impact of diversion from its own optimum. As 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.[13] This scenario is quantified in Table 4 for different investment strategies included in 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)	$(V-I)_{\text{PA}}$	$(V-I)_{\text{TOC}}$	$\Sigma_i(V-I)_i$
a) *PA individual optimum:* $(37.63, 11.12)$	1110.0	649.8	1759.8
b) *Private service port optimum:* $(37.63, 11.17)$	1109.8	650.1	1759.9
c) *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 the service port optimum, which entails 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 larger investment, which is already closer to its own optimum. As the TOC can now invest in $K = 11.17$ M TEU p.a. instead of 11.12, the TOC's $V - I$ increases with 0.3

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

million euro. This leads to an aggregated gain of 0.1 million euro. In reality, such a situation would hardly be observed if the PA were privately owned, since only the own welfare would be maximised. Therefore, a public PA owner, caring about aggregated social welfare, is introduced in the next subsections. Deviating from the aggregated optimum would lead to a destruction of welfare, compared to situation b). 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 argued before, the additional aggregated profit in situation b) can be distributed among the PA and the 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 2.2.3. Additionally, it is noteworthy that the deviations in project $V - I$ are limited in absolute terms for both actors. This favours the negotiations between the actors.

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 46.9% and 59.475%, 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's incentives to deviate from the contract should be minimised. In this light, the PA needs to have sufficient power to enforce the concession contract (Wang & Pallis, 2014).

However, if 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. Although these latter two cases bear an incentive for the TOC to deviate from the PA's optimum, 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. As was explained before, 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. The TOC then 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, allowing the PA to 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		Conditional optimal investment strategy
PA	(**37.43**, *11.11*)		$=$
TOC	(**38.00**, ~~*11.26*~~)	$\rightarrow$	$(X^*_{T,\text{TOC}}(\mathit{11.11}), \mathit{11.11}) = (\mathbf{37.43}, \mathit{11.11})$

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 to invest later and in more capacity than the PA. Hence, the TOC knows that it has to reduce its investment size accordingly, to the 11.11 million TEU per year of the PA. Taking this into account, the TOC calculates its conditional optimal threshold $X^*_{T,\text{TOC}}(11.11) = 37.43$ euro per TEU, 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 $X^{**}_{T,\mathrm{PA}} > X^{**}_{T,\mathrm{TOC}}$, coinciding with $K^{*}_{\mathrm{TOC}}(X^{**}_{T,\mathrm{PA}}) = K^{**}_{\mathrm{PA}}$.

5.2 Government involvement

Next to a private owner maximising profit, also a social welfare-maximising government has to be considered as a PA shareholder in the analysis. As was explained, the government owns a share s_G of the service port. The private partner then has the remaining share $1 - s_G$. The share of total consumer surplus taken into account by the government is given by s_{CS}. Some possible scenarios are given in Table 6.

Table 6: Optimal $X^*_T(K)$, $K^*(X)$ and (X^{**}_T, K^{**}) under different s_G and s_{CS} in a service port, partly or fully publicly owned.

s_G	s_{CS}	**Timing** $X^*_T(K = 11.17)$	**Size** $K^*(X = 37.63)$	**Decision** (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. If the government's share of ownership or the considered share of consumer surplus is higher, the considered project benefits will be higher as well, as the local benefits and CS are taken more into account in the PA's operational objective function $\overline{\Pi}_{\mathrm{PA}}(X, K)$. This is translated into a lower threshold for $X^*_T(K)$, which goes again hand in hand with a larger 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. If the government's share of ownership 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 remarkable, as it is opposite to the common real options finding, where more capacity leads to a later timing or vice versa due to the dominating effect of the positive $K^*(X)$ and $X^*_T(K)$-functions.

5.3 Landlord port with public ownership

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 $X^*_{T,\mathrm{a}}(K)$, $K^*_\mathrm{a}(X)$ and $(X^{**}_{T,\mathrm{a}}, K^{**}_\mathrm{a})$ under different α_5 in a landlord port with public ownership.

α_5	**Actor a**	**Timing** $\boldsymbol{X^*_{T,\mathrm{a}}(K_\mathrm{a} = 11.17)}$	**Size** $\boldsymbol{K^*_\mathrm{a}(X = 37.63)}$	**Decision** $\boldsymbol{(X^{**}_{T,\mathrm{a}}, K^{**}_\mathrm{a})}$
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 profits, costs and operational objective function as before. For the same concession fee, their optimal decision remains unchanged. Public involvement in the model only has an impact on the PA's optimal decision, which will be earlier and larger. As a result, the α_5's matching the timing or size of the project will alter.

From both Table 2 and Table 7, it can be noted that, independent of the amount of public money involved, the project will become less attractive for the TOC with a higher concession fee. The reason is that they retain a lower share of their profit. Unexpectedly however, it is optimal for the TOC individually to invest in more capacity. This counter-intuitive result is explained by the fact that the TOC reacts by postponing the investment to a moment when the market has grown more, requiring more capacity. At the same time, the investment becomes more attractive for the PA. As a result, the PA wants to invest earlier, although its optimal capacity will then be lower.

The combination of mixed ownership of the PA and a landlord port model leads to two different results compared to the private landlord port setting. First, 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 considered in the analysis too. Second, 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 for example, $X^{**}_{T,\mathrm{PA}}$ equals $X^{**}_{T,\mathrm{TOC}} = 36.08$ euro per TEU, which is higher than the threshold $X^{**}_T (= 35.98)$ in Table 6. This is caused by the fact that the PA's optimum is influenced by its public ownership, whereas the TOC's optimal investment decision and optimal throughput level are not altered, as the private TOC does not take social welfare into account. As a private party, it only considers profit in its operational objective function.[14]

In the present scenario, the two described concession strategies remain possible. First, the PA could aggregate the operational objective functions of itself and the TOC and invest at the optimum of a service port. Through the concession agreement, the PA could then urge the TOC to handle at least a certain minimal throughput. Negotiating a favourable (i.e. lower) concession fee could be an adequate incentive for this. Second, 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

[14]Because a private TOC is a profit and not a social welfare maximiser, the optimal throughput set by the TOC in a public landlord port will differ from the optimal throughput set by the single public actor in a public service port. This in turn influences the operational objective function and investment decision of both actors.

of (36.27, 11.24) to a size of $K_{\text{TOC}} = 11.16$ M TEU p.a. The corresponding $X^*_{T,\text{TOC}}(11.16)$ would then be 35.96 euro per TEU, which equals $X^{**}_{T,\text{PA}}$.

6 Investment decision sensitivity to an altered economic situation

In this section, the sensitivity of the results to changes in other parameters is discussed. Table 8 shows how the investment decisions of the different actors 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.

Table 8: Changes of the PA and the TOC's optimal investment decision $(X^{**}_{T,\text{a}}, K^{**}_{\text{a}})$ at the respective α_5^K's and α_5^X's under different parameter changes in a landlord port with public ownership.

Parameter alteration	α_5	**Actor a**	**Decision** $(X^{**}_{T,\text{a}}, K^{**}_{\text{a}})$
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.

With the monetary scaling factor of congestion $A = 4$ instead of 5, the equalled investment threshold and installed capacity for the PA and the 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 of a problem to the port users, so that relatively more throughput is acceptable at the same infrastructure and that less capacity is required. If uncertainty is higher, the investment is made at a later moment, but the installed capacity will also be higher. These conclusions can also be drawn in a private service port setting, confirming robustness of our model. Additionally, the increase of uncertainty (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 providing less capacity than what would be optimal for the TOC. However, between α_5^X and α_5^K, the TOC has a larger incentive to deviate from the PA's optimum, because it is optimal to install less capacity than what has already been provided by the PA and at a later timing. This contains a reasonable incentive for the TOC to deviate by handling less cargo than agreed under the concession agreement. To avoid this, the PA could select the second investment strategy of urging 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. If the average local benefits per TEU were 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 consumer surplus are not included in the private TOC's operational 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.

7 Conclusions and future research

A private service port with one actor is the easiest setting to analyse new port capacity investment decisions, since this single, profit maximising actor takes all decisions in the port. This paper presents the case of a new public port with two actors: a TOC handling the cargo under a concession agreement with the PA that manages the port and owns the land. This PA can be (partly or fully) publicly owned and experiences little competition from nearby ports. The case studied here leads to two extensions to real options modelling of capacity investment decisions in a port under congestion and uncertainty. This paper adds (i) the division of the port income and costs between the actors, as expressed by the α's in our model, and (ii) the inclusion of social welfare in the PA's operational objective function to the model.

Our results show that the PA's and TOC's different objectives in a landlord port lead to a decision interval constituted by the 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 project value *minus* investment costs $V - I$. The concession fee can then be used as a redistribution mechanism of this $V - I$. Another possible strategy for the PA is to urge 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 remaining investment decision variable is then conditionally optimised and could equal the optimal value of the PA.

The results also bear worthy capacity investment policy lessons to be learnt. Since the benefits of port capacity are not only for current and future port users, but also for the economy of an entire region, the involvement of public money has a positive impact. First of all, more PA shares held by the government leads to larger and earlier investments in port capacity, leading to more benefits and positive externalities for the entire economy. This finding is opposite to the common RO finding, where more capacity leads to a later timing or vice versa. Another advantage of involving a public owner in the PA is that the concession fee can be set to trigger investment at the aggregated optimum. In such a case, the concession fee instrument will not merely be used to maximise PA profits, but can rather enable an equitable distribution of income and costs in the port. Of course, the PA should at the same time avoid incentives for the TOC to deviate from the concession agreement. Interesting to observe in light of reaching the aggregated optimum is that the optimum of a service port is not always reachable by a landlord port when the PA is (partly) publicly owned and the TOC privately. The TOC sets the optimal throughput without taking social welfare into account. This leads to a higher deviation from the aggregated optimal throughput and hence the investment strategy in a service port made by a single port actor, partly or fully owned publicly. As a result, the concession agreement is an important instrument to align the objectives of the TOC, the PA and the government. Finally, the model allows drawing two additional conclusions. Both 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, where the port operator is one company (TOC or part of the PA), opens up some viable ways for future research. The impact of inter- and intra-port competition following the presence of multiple competing operators, as well as the impact of vertical integration with other logistics chain actors such as hinterland companies, would be interesting to analyse in a future capacity investment decision making model (De Borger & De Bruyne, 2011; Huisman & Kort, 2015). Moreover, asymmetrical information between parties may exist, with some parties not disposing of perfect information. The impact of a relaxation of this assumption would be an interesting topic of a new analysis. To model the difference in bargaining power of actors, Schneider et al. (2010) proposes among other things a Nash-bargaining game. This would be an interesting approach to define the concession fees optimising the actors' discounted project values in a specific situation.

Acknowledgements

This research is funded by a PhD grant of the Research Foundation Flanders (FWO). In addition, the authors want to thank Christophe Smet, Siri Pettersen Strandenes, Trevor Heaver, Anming Zhang, Michele Acciaro and participants at different conferences for their valuable help in improving the model and the paper. All remaining errors are ours.

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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 the 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 $\beta_1 = \dfrac{\frac{\sigma^2}{2} - \mu + \sqrt{\left(\frac{\sigma^2}{2} - \mu\right)^2 + 2r\sigma^2}}{\sigma^2}$ (Huisman & Kort, 2015). It is shown that the PA forcing the TOC to invest at its own optimum does in this case only cause 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.