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Time to build: A real options analysis of port capacity expansion investments under uncertainty

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Abstract

Port capacity investments are large, expensive and uncertain. They also involve long construction lead times. Therefore, choosing the timing and size of port investments appropriately to serve trade growth is important. This paper presents a real options model to value the option of single-phase (service) port expansions with flexible investment timing and size under uncertainty. The model moreover takes the construction lead time into account. This model allows comparing investment in the expansion of a port already operating and generating revenues with an investment in a greenfield project. An existing port has incentives to protect users from congestion resulting in delays and to protect their port revenues. Therefore, the higher the port users' aversion to waiting, the earlier the port is expanded and the smaller the expansion. Oppositely, in a greenfield project, increased waiting-time aversion leads to projects being undertaken later and being larger. The impact of increased time to build on both the investment timing and size is ambiguous, since this construction lead time increases uncertainty, but at the same time also reduces the present value of cash flows. Increased public ownership leads to earlier investment, but not necessarily more capacity.

Highlights:

- Time to build is considered in the port capacity expansion decision.
- The real options model moreover considers congestion and uncertainty.
- The impact of time to build on investment size and timing is ambiguous.
- The higher the service delay costs, the earlier the expansion takes place. The impact on the size is limited.
- Publicly owned ports expand a lot earlier than private ports.

Keywords: port capacity expansion; time to build; investment size and timing; real options; uncertainty.

1 Introduction

Port activities play an important role in international and regional trade and maritime transportation. Moreover, they make up a significant part of the worldwide economic activity. In order to

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perform these port activities, port capacity is required. The capacity of a port, often expressed as the number of ships or the amount of cargo that can be processed in a certain time period, is determined by many interrelated elements, such as maritime and hinterland access, infrastructure (e.g., docks), superstructure and equipment (e.g., cranes) (Verhoeven, 2015; Vanelslander, 2014). According to UNCTAD (2015) and De Langen et al. (2018) the demand for cargo handling is uncertain but growing. This especially holds for the container trade segment. Due to uncertain arrivals of ships, congestion and waiting time might build up at some moments, followed by periods of empty berths. The resulting congestion poses a problem to the shipping companies, as congestion causes costs, as well as to the ports, who need to reschedule their operations (Blauwens et al., 2016; Balliauw, Kort, & Zhang, 2019). As a result of waiting-time averse shipping companies, the port risks losing clients and/or profit when the available capacity is insufficient. Other consequences involve a slowdown of the economy, decreased GDP and increased trade distances and freight delays. To avoid such negative effects, ports are required to sufficiently invest in the elements determining capacity (Kauppila et al., 2016). According to a survey of De Langen et al. (2018) and subsequent extrapolations by these authors, investments of about 50 billion euro are needed in the European ports in the period 2018-2027. Of these projects, about 70% involve capacity expansions (De Langen et al., 2018).

The majority of the theoretical literature on port capacity investments considers greenfield projects, i.e. ports that are built from scratch (Xiao et al., 2012). One of the counter-intuitive findings in this setting is that higher congestion costs as a result of customers' higher value of time,[1] lead to delaying the investment in a new port, which would be larger though (Balliauw, Kort, & Zhang, 2019). In reality however, the majority of port capacity investment projects encompass expansion projects. Chen & Liu (2016) are one of the few authors studying port expansion investments in a theoretical way. However, they do not account for the current design capacity level of the port either. In the Hamburg-Le Havre range, many examples of expansion projects in ports of different sizes are present, e.g. Maasvlakte 2 in Rotterdam and the planned Saeftinghe dock in Antwerp. The question remains if increased waiting-time aversion leads to delaying capacity expansions of already active ports as well. One could expect that the management of the port would have an incentive to anticipate the investment in such a case, in order to reduce the congestion already present when the instrument of congestion pricing cannot be exploited any further in a profitable way. This is opposed to a greenfield port project.

Additionally, it takes a lot of time to build large infrastructure projects such as port capacity investment projects (Meersman & Van de Voorde, 2014a; Vanelslander, 2014; Aguerrevere, 2003). This period between making the investment and project completion, which coincides with the start of the operation of the newly added capacity, is defined here as the construction lead time. During this construction lead time, the performance of the market and hence the project's profitability could change due to the uncertainty of demand. This also has an impact on a port's investment decision and needs to be considered. However, it is assumed here that the construction, also referred to as installation, of the additional capacity has no impact on the operation of the already existing port facilities. This is plausible when the port is expanded with large docks directly accessible from the sea or river (with or without an additional lock).

In order to analyse investment decisions under uncertainty, the real options (RO) approach is better suited than the more traditional net present value approach (Dixit & Pindyck, 1994). Even if uncertainty is low or absent, the NPV rule can be (very) wrong, due to its underlying assumption that investing in an irreversible project is a now-or-never decision. In reality, managers have the

[1] A terminal for food containers (reefers) has more waiting-averse customers than a terminal for containers with toys.

flexibility to postpone investment, e.g. in order to gain more information about the uncertain environment. This underlying option has a value, that is overlooked by the NPV rule. Real options models offer a more appropriate method to evaluate flexible investments under uncertainty and make better investment decisions. RO models monetarily quantify the value of managerial flexibility to react to uncertainty in the best possible way. Only when these options are considered in project appraisal, the investment decision can be valued correctly. To this end, RO models use stochastic calculus and dynamic programming to optimise an objective function including a random term with respect to the investment decision variables (Dixit & Pindyck, 1994).

The available RO literature considering some amount of construction lead time and studying its impact by comparing with cases where the time to build is zero, is however rather limited. Although Dixit & Pindyck (1994) and Kydland & Prescott (1982) already indicated the important implications of time to build on investment decisions, Marmer & Slade (2018) more recently argued again that investment lags should be given more attention in theoretical and empirical work. In his study for non-storable commodities, Aguerrevere (2003) found an ambiguous relationship between the time to build and the size of the investment project. Moreover, he found that introducing time to build leads to the observation that firms anticipate their capacity expansion to moments before current capacity is fully occupied. Also Bar-Ilan & Strange (1996) found that higher construction times lead to earlier investments in a production environment. Moreover, time to build influences the effect of uncertainty on the timing of the investment. Whereas traditional RO analysis demonstrates that increased uncertainty leads to delaying the investment, increased uncertainty in combination with time to build may lead in some cases to anticipating the investment timing. This illustrates the importance of considering time to build in the model. Majd & Pindyck (1987) and Milne & Whalley (2000) quantified the option value of altering the construction lead time through the use of a different technology.

The objective of this paper is to analyse the impact of time to build and the (theoretical design) capacity already in place on the port capacity expansion decision under uncertainty. In this paper, the port under consideration, which can be owned privately, publicly or by a combination of both, has the option to invest in one port expansion project,[2] which is fully deployed in one phase.[3] The project consists of expansion of the port infrastructure (e.g., dock and quay walls) and the irreversible elements of the superstructure (e.g., pavements) at this dock. To value this investment option, a continuous time and state RO approach is used. Since growth, uncertainty, public money involvement and congestion considerably influence the investment decision, the impact of changes in these economic characteristics on the investment decision needs to be studied. These additions to the academic literature will allow practitioners to make well-considered port investment decisions, taking into account as much relevant information as possible.

In order to focus on the impact of time to build on the (unrestricted) optimal expansion decision of a port, port competition is left beyond the scope of this paper. The same holds for the division between terminal operators and the port authority in a landlord port, which is beyond the scope of this paper as well. Focusing on a service port, which is owned and operated by one single actor, namely the port authority (PA), and omitting competition allows for better mathematical tractability of the model. Moreover, it allows to compare the results from this paper with the results of Balliauw et al. (2020), who present a base case of the modelling used in this paper. In

[2] The expansion project involves a new dock in an existing port. This is sometimes called greenfield expansion, as opposed to brownfield expansion. In this paper however, greenfield refers to a new port, built from scratch, whereas expansion refers to (greenfield) expansion.

[3] Since phased investment analysis requires a different modelling approach, this is beyond the scope of this paper, and should be considered the main point of focus of a follow-up study.

order to extend this paper's model to a duopoly case, the approach of Balliauw, Kort, & Zhang (2019) and Huisman & Kort (2015) can be followed. In case of small cost differences, inter-port competition and resulting preemption strategies drive the option value down. This leads to an anticipated investment timing of the first investor, the leader in a Stackelberg leader-follower competition model. If at the moment of investment, the market is too small to be served by additional ports, the leader will deter investment of the other port, denominated the follower. If the market is large enough for two active ports, the size of the leader's investment will be smaller in order to accommodate the investment of the follower port. The insights from a landlord port can be retrieved from Balliauw, Kort, Meersman, et al. (2019) and are complementary to the investment optima found in this paper.

The structure of this paper is as follows. Section 2 outlines the basic model to determine the value of an investment in port capacity expansion with time to build. The analysis starts from the more easy-to-analyse greenfield project without time to build, to subsequently introduce and focus on the specific implications of considering time to build in expansion projects. Section 3 describes how the optimal investment thresholds are determined according to the real options approach. The parameters used for the numerical simulations are given in Section 4, followed by a discussion of the results in Section 5. The final section gives the main conclusions and presents avenues for future research.

2 Basic model for determining the expansion project value, including time to build

In this paper, a service port is considered. This port model is opposed to a landlord port, where the terminals are operated by a different actor than the one owning the port. In order to determine the (net present) value of an investment project, for which a certain investment cost is paid, the following steps are needed. First, for a private port, the optimal profit generated by the project at each point in time is calculated, by maximising the difference between revenues and costs with respect to throughput. This maximisation is influenced by the uncertain demand and the aversion to waiting of the port customers. For a public port, not profit, but social welfare at each point in time is maximised. These instantaneous profits or social welfares are subsequently discounted and summed over time using an integral in order to derive the net present value of the project.

The following inverse demand function relating the full price or gross willingness to pay, $\rho(t)$, to throughput $q(t)$ at time t is assumed:

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

with B the slope of the inverse demand function $\rho(t)$. Here, this slope is normalised to 1. $X(t)$ is the intercept of this function and follows a geometric Brownian motion (GBM) to express the uncertainty in demand:

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

with $\mathrm{d}Z$ the increment of a standard Wiener process. The parameter modelling the drift as a proxy for economic growth is μ, whereas σ expresses the drift variability or uncertainty. The GBM has been proven a good approach to model uncertain demand in established services such as the transportation service (Lindsey & De Palma, 2014; Marathe & Ryan, 2005). In the remainder of this paper, the temporal dependencies will be omitted for the sake of readability.

The full price ρ is the sum of the price p paid by the port customers to have their ships loaded and unloaded *plus* additional costs incurred at the port (Xiao et al., 2012). In this paper, this extra cost for the shipping companies is the cost of congestion. It is caused by ships that need to wait in a port due to high capacity occupancy rates. Hence, the price to handle one twenty-foot equivalent unit (TEU) can be written as

$$p(t) = X(t) - Bq(t) - AX(t)\frac{q(t)}{K^2}. \tag{3}$$

The unit cost of congestion is modelled by the latter term, to express that the willingness to pay of customers is reduced if congestion is higher, since they are waiting-time averse (Blauwens et al., 2016). According to queuing theory insights from De Borger & Van Dender (2006); Yuen et al. (2008); Xiao et al. (2012); Zhang & Zhang (2006); Chen & Liu (2016), total congestion costs equal $AX(q/K)^2$ (Balliauw, Kort, & Zhang, 2019). Total congestion costs are increasing in the occupancy rate, i.e., throughput divided by design capacity. In this research, total congestion costs vary with the square of the occupancy rate, $(q/K)^2$, which is used as a proxy for waiting time (Zhang & Zhang, 2006; De Borger & Van Dender, 2006; De Borger & De Bruyne, 2011; De Borger et al., 2005, 2007). The average congestion cost per unit from Equation (3) is then found by dividing total congestion costs by q.

Xiao et al. (2012), De Borger & Van Dender (2006), Yuen et al. (2008) and Chen & Liu (2016) make delays D linearly dependent on capacity occupancy. However, queuing theory in ports shows that congestion only starts at occupancy rates of about 50%, and increases sharply beyond 75% to 80% (Blauwens et al., 2016; Kauppila et al., 2016). The specification of Zhang & Zhang (2006) reflects this insight by letting delay depend on a scale factor *times* $q/[K(K-q)]$. It builds on estimates from steady-state queuing theory, with the underlying assumption of Poisson distributed arrivals (Lave & DeSalvo, 1968). Four conditions are satisfied in the work of Zhang & Zhang (2006):

$$\frac{\partial D}{\partial q} > 0, \frac{\partial D}{\partial K} < 0, \frac{\partial^2 D}{\partial q^2} > 0, \frac{\partial^2 D}{\partial q \partial K} < 0. \tag{4}$$

The above conditions are crucial for a good implementation of queueing theory insights in a port. However, the condition $\partial^2 D/\partial q^2 > 0$ does not hold for the linear specification on the one hand. On the other hand, the specification of Zhang & Zhang (2006) involves one important disadvantage, namely that delays, and hence costs as well after a multiplication with a monetary scale factor, become infinite at full occupancy. This is not observed in reality either. A functional specification that highly resembles the specification of Zhang & Zhang (2006) would be a higher-order term of occupancy in the delay function, such as a fourth- or fifth-order term. This would satisfy all conditions of Zhang & Zhang (2006) in Equation (4), whereas full occupancy would not ex-ante be excluded. However, the analytical optimisations performed in this paper would become infeasible, due to quantity flexibility involving not only aggregate project value, but also instantaneous profit maximisation.[4] A second-order dependency would already be more realistic than the linear relationship, and would also satisfy the required conditions. However, calculations would still be too complicated. Therefore, a proxy for q is needed in order to substitute a factor q in $q \cdot q$. Since the uncertain reservation price, X, is positively correlated with the optimal throughput at any point in time, it is a good proxy for q. Hence in this paper, q^2 is substituted by $X \cdot q$ and the conditions in Equation (4) still hold (Balliauw et al., 2020). The advantage of this approach where congestion costs are linked to the state of the market are further elaborated upon in Balliauw (2020).

[4]In this paper, quantity is assumed flexible and can be adapted to the market circumstances. This is opposed to throughput either being fixed at zero or maximum capacity (Hagspiel et al., 2016). The maximisation of profit with respect to the optimal quantity would involve a sixth order function to be maximised. Even a second-order dependency on occupancy would involve a third-order function in this optimisation.

Subsequently, monetary scale factor A transforms delays into costs (Xiao et al., 2012; Balliauw et al., 2020). Factor A depends on the port users and goods categories involved (Yuen et al., 2008). The monetary scale factor is an expression of the value of time (De Jong, 2007) and is higher for shipping companies that transport goods which are more urgently needed or more impacted by time and for shipping companies with more stringent sailing schemes. In such cases, congestion poses a higher problem for the port user. Moreover, in this paper's model, the excess growth of delay costs compared to the customers' willingness to pay, reflected by A, is assumed fixed over time. This is reasonable due to a relatively stable liner customer base in a port (Verhoeven, 2015; Heaver et al., 2001). Therefore, including X in the congestion cost function involves an important benefit. The excess growth of X, compared to the growth of q, takes into account future increasing values of time (De Jong, 2007). Moreover, this approach ensures that congestion costs and customers' willingness to pay evolve in a similar direction.

The profit generated in the port can be calculated as

$$\pi(X, K, q) = pq - cq - c_h K, \tag{5}$$

with c the constant marginal operational cost of handling one extra TEU and c_h the constant marginal capacity holding cost, defined as the cost to maintain the capacity K in place at its current level.

The PA is however not always privately owned (Suykens & Van de Voorde, 1998). Also a public government could own shares of the PA. A public government would not only consider profits, but would maximise social welfare:

$$SW = \pi_{\mathrm{PA}}(X, K, q) + \lambda q + s_{CS} \cdot Bq^2/2, \tag{6}$$

with λ the spillover benefit for the local economy per unit q, s_{CS} the share of consumer surplus considered by the government (e.g. at city or country level) and $Bq^2/2$ the consumer surplus as calculated in Xiao et al. (2012). This leads to the following PA's operational objective function, which is the weighted sum of the owners' objectives:

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

with s_G the relative number of PA shares owned by the government. (Xiao et al., 2012)

Throughput should always be greater than or equal to zero. As a result, q^{opt} is set to 0 in case of an optimal throughput level below zero (Dangl, 1999). Design capacity K however is not considered a hard constraint for the throughput level, to allow for the exceptional case wherein throughput exceeds capacity at a high cost (Balliauw, Kort, & Zhang, 2019). As a result, q^{opt} is defined in two regions R_j for X: $R_1 = [0, c - s_G\lambda)$ and $R_2 = [c - s_G\lambda, \infty)$. Applying the first order condition to Π leads to the optimal throughput level q^{opt} at each point in time:

$$q^{opt}(X, K) = \begin{cases} 0, & X < c - s_G\lambda, \\ \dfrac{[X - (c - s_G\lambda)]K^2}{2(AX + BK^2) - s_G s_{CS} BK^2}, & X \geqslant c - s_G\lambda. \end{cases} \tag{8}$$

Subsequently, the optimal $\overline{\Pi}(X, K) = \Pi(X, K, q^{opt}(X, K))$ can be calculated in the same two regions as well (Hagspiel et al., 2016).

In order to calculate V', the value of a greenfield project without time to build, the steps described by Dixit & Pindyck (1994) can be followed. This is the most easy case to study and is extended with time to build in expansion projects in Equations (14)-(16). First,

$$V' = \mathbf{E} \int_0^\infty \max_q \{\Pi(T + \tau)\} \mathrm{e}^{-r\tau} \mathrm{d}\tau, \tag{9}$$

with r the discount rate and T the timing of the investment, is rewritten as a dynamic programming problem as follows:

$$V'(X,K) = \overline{\Pi}(X,K)\mathrm{d}t + \mathrm{e}^{-r\mathrm{d}t}\,\mathbf{E}(V'(X,K) + \mathrm{d}V'(X,K)). \tag{10}$$

To this equation, Itô's Lemma and the Bellman Equation (Dixit & Pindyck, 1994) are applied in order to arrive at a differential equation for the project value $V'(X,K)$ as a function of the value of X at the moment of investment and the installed, i.e. built, capacity K:

$$\frac{\sigma^2}{2}X^2\frac{\partial^2 V'}{\partial X^2}(X,K) + \mu X\frac{\partial V'}{\partial X}(X,K) - rV'(X,K) + \overline{\Pi}(X,K) = 0. \tag{11}$$

By solving this equation in each region R_j for X ($j = 1,2$), the following solution for V' is derived:

$$V'(X,K)|_{X\in R_j} = V'_j(X,K) = G_{j,1}(K)X^{\beta_1} + G_{j,2}(K)X^{\beta_2} + \overline{V}'_j(X,K), \tag{12}$$

with $\overline{V}'_j(X,K)$ a particular solution of differential equation (11) with $\Pi = \Pi_j$ (see Balliauw et al. (2020) for additional background and the mathematical derivation). The factors $G_{j,i}$ are parameters that can be determined through the boundary conditions. The roots β_1 and β_2 equal

$$\beta_1 = \frac{\frac{\sigma^2}{2} - \mu + \sqrt{\left(\frac{\sigma^2}{2} - \mu\right)^2 + 2r\sigma^2}}{\sigma^2} > 1, \qquad \beta_2 = \frac{\frac{\sigma^2}{2} - \mu - \sqrt{\left(\frac{\sigma^2}{2} - \mu\right)^2 + 2r\sigma^2}}{\sigma^2} < 0. \tag{13}$$

Because $\beta_2 < 0$, $G_{1,2}$ equals 0 and in order to avoid speculative bubbles, $G_{2,1}$ needs to equal 0 as well. The values of the other two $G_{j,i}$'s, representing the option to start or stop operations, can be determined using smooth pasting and value matching conditions (Dixit & Pindyck, 1994).

The value function $V'(X,K)$ is however not sufficient to determine the optimal size and timing of the investment of the described port. In order to account for (i) the amount of capacity already present in expansion projects, and (ii) the construction lead time between making the investment and the project completion, two additional elements are included in the model, more specifically by adapting $V'(X,K)$.

Expansion project First, Eq. (12) determined V', the value of a greenfield project with existing capacity $K_0 = 0$. The value of an expansion project of size ΔK with existing capacity K_0 is calculated as the difference in value V' after and before installing the expansion project at the moment that the demand shift parameter equals X, resulting from the additional cash flows generated by the expansion from the moment of project completion on:

$$\Delta V'_j(X,\Delta K,K_0) = V'_j(X,K_0+\Delta K) - V'_j(X,K_0), \tag{14}$$

with $V'_j(X,0) = 0$, so that $\Delta V'_j(X,\Delta K,0) = V'_j(X,\Delta K)$.

Construction lead time Second, during the construction lead time, denoted by θ and assumed independent of the size of the expansion,[5] the market changes in an uncertain way, as is expressed by the GBM for demand shift parameter X. As a result, the project value will be different from what its value would have been if the construction lead time had equalled zero.

To account for the uncertainty impacting demand during the time to build a project, the expected evolution during this period of the uncertain parameter X following a GBM needs to be

[5] The impact of this assumption on the results is discussed in Section 5.1.

included in the model. Assuming that X was equal to X_0 at time $t = 0$, the probability density function for X at time $t = \theta$ is given by:

$$\phi(X, X_0, \theta) = \frac{1}{\sqrt{2\pi}} \frac{1}{X\sigma\sqrt{\theta}} \exp\left(-\frac{\left(\ln X - \ln X_0 - \left(\mu - \frac{1}{2}\sigma^2\right)\theta\right)^2}{2\sigma^2\theta}\right). \quad (15)$$

Using this information, the discounted expected value $\Delta V(X, \Delta K, K_0, \theta)$ of an expansion project with size ΔK and existing capacity K_0, installed at the moment that the demand shift parameter equals X and taking θ years to complete can be calculated as follows (Aguerrevere, 2003):

$$\begin{aligned} \Delta V(X, \Delta K, K_0, \theta) \quad = \quad & e^{-r\theta} \left[\int_0^{c - s_G\lambda} \phi(X', X, \theta) \cdot \Delta V_1'(X', \Delta K, K_0) \, \mathrm{d}X' \right. \\ & \left. + \int_{c - s_G\lambda}^{\infty} \phi(X', X, \theta) \cdot \Delta V_2'(X', \Delta K, K_0) \, \mathrm{d}X' \right]. \end{aligned} \quad (16)$$

The integrals together calculate the weighted average project value for each possible value of X over the different regions for X. The probability density function of X is used to determine the weights. The first factor, discount factor $e^{-r\theta}$, is required to account for the construction lead time θ during which no cash flows are generated. This time lag is situated between the moment the investment is made and the start of port operations at the site, immediately after project completion.

3 Determining the optimal project investment size and timing

Applying dynamic programming to the model developed in the previous section allows determining the optimal size and timing of the expansion project (Dixit & Pindyck, 1994). The investment problem objective function comes down to maximising the expected future discounted profit stream minus the investment outlay of the project with respect to the timing T, where $X(t = T) \underset{\nearrow}{=} X_T$, and the expansion size is ΔK (Huberts et al., 2015). If $X(t = 0) < X_T$ so that it is not optimal to invest from the beginning, the investment problem objective function is given by the following equation:

$$\max_{T \geqslant 0, \Delta K \geqslant 0} \mathbf{E} \left\{ \left[\Delta V(X_T, \Delta K, K_0, \theta) - I(\Delta K) \right] \mathrm{e}^{-rT} | X(t = 0) = X \right\}, \quad (17)$$

with $I(\Delta K)$ the investment cost of one single project for installing or expanding port capacity. Typically, such an investment cost is given by the following function:

$$I(\Delta K) = FC_I + \gamma_1 \Delta K - \gamma_2 \Delta K^2 + \gamma_4 \Delta K^4. \quad (18)$$

The negative second order term indicates economies of scale in the investment size, whereas the fourth order term reflects a boundary beyond which further expansion becomes extremely costly, e.g., following the need to expropriate houses. The latter is a consequence of a limited amount of land available for port expansion, which in turn has a high opportunity cost (Balliauw, Kort, & Zhang, 2019; Haralambides, 2002).[6]

[6]Note that this investment cost function applies to one port project. It does not represent the expansion path of a port over time, as that is lumpy and can never be continuous due to the characteristics of port investments. Moreover, a fourth order term yields a more realistic shape than a third order function, of which the first order derivative is symmetrical about the inflection point.

According to Dangl (1999), the optimal investment decision can be calculated through option value

$$F(X) = \max\{\mathrm{e}^{-r\mathrm{d}t}\,\mathbf{E}(F(X) + \mathrm{d}F(X)), \max_{K}[\Delta V(X, \Delta K, K_0, \theta) - I(\Delta K)]\}. \tag{19}$$

Here, the left argument is the value of waiting, which is the option value as long as $X < X_T$. As soon as X exceeds for the first time the critical threshold X_T, which maximises the investment problem objective function, it becomes optimal for the port to invest and the value of the option equals the return of the investment (also, see Dixit & Pindyck (1994) for a more detailed explanation of the real options methodology). The capacity of the expansion (ΔK) is chosen such that this return of the investment is maximised. If $X > X_T$ from the beginning ($t = 0$), investment takes place immediately.

The optimal size of the expansion project $\Delta K^*(X, K_0, \theta)$, given the capacity already present and the time to build it, is determined through the first order condition. The marginal value should equal the marginal cost of installing additional capacity as follows:

$$\frac{\partial \Delta V}{\partial \Delta K}(X, \Delta K, K_0, \theta) = \frac{\partial I}{\partial \Delta K}(\Delta K). \tag{20}$$

Also the second order condition needs to hold here. This optimisation corresponds to the inner maximisation of Eq. (19).

The outer maximisation of Eq. (19), through applying value matching and smooth pasting conditions, leads to the optimal timing, expressed as optimal threshold $X_T^*(\Delta K, K_0, \theta)$. The optimal investment strategy involving both size and timing ($X_T^{**}(K_0, \theta)$, $\Delta K^{**}(K_0, \theta)$) is finally determined through solving the system

$$\begin{cases} X_T^{**}(K_0, \theta) = X_T^*(\Delta K^{**}(K_0, \theta), K_0, \theta), \\ \Delta K^{**}(K_0, \theta) = \Delta K^*(X_T^{**}(K_0, \theta), K_0, \theta). \end{cases} \tag{21}$$

All these decision variables remain functions of existing capacity K_0 and time to build θ.

The assumptions underlying the model are summarised in Table 1

4 Setting the parameters

The equations making up the model are summarised in Table 2, including the numerical values for the different parameters. The initial capacities of a port before expansion are set to zero, five, ten or fifteen million TEU per year, representing respectively a new port, medium-sized ports such as Bremen or Valencia, large ports such as Rotterdam or Antwerp, or even larger Chinese ports (Vlaamse Havencommissie, 2016). The expansion decision deals with a new container terminal with an annual theoretical design capacity of about 8 to 14 million TEU per year, such as Deurganckdok or Saeftinghedok in Antwerp (Port of Antwerp, 2016; Vanelslander, 2014) and Maasvlakte 2 in Rotterdam (Zuidgeest, 2009). Based on these examples, the respective investment costs are estimated to amount to about one to three billion euro, depending on the construction technology used. The time to build a new dock of the aforementioned size can amount to three years or more, as a result of various uncertain factors such as political decisions and environmental actions. This led to a final construction lead time of six years for the Deurganckdok (1999-2005), which was longer than initially planned. The Maasvlakte 2 project in Rotterdam took five years to complete (2008-2013) (Port of Rotterdam, 2018), whereas the construction time of the Liverpool 2 construction project was only three years (Ship Technology, 2018). In this paper, time to build is varied between zero and six years, to study the impact of an increase of time to build on the

Table 1: Overview of the model assumptions.

Topic	**Assumption(s)**
Project type?	Port expansion
Capacity constraint?	Soft constraint
Port type?	Public and/or private service port*
Port competition?	No (1 port in model)
Time to build?	Included in the model
Phased investment?	Project installed at once
General assumptions	Price (sum of port dues and terminal tariff) transparency → Linear additive inverse demand function
	Demand uncertainty, modelled using a GBM with constant, independent growth (μ) and uncertainty (σ) parameters
	Growth market with $r > \mu > 0$, to ensure RO model convergence**
	Poisson-distributed ship arrivals at the port: delays start at about 50% and increase sharply beyond 75-80% occupancy
	User congestion costs depend on dock users' average value of time. This value of time follows the same trend as the market, which is increasing in this paper's setting.
	Investment cost: increasing fourth order polynomial with economies of scale and size boundary
	Deterministic, linear operational and capacity holding costs
	Flexibility of investment timing and size → Option to postpone the investment
	Once-and-for-all investment decision with flexible throughput levels
	Infinite project life time (maintenance executed)
	Capacity expansions are available and operated immediately after completion.
	Construction of additional capacity has no impact on the operation of already existing port facilities.

*: Owned and operated by one single actor.

**: Condition $r > \mu$ leads to a finite timing decision, instead of infinite investment postponement. Sensitivity tested with negative growth rates as well.

SCOPE: Theoretical design capacity for container throughput services. Other port services disregarded (sufficiently present or realised by actors other than the PA or terminal operators). Focus on lumpy investment in port infrastructure and irreversible elements of superstructure.

Table 2: Model overview.

Variables		
p	$=$	price
q	$=$	throughput
$K = K_0(\in \{0, 5, 10, 15\}) + \Delta K$	$=$	total capacity after investment
	$=$	existing capacity *plus* capacity expansion
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
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
Investment cost $I = FC_I + \gamma_1\Delta K - \gamma_2\Delta K^2 + \gamma_3\Delta K^3 + \gamma_4\Delta K^4$		
$FC_I(= 80)$	$=$	fixed investment cost
$\gamma_1(= 180)$	$=$	first order coefficient
$\gamma_2(= 19)$	$=$	coefficient reflecting economies of scale of investment cost
$\gamma_3(= 0)$	$=$	omitted third order coefficient
$\gamma_4(= 0.12)$	$=$	coefficient posing boundary to maximum size of the project
Time to build the project $\theta(\in \{0, 1, 2, 4, 6\})$ years		
Operational objective function $\Pi = \pi + s_G \cdot \lambda q + s_G s_{CS} \cdot CS$		
π	$=$	port profit $= pq - TC$
$\lambda(= 0.4)$	$=$	spillover benefits per unit q
CS	$=$	consumer surplus, i.e. $Bq^2/2$
$s_G(\in [0; 1])$	$=$	share of port owned by the government
$s_{CS}(\in [0; 1])$	$=$	share of total CS taken into account by the government

investment decision. It would in the described model and calculations also be possible to make time to build dependent on the size of the investment:

$$\theta = \Theta \Delta K. \tag{22}$$

This has not been done in this paper, since the focus is on large projects only, with a wide range of construction lead times. Nevertheless, doing this would not alter the findings qualitatively. The quantitative impact would be negligible too, as can be seen in one elaborated example in Section 5.1.

The other parameters in this paper are determined as follows. The growth and uncertainty are estimated by regressing an exponential trend on container throughput data from the ports of Antwerp and Rotterdam between 2010 and 2015 (Vlaamse Havencommissie, 2016). The growth rate of the estimated exponential growth model is positive and lies between 1.5 and 2%. It is significant at the 5% level. The root of the squared error is close to 15%. Therefore, σ is set to 10 and 15% in this paper. For the discount rate, the same 6% of Aguerrevere (2003) is used. Throughput and capacity (q, K_0 and ΔK) are in million TEU per year, while price p, marginal operational cost $c(=1)$ and capacity holding cost $c_h(=0.5)$ are given in euro per TEU (Vergauwen, 2010; Meersman & Van de Voorde, 2014b; Wiegmans & Behdani, 2018). This, moreover, reflects that operational variable costs (c) in infrastructure projects are relatively low (Wiegmans & Behdani, 2018). Based on Estache & Trujillo (2009), Benacchio & Musso (2001) and Coppens et al. (2007), the spillover effects per TEU are estimated at 40% of the operational cost, leaving λ at 0.4. The share of public ownership and the share of consumer surplus are varied between 0 and 1.

The most difficult parameter to estimate, is A, the monetary scaling factor of the congestion cost. A is set to 5, to model a significant impact of congestion on the price level, at the same time resulting in realistic price levels (Vergauwen, 2010; Meersman & Van de Voorde, 2014b).[7] It should be kept in mind that estimating the project's exact A is not the objective of this paper. However, by varying A in the sensitivity analysis, the impact of a change in congestion cost can be analysed.

Next to varying initial (existing) port capacity K_0, time to build θ and monetary scaling factor A, sensitivity of the results with respect to growth rate μ, uncertainty σ, relative amount of PA shares owned publicly, s_G, and the relative share of total consumer surplus considered, s_{CS}, is studied in the next section as well.

5 Results and discussion

The numerical model solutions in Tables 3 - 5 allow analysing the impact of a number of project and economic characteristics on the final investment decision of a port. In the following subsections, the impact of time to build, existing capacity and public ownership are numerically calculated, since no analytical solutions can be obtained. Next to a base case, sensitivity analyses under different congestion costs, growth and uncertainty on the expansion decision are performed, which

[7] For $A = 5, X = 37$ euro per TEU, $K = 11$ M TEU p.a., $c = 1$ euro per TEU and $B = 1$, the throughput q would equal 7.11 M TEU p.a. This yields an occupancy rate of 68%. The congestion cost per TEU would on average equal about 11 euro per TEU (AXq/K^2). This seems plausible, compared with the value of about 40 euro per container (not per TEU) per hour (De Jong, 2007) and given that congestion will not yet pose a too large problem in this example. Moreover, in the more highly congested ports of Antwerp and Rotterdam, a congestion charge of about 20 euro per container has been imposed temporarily (CONTARGO, 2018). This validates the plausibility of the selected values for A.

allow to verify these characteristics' impact on the investment decision as well. The structure of the following tables is as follows: the base case in each table, which corresponds to a specific ownership structure, allows for comparison with the situations in which one additional parameter is altered. These altered parameters are respectively the monetary scaling factor, the uncertainty and the growth rate.

5.1 The impact of time to build

Projects involving longer construction lead times, i.e. a higher θ, are installed later in most of the cases. This finding is analogous to the outcome of an increase in uncertainty. If time to build were higher, the exposure to uncertainty would be higher too, because more time without profit flows passes after the investment decision. During this time, demand follows an uncertain path. This has an uncertain impact on the present value of the future profit flow. As a result, the reaction to this increased uncertainty is to postpone the investment, when the market is larger, in order to increase the probability of sufficiently high profits.

However in some cases, increased time to build leads to anticipating the investment, especially compared with cases with an investment threshold X_T that is already relatively high. This can be explained by the fact that time to build also encompasses an incentive to anticipate the investment. The reason is that the present value (PV) of the future profit flow will be relatively lower due to this construction lag between making the investment and project completion. Moreover, the stochastic discount factor increases more than linearly in the investment threshold (Huisman & Kort, 2015). In order to avoid higher discounting of the future profit flows and prevent a too low project value, ports may react by investing earlier. Aguerrevere (2003) in this light shows that also firms without congestion costs expand before their infrastructure is fully occupied because of the time to build.

The main impact of time to build on the investment decision can be summarised as follows:

Result 1 *Under the assumptions given in Table 1, the port adapts its strategy by installing less capacity and / or investing at a later moment if the construction lead time is higher, because the latter reduces the project's attractiveness.*

In some example expansion projects, an opposed impact of time to build on the final project size or timing decision is however observed. In Table 3 in the base case for example, the expansion of a port with existing capacity of 5 million TEU per year and construction lead time of one year is installed later, but the size of the project is smaller than in case there were no construction lead time. Such an observation where both primary effects (smaller project and later timing) are strong, is uncommon in the RO literature, where the positive relationship between investment size and timing often dominates in the final investment optimum. Hence, it is more common in RO that the project size is larger when investment takes place at a moment when the market has grown more, i.e. later, or vice versa. Examples of this common RO observation are found in the same base case in Table 3. If the construction lead time were one year, a port with existing capacity of 15 million TEU per year would install a smaller project earlier than in a case without time to build. Oppositely, a greenfield project with one year of construction lead time would be larger and installed later than a greenfield project without time to build. This ambiguous impact of time to build on the investment decision is in line with the findings of Aguerrevere (2003).

The previous examples illustrate the existence of a so-called double delay. There is a first delay between *now* and the investment moment and a second delay between the investment moment and the availability of the new capacity, which is immediately after project construction completion. The double delay leads to three opposing effects. First, the longer delay leads to increased uncertainty, which results in postponing the investment. Second, this delay reduces the project's attractiveness, due to higher discounting, in turn leading to investment postponement. Finally, ports will also seek to compensate for the longer delay by anticipating the investment. The final, net result is the outcome of the interaction of these three effects and is ambiguous.

The ambiguity of the time-to-build effect also causes in some cases a non-monotonic relationship between the length of the construction lead time and the timing of the investment. An example of this relationship is found in the base case with $K_0 = 15$ in Table 3. It seems that at lower construction lead times, the anticipation effect dominates. In order to make up for a later project delivery, the investment timing decision is anticipated. However, at higher construction lead times, it seems that the increased uncertainty effect due to longer construction lead times dominates, leading to postponing the investment timing.

In order to test for the sensitivity with respect to the specification of time to build, the optimal strategy for the base case with $K_0 = 10$ and $\theta = 6$ is calculated for an alternative scenario. If time to build would equal $0.6\Delta K$, the optimal investment strategy would not equal (40.24, 10.28), but it would be (40.28, 10.27). If however $\theta = 6\Delta K/10.28$, the original optimum would even be retained. This shows that the impact of including the decision variable ΔK in the time to build is negligible, as long as the considered time to build itself remains the same.

5.2 The impact of existing port capacity

Next to time to build, the amount of existing capacity in the port also has an impact on the optimal investment decision. This impact of existing capacity is derived from the calculated optima in Tables 3-5 and is summarised as follows:

Result 2 *Under the assumptions given in Table 1, it takes more time before a port with a higher current capacity becomes too highly occupied. Hence, it is possible to postpone capacity expansion longer in order to reduce the costly congestion in the port. Because of the positive relationship between investment timing and size, the installed capacity will also be larger.*

In the results, an important difference is observed between cases with existing capacity exceeding the size of an optimal greenfield project and cases with less existing capacity than this optimal greenfield project with all other economic parameters equal. If the existing capacity is below the optimal capacity that would be installed in a one-shot greenfield investment project, too much costly congestion will arise soon and expansion is required sooner than the optimal investment timing of the corresponding greenfield project. Because of the earlier timing, and because some capacity is already present, the size of the expansion will also be lower than the size of the greenfield project. However, total capacity after expansion $(K_0 + \Delta K^{**}(K_0, \theta))$ will be higher than the size of the optimal greenfield project. This is partly explained by the fact that the port will strive to adapt the investment size to benefit as much as possible from the investment size scale economies. Moreover, each expansion encompasses the installation of free, initially unused, capacity to attract the shipping lines. As a result, the finding of Chronopoulos et al. (2017) is confirmed, that stepwise investment leads to the investment in more capacity than when the capacity is to be installed at once. However, if existing capacity exceeds the size of the optimal greenfield project $(K_0 > \Delta K^{**}(0, \theta))$, the timing of the expansion will be later than the timing of the optimal greenfield project. Depending on how much higher the optimal threshold for X is, the size of the project will be higher or lower than the size of the optimal greenfield project. In

Table 3: Optimal investment strategies $(X_T^{**}(K_0,\theta), \Delta K^{**}(K_0,\theta))$ under different construction lead times and initial capacities in a private port.

Base case.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(37.71, 11.19)	(31.83, 10.03)	(39.01, 10.46)	(49.46, 11.17)
Time	$\theta = 1$	(38.57, 11.20)	(32.20, 10.02)	(39.16, 10.43)	(49.41, 11.11)
to	$\theta = 2$	(39.47, 11.21)	(32.59, 10.02)	(39.33, 10.40)	(49.39, 11.06)
build	$\theta = 4$	(41.40, 11.23)	(33.45, 10.00)	(39.74, 10.34)	(49.40, 10.95)
	$\theta = 6$	(43.52, 11.25)	(34.40, 9.99)	(40.24, 10.28)	(49.48, 10.84)

A set to 4.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(34.20, 10.98)	(31.11, 10.01)	(40.00, 10.61)	(52.16, 11.44)
Time	$\theta = 1$	(34.91, 11.00)	(31.41, 10.00)	(40.08, 10.57)	(52.01, 11.38)
to	$\theta = 2$	(35.66, 11.01)	(31.73, 9.99)	(40.19, 10.53)	(51.89, 11.31)
build	$\theta = 4$	(37.25, 11.04)	(32.42, 9.98)	(40.45, 10.46)	(51.72, 11.19)
	$\theta = 6$	(39.00, 11.07)	(33.21, 9.96)	(40.80, 10.40)	(51.56, 11.07)

σ set to 0.15.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(56.42, 13.47)	(43.64, 11.89)	(56.10, 12.94)	(78.61, 14.73)
Time	$\theta = 1$	(57.48, 13.46)	(43.83, 11.84)	(55.56, 12.81)	(76.74, 14.49)
to	$\theta = 2$	(58.54, 13.44)	(44.06, 11.79)	(55.08, 12.69)	(71.85, 13.97)
build	$\theta = 4$	(57.16, 13.04)	(44.48, 11.69)	(52.69, 12.30)	(61.36, 12.82)
	$\theta = 6$	(53.68, 12.42)	(43.77, 11.44)	(48.77, 11.73)	(54.44, 11.98)

μ set to 0.02.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(42.75, 12.47)	(34.84, 11.16)	(44.16, 11.97)	(59.43, 13.29)
Time	$\theta = 1$	(43.45, 12.47)	(35.00, 11.13)	(43.95, 11.90)	(58.69, 13.16)
to	$\theta = 2$	(44.18, 12.47)	(35.19, 11.10)	(43.77, 11.83)	(58.00, 13.04)
build	$\theta = 4$	(45.77, 12.46)	(35.62, 11.05)	(43.49, 11.69)	(56.76, 12.81)
	$\theta = 6$	(47.49, 12.46)	(36.15, 11.00)	(43.31, 11.57)	(55.09, 12.53)

μ set to -0.01.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(37.74, 9.21)	(32.46, 8.02)	(38.48, 7.98)	(46.63, 8.12)
Time	$\theta = 1$	(39.62, 9.24)	(33.74, 8.04)	(39.72, 7.99)	(47.97, 8.12)
to	$\theta = 2$	(41.62, 9.26)	(35.08, 8.06)	(41.03, 8.00)	(49.37, 8.12)
build	$\theta = 4$	(46.00, 9.31)	(37.98, 8.10)	(43.83, 8.02)	(52.34, 8.13)
	$\theta = 6$	(50.96, 9.35)	(41.21, 8.14)	(46.90, 8.03)	(55.58, 8.13)

Base case parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.10, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, s_G = 0, s_{CS} = 0, \lambda = 0.4.$

Table 4: Optimal investment strategies $(X_T^{**}(K_0,\theta), \Delta K^{**}(K_0,\theta))$ under different construction lead times and initial capacities in a port that is 50% publicly owned by a government taking 50% of the consumer surplus into account.

Base case.

		Existing capacity			
		$\boldsymbol{K_0 = 0}$	$\boldsymbol{K_0 = 5}$	$\boldsymbol{K_0 = 10}$	$\boldsymbol{K_0 = 15}$
	$\boldsymbol{\theta = 0}$	(36.07, 11.22)	(29.80, 10.02)	(36.07, 10.41)	(45.41, 11.08)
Time	$\boldsymbol{\theta = 1}$	(36.93, 11.23)	(30.18, 10.01)	(36.24, 10.38)	(45.40, 11.02)
to	$\boldsymbol{\theta = 2}$	(37.83, 11.24)	(30.57, 10.00)	(36.43, 10.34)	(45.40, 10.97)
build	$\boldsymbol{\theta = 4}$	(39.76, 11.26)	(31.43, 9.99)	(36.87, 10.29)	(45.48, 10.87)
	$\boldsymbol{\theta = 6}$	(41.87, 11.28)	(32.38, 9.98)	(37.38, 10.23)	(45.64, 11.77)

A set to 4.

		Existing capacity			
		$\boldsymbol{K_0 = 0}$	$\boldsymbol{K_0 = 5}$	$\boldsymbol{K_0 = 10}$	$\boldsymbol{K_0 = 15}$
	$\boldsymbol{\theta = 0}$	(32.58, 11.01)	(29.03, 9.99)	(36.89, 10.54)	(47.77, 11.34)
Time	$\boldsymbol{\theta = 1}$	(33.28, 11.03)	(29.33, 9.98)	(36.99, 10.51)	(47.67, 11.28)
to	$\boldsymbol{\theta = 2}$	(34.02, 11.04)	(29.65, 9.98)	(37.11, 10.47)	(47.58, 11.22)
build	$\boldsymbol{\theta = 4}$	(35.61, 11.07)	(30.35, 9.96)	(37.41, 10.41)	(47.49, 11.10)
	$\boldsymbol{\theta = 6}$	(37.35, 11.10)	(31.14, 9.95)	(37.78, 10.35)	(47.47, 10.99)

σ set to 0.15.

		Existing capacity			
		$\boldsymbol{K_0 = 0}$	$\boldsymbol{K_0 = 5}$	$\boldsymbol{K_0 = 10}$	$\boldsymbol{K_0 = 15}$
	$\boldsymbol{\theta = 0}$	(53.72, 13.45)	(40.61, 11.81)	(51.25, 12.75)	(70.62, 14.41)
Time	$\boldsymbol{\theta = 1}$	(54.79, 13.44)	(40.84, 11.76)	(50.84, 12.64)	(69.17, 14.19)
to	$\boldsymbol{\theta = 2}$	(55.91, 13.43)	(41.11, 11.72)	(50.49, 12.53)	(66.87, 13.90)
build	$\boldsymbol{\theta = 4}$	(55.54, 13.12)	(41.70, 11.63)	(49.23, 12.24)	(58.69, 12.92)
	$\boldsymbol{\theta = 6}$	(52.54, 12.53)	(41.58, 11.44)	(46.38, 11.77)	(52.37, 12.10)

μ set to 0.02.

		Existing capacity			
		$\boldsymbol{K_0 = 0}$	$\boldsymbol{K_0 = 5}$	$\boldsymbol{K_0 = 10}$	$\boldsymbol{K_0 = 15}$
	$\boldsymbol{\theta = 0}$	(40.78, 12.48)	(32.50, 11.11)	(40.55, 11.84)	(53.92, 13.08)
Time	$\boldsymbol{\theta = 1}$	(41.49, 12.47)	(32.69, 11.08)	(40.40, 11.77)	(53.31, 12.96)
to	$\boldsymbol{\theta = 2}$	(42.24, 12.47)	(32.89, 11.05)	(40.27, 11.71)	(52.75, 12.84)
build	$\boldsymbol{\theta = 4}$	(43.85, 12.47)	(33.36, 11.00)	(40.09, 11.58)	(51.75, 12.63)
	$\boldsymbol{\theta = 6}$	(45.60, 12.47)	(33.92, 10.96)	(40.01, 11.47)	(50.74, 12.41)

μ set to -0.01.

		Existing capacity			
		$\boldsymbol{K_0 = 0}$	$\boldsymbol{K_0 = 5}$	$\boldsymbol{K_0 = 10}$	$\boldsymbol{K_0 = 15}$
	$\boldsymbol{\theta = 0}$	(36.19, 9.27)	(30.51, 8.06)	(35.78, 8.00)	(43.13, 8.12)
Time	$\boldsymbol{\theta = 1}$	(38.03, 9.29)	(31.73, 8.08)	(36.96, 8.00)	(44.40, 8.12)
to	$\boldsymbol{\theta = 2}$	(39.98, 9.32)	(33.02, 8.10)	(38.20, 8.01)	(45.71, 8.13)
build	$\boldsymbol{\theta = 4}$	(44.27, 9.36)	(35.81, 8.14)	(40.86, 8.03)	(48.52, 8.13)
	$\boldsymbol{\theta = 6}$	(49.12, 9.41)	(38.92, 8.18)	(43.78, 8.05)	(51.58, 8.14)

Base case parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.10, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, s_G = 0.5, s_{CS} = 0.5, \lambda = 0.4.$

Table 5: Optimal investment strategies $(X_T^{**}(K_0,\theta), \Delta K^{**}(K_0,\theta))$ under different construction lead times and initial capacities in a public port.

Base case.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(31.58, 11.44)	(23.73, 10.06)	(26.93, 10.26)	(32.66, 10.79)
Time	$\theta = 1$	(32.42, 11.45)	(24.10, 10.06)	(27.13, 10.24)	(32.73, 10.74)
to	$\theta = 2$	(33.30, 11.46)	(24.49, 10.05)	(27.34, 10.21)	(32.81, 10.69)
build	$\theta = 4$	(35.20, 11.47)	(25.32, 10.04)	(27.82, 10.16)	(33.03, 10.60)
	$\theta = 6$	(37.28, 11.48)	(26.25, 10.03)	(28.36, 10.11)	(33.33, 10.52)

A set to 4.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(28.03, 11.26)	(22.72, 10.03)	(27.15, 10.38)	(33.94, 11.01)
Time	$\theta = 1$	(28.71, 11.27)	(23.02, 10.02)	(27.29, 10.34)	(33.94, 10.96)
to	$\theta = 2$	(29.43, 11.28)	(23.33, 10.01)	(27.45, 10.31)	(33.96, 10.91)
build	$\theta = 4$	(30.96, 11.30)	(24.02, 10.00)	(27.81, 10.26)	(34.05, 10.81)
	$\theta = 6$	(32.65, 11.32)	(24.77, 9.99)	(28.23, 10.21)	(34.22, 11.72)

σ set to 0.15.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(46.60, 13.58)	(31.77, 11.64)	(36.81, 12.20)	(47.34, 13.38)
Time	$\theta = 1$	(47.69, 13.57)	(32.08, 11.60)	(36.72, 12.11)	(46.70, 13.22)
to	$\theta = 2$	(48.84, 13.55)	(32.43, 11.57)	(36.66, 12.03)	(46.13, 13.07)
build	$\theta = 4$	(50.40, 13.42)	(33.22, 11.50)	(36.65, 11.87)	(44.93, 12.76)
	$\theta = 6$	(49.07, 12.94)	(34.03, 11.42)	(36.51, 11.68)	(42.70, 12.31)

μ set to 0.02.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(35.51, 12.66)	(25.59, 11.03)	(29.60, 11.47)	(37.29, 12.39)
Time	$\theta = 1$	(36.23, 12.65)	(25.81, 11.01)	(29.58, 11.42)	(37.01, 12.30)
to	$\theta = 2$	(36.98, 12.65)	(26.06, 10.99)	(29.59, 11.36)	(36.76, 12.21)
build	$\theta = 4$	(38.61, 12.64)	(26.60, 10.94)	(29.66, 11.26)	(36.35, 12.03)
	$\theta = 6$	(40.41, 12.63)	(27.22, 10.91)	(29.80, 11.16)	(36.03, 11.87)

μ set to -0.01.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(31.83, 9.53)	(24.55, 8.25)	(27.18, 8.08)	(31.83, 8.16)
Time	$\theta = 1$	(33.55, 9.55)	(25.61, 8.26)	(28.15, 8.09)	(32.83, 8.16)
to	$\theta = 2$	(35.37, 9.57)	(26.72, 8.28)	(29.17, 8.10)	(33.87, 8.16)
build	$\theta = 4$	(39.36, 9.59)	(29.15, 8.32)	(31.35, 8.12)	(36.09, 8.17)
	$\theta = 6$	(43.93, 9.63)	(31.87, 8.35)	(33.77, 8.14)	(38.53, 8.18)

Base case parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.10, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, s_G = 1, s_{CS} = 1, \lambda = 0.4$.

addition to the positive effect of a later timing on the investment size, the capacity in place has a negative effect on the size of the port expansion project.

5.3 The impact of congestion costs and aversion to waiting

For greenfield projects, a positive relationship between costs of congestion and investment size and timing is found. Such port projects for customers or goods that are more time-sensitive, resulting in a higher user cost of congestion, are installed later, because they are less attractive. Additionally, more capacity is needed to reduce occupancy rates and hence the more costly congestion.

Oppositely, many expansion projects where the existing capacity and the current throughput level are sufficiently high, are installed earlier if congestion has a larger impact on the customers. If the port is already active ($K_0 > 0$), congestion has a persistent and daily impact on the customers' and the port's profit. The port has a substantial incentive to install the expansion project sooner to avoid persistent congestion in the future. The following result is derived:

Result 3 *Under the assumptions given in Table 1, if the port's users are more waiting-time averse, port expansion ideally takes place earlier, i.e., when the market is smaller. Consequently, the size of the expansion project will be slightly smaller too.*

This finding is in line with the findings of Meersman & Van de Voorde (2014a), namely that active ports have a larger incentive to expand on time to avoid fully occupied capacity and to dispose of sufficient free capacity in order to attract the shipping lines.

5.4 The impact of public ownership

If welfare is taken more into account in the operational objective function, e.g. as a result of increased public ownership or the government considering a larger share of the consumer surplus, this has a substantial impact on the investment decision. From the literature, it was already known that increased public ownership leads to investing earlier in additional capacity (Asteris et al., 2012). Opposed to the common RO finding that later investment is associated with more capacity, in such a case there are some instances of greenfield projects where larger investments take place earlier (Balliauw, Kort, & Zhang, 2019).

However, as argued, disposing of additional port capacity becomes more urgent in case of expansion projects. Existing capacity cannot accommodate the higher amount of throughput that is desired as a result of the project's increased attractiveness for a government considering social welfare more. By consequence, the following result can be formalised:

Result 4 *Under the assumptions given in Table 1, the timing of the expansion will be a lot sooner if more public money is involved. The net impact of increased public ownership on the investment size will be limited, but often negative for expansion projects.*

This result illustrates the importance of timely removing barriers to economic growth, such as a lack of port capacity. Port expansion should take place in time, to maximise the welfare effects that are generated by ports.

Balliauw, Kort, & Zhang (2019) and (Balliauw, Kort, Meersman, et al., 2019) already showed that increased public ownership leads to an increased consideration of social welfare in the operational objective function of the port. As a result, port capacity investment projects become more attractive, which leads to investing earlier and/or more. In the case of expansion projects, where the incentive to avoid congestion is even higher than in greenfield projects due to the already present operations, the investment always takes place a lot earlier in public ports compared to private ports. The positive RO relationship between timing and size exerts a negative pressure on the investment size, as opposed to the positive pressure resulting from the increased project attractiveness. The net outcome depends on the specific case studied and its project attractiveness. It can be positive or negative. In most cases however, the size of a public port expansion is smaller than the size of a private port expansion. Nevertheless, the size differences are limited.

5.5 The impact of growth and uncertainty

The calculations here confirm the finding that increases in growth and uncertainty often lead to an increase in the size of a port capacity investment project and a later investment timing (Hagspiel et al., 2016). Bar-Ilan & Strange (1996) however show that with a long construction lead time, the impact of increased uncertainty on timing can become negative, leading to an earlier investment. This finding is confirmed empirically by Marmer & Slade (2018) in the U.S. copper mining industry with considerable construction lead times. Because higher uncertainty may result in higher upward jumps of demand, more capacity will be needed to accommodate demand peaks. The effect of downward jumps is asymmetric, since during demand troughs it is possible to reduce throughput levels.

The results displayed in Tables 3 - 5 did not illustrate the negative impact of time to build θ on the uncertainty's effect on the investment decision. This observation of investment anticipation as a result of increased uncertainty in combination with a high time to build can however be made in this paper's model as well. The following small example with a substantially higher construction lead time is used. In the base case from Table 3, expanding a private port with an existing capacity of 10 million TEU per year ($K_0 = 10$) and a construction lead time θ of 15 years gives the following optima:

- $\sigma = 0.1$**:** (41.63 euro per TEU, 9.84 M TEU per year),
- $\sigma = 0.11$**:** (41.53 euro per TEU, 9.90 M TEU per year).

This example confirms the robustness of the model with respect to the finding of Bar-Ilan & Strange (1996) and Marmer & Slade (2018). Notwithstanding the anticipated timing of the investment, the size increases, in order to be sufficiently able to accommodate higher potential upward deviations in demand.

In case growth becomes negative, the investment threshold for X would become that high that it would be very unlikely to reach this value from below, because only in the exceptional case that demand were to become sufficiently high, it would be optimal to invest. This higher investment threshold is required to guarantee a sufficient project value V, notwithstanding the expected decline in demand during the construction lead time. The project would also be smaller compared with cases with positive economic growth, as the negative demand growth would lead to lower future occupancy rates. It is also apparent that an increase of time to build in case of negative growth results in an increase of the project size. This is due to the sharp increase of the investment threshold. Hence, if the economy is expected to decline, investment will only take place at a moment that demand is sufficiently large. Moreover, the investment will be small to account for the declining demand in the future. Additionally, with negative growth in the port sector, public money might be used to create more welfare in other sectors.

In order to study sensitivity of the investment decision with respect to uncertainty, some scenarios from the base case in Table 3 have been recalculated in the deterministic case (with $\sigma = 0$):

Table 6: Optimal investment strategies ($X_T^{**}(K_0 = 10, \theta = 4), \Delta K^{**}(K_0 = 10, \theta = 4)$) under different values of r and σ in a private port.

		Uncertainty		
		$\sigma = 0.09$	$\sigma = 0.10$	$\sigma = 0.11$
Dis-	$r = 0.05$	(38.27, 11.16)	(41.03, 11.64)	(44.45, 12.20)
count	$r = 0.06$	(37.96, 10.03)	(39.74, 10.34)	(41.79, 10.67)
rate	$r = 0.07$	(39.45, 9.44)	(40.90, 9.68)	(42.49, 9.93)

Other parameter values:
$A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, s_G = 0, s_{CS} = 0, \lambda = 0.4.$

- $\theta = 0, K_0 = 10 : (28.68, 8, 52)$
- $\theta = 4, K_0 = 10 : (34.84, 9.48)$
- $\theta = 0, K_0 = 15 : (35.20, 8.77)$
- $\theta = 4, K_0 = 15 : (44.26, 9.76)$

Dixit & Pindyck (1994) already showed that even in the deterministic case, there is some value of waiting. This can be verified in the calculated examples too. At the optimal investment thresholds, the value of the expansion project (ΔV) exceeds the investment cost (I). This implies that at the moment that X is below the investment threshold, it is better to wait. Waiting allows maximising the value of the investment project, even if the NPV of the project is already positive at this moment (Balliauw et al., 2020). Moreover, the additional calculations show that the impact of existing capacity and time to build on the flexible size and timing of the investment are not different in the deterministic case than in the case with uncertainty. In addition, the sensitivity analysis confirms the observation of Dixit & Pindyck (1994) that (increased) uncertainty leads to postponing the investment, which however will be larger.

Another macroeconomic phenomenon that requires attention is the relationship between interest rates and uncertainty. When uncertainty rises, households increase precautionary savings, which in turn has a negative effect on interest rates (Hartzmark, 2016). The impact of these combined effects can be seen in Table 6. As discussed before, both an increase in uncertainty and a decrease in the interest rate used as the discount factor lead to an increase in the size of the port investment. As a result, the outcome of the combined effect is also a considerable increase of the project size. Although increased uncertainty leads to investment postponement, the impact of the discount rate is ambiguous and dependent on the discount rate. Therefore, the net impact of the combined effects on timing depends on the interest rate as well.

6 Conclusions and future research

In this paper, the specific impacts of time to build and expansion of existing capacity have been given attention in the analysis of one-shot port capacity investment decisions under congestion and uncertainty. These investments are to be optimised with respect to the timing and size. Considering time to build and expansion is important to more accurately model reality. Time to build reduces the attractiveness of a project and increases the uncertainty. As a result, ports tend to postpone their investment to wait for a larger market. However, time to build also urges ports to anticipate their investment, especially when the investment threshold is already high, to make sure that the capacity is ready when it is needed. The impact of time to build on size is even more ambiguous, due to the supplementary positive impact of a later timing on the size, next to the negative impact of a less attractive project. One general result holds: due to time to build, port expansion will take place later or the expansion will be smaller. In some cases, a combination of both effects is perceived. Existing capacity has an impact on the effect of congestion costs on the investment decision as well. Because the port is already operating and generating revenues, it has a larger incentive to avoid congestion as soon as possible for each unit of throughput handled. Therefore, the larger the waiting-time aversion of port customers, the sooner the port has to expand. The impact on the size of the expansion is however limited. This finding is opposed to larger greenfield projects, which are installed later under similar economic circumstances. Finally, it is observed that increased public ownership leads to earlier investment, but not necessarily more capacity in port capacity expansions. Public port ownership however facilitates the full exploitation of potential port benefits.

The findings of this paper have some important implications for practitioners and policy makers. Time to build erodes the project value, because it reduces the present value of the profit streams. Moreover, it increases the exposure to uncertainty. This may among other things lead to further postponing the investment decision. As a result, time to build encompasses an incentive to take actions reducing construction lead times. Governments for example may try to limit long internal discussions and arguments with external action groups. The rewards may include higher profit flows, sooner investment and often less capacity that needs to be installed to achieve a similar level of social welfare. The resources that are saved can be used elsewhere.

The methodology used in this paper opens up an interesting avenue for future research. In this paper, the time to build is assumed to be known ex-ante. It could be interesting to study the impact of uncertain time to build, with or without investment size dependency, on the timing and the size of the investment. This would however complicate the calculations, as interactions between uncertain variables might lead to a necessity of using Monte Carlo simulations. In this setting, the time to build could be drawn from a simple random distribution, such as the uniform distribution. If the calculations are still feasible, also a Gaussian or a right skewed distribution such as Chi-squared could be used.

Moreover, it might be interesting to add time to build, port expansion, port competition and the division between port authorities and terminal operators in one model. In this paper, the focus was on time to build and port expansion. In the next phase of this research, the insights from competition and landlord models are to be implemented in the findings from this paper. However, the results from a model combining all of these characteristics can demonstrate that the insights from each individual model are stable and robust when they are all added to the same model.

Finally, phased investment, which requires a different modelling approach, also opens up a very important avenue for future research. It would be worthwhile to check if the findings of Kort et al. (2010) and Chronopoulos et al. (2017), namely that phased investment leads to an earlier first investment and a larger total investment size, remain valid in such a port model setting, also including time to build, uncertainty, congestion costs and port competition.

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