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Reference:

Balliauw Matteo, Meersman Hilde, Van de Voorde Eddy, Vanelslander Thierry.- Tow ards improved port capacity investment decisions under uncertainty : a real options approach

Transport review s - ISSN 0144-1647 - 39:4(2019), p. 531-552
Full text (Publisher's DOI): https://doi.org/10.1080/01441647.2018.1556228
To cite this reference: https://hdl.handle.net/10067/1556740151162165141

Towards improved port capacity investment decisions under uncertainty: a real options approach

Matteo Balliauw[1], Hilde Meersman[1], Eddy Van de Voorde[1], and Thierry Vanelslander[1]

[1]Department of Transport and Regional Economics, University of Antwerp, Prinsstraat 13, 2000 Antwerp, Belgium

Abstract

Port activity plays an important role in facilitating international trade. Sufficient capacity is indispensable for a port to attract flows to a region and retain them. The capacity decision is the result of a trade-off between investment and waiting costs. Traditional methods to value expansion projects do not deal adequately with managerial flexibility in the face of uncertainty from different sources in the complex port environment. In this paper, real options (RO) models are identified as an alternative method to making project valuations and investment decisions, as they attribute the correct value to managerial flexibility under uncertainty. In order to be able to build and use such RO models for port capacity investment decisions, the sources and implications of uncertainty in the port and the different RO model specifications need to be understood. To this end, both the literature about uncertainty in the port context and the literature about real options models are reviewed in order to provide researchers who want to build their own decision making models, with the necessary knowledge of both fields. The review makes clear that the complex interactions in and competition between the logistics chains and their actors coming together in ports have significant impacts on port capacity. Uncertainty is also caused by uncertain international trade flows and changes in legislation following new technologies and environmental impacts. An analysis of the components of some general RO models shows how the options of flexible output, investment size and timing are valued by RO models in a setting with demand uncertainty. Moreover, the review presents researchers with insights in how to deal with cooperative and competitive interactions in the chain, time to build, cyclical markets and legislation changes. It also shows how to value the expansion and the phased investment options. The new insights resulting from this review are subsequently combined in a framework that serves as a guideline to build RO models for port capacity investments. Finally, an exemplifying application of the framework is used to build an actual port capacity investment decision model.

Keywords: port capacity, investment, valuation, decision making, real options, uncertainty

1 Introduction

Ports perform important activities to facilitate the international transportation of goods and international trade, such as cargo handling and storage (Blonigen & Wilson, 2008). Sufficient capacity is required in ports to perform port operations effectively and efficiently. In addition, since ports create value for the economy, too little capacity could result in GDP declines and freight delays in the region (De Langen et al., 2018). In a port and in transportation in general, it is even more important than in a production environment to have the optimal amount of capacity installed, since the transport service is not storable (de Weille & Ray, 1974).

When deciding on the optimal capacity in a port, an important trade-off between two cost components needs to be considered. On the one hand, investment costs are the expenses for expansion and maintenance of the capacity in place. This cost is positively related to the amount of capacity. On the other hand, congestion costs are incurred by the transporting firm that has to wait in the port due to bottlenecks. As shown by Blauwens et al. (2016) and De Borger et al. (2008), the value of time for a ship waiting can be high and forms an important part of the generalised cost of the maritime logistics chain. Such congestion costs can be avoided by additional capacity, since it decreases the probability of waiting (Macário, 2014). Of course, also other solutions are possible, such as congestion pricing (Zhang, 2007).

A mismatch between demand and capacity can result in periods of scarcity or overcapacity. Underinvestment could result in congestion and costly waiting times with a resulting loss in social welfare in the form of lost consumer surplus. Overinvestment could lead to overcapacity at high investment costs. Nevertheless, overcapacity is often encountered as a result of the large investment size and long lead-times (Meersman & Van de Voorde, 2014a). Overcapacity may also exist in a port to reduce the attractiveness of a competitor's investment option, known in literature as entry deterrence (Huberts et al., 2015). Prices may be lowered in the case of overcapacity to attain a desired capacity utilisation rate (Meersman et al., 2010; Xiao et al., 2013). The possibility of periods of imbalance indicates the importance of a joint analysis of the amount of available capacity, amount and timing of capacity expansion and the level of output price (Strandenes, 2014).

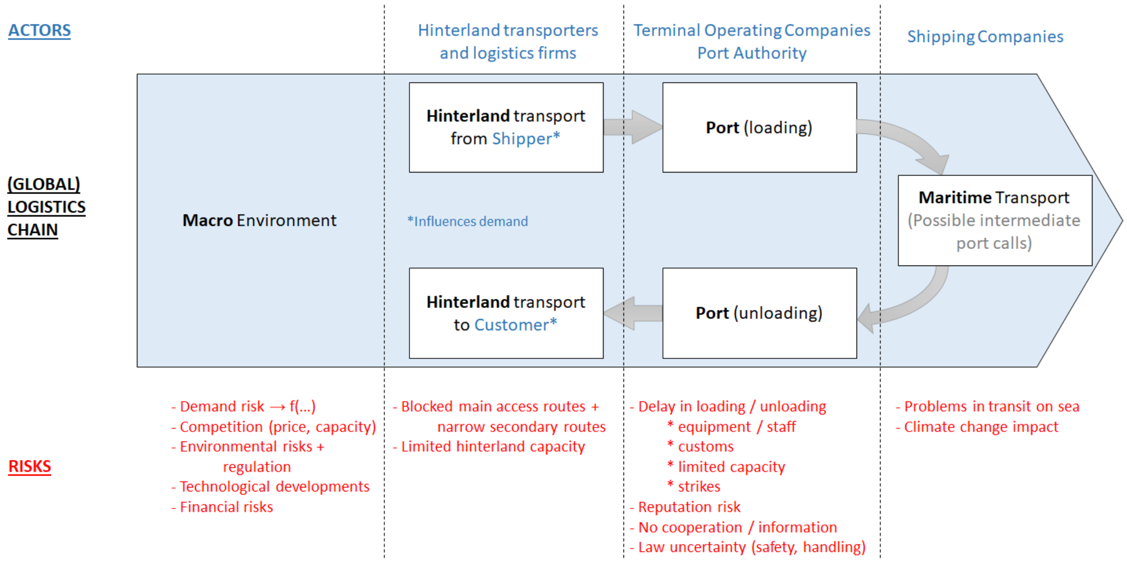
Port capacity investment decisions involve considerable risk and uncertainty for the investing port actors, such as port authorities, terminal operating companies (TOC) and governments (Kakimoto & Seneviratne, 2000b; Musso et al., 2006). They arise from many sources: different economic decisions taken by many logistics actors in competitive logistics chains; unpredictable income from trade, uncertainty about the amount of seaborne traffic and possible resulting congestion; uncertainty about new technological, environmental, political and legal developments (Meersman, 2005; Giuliano, 2007). Variability and uncertainty, risk and managerial flexibility are not taken into account fully in traditional valuation methods such as net present value (NPV) and internal rate of return (IRR) analyses (Trigeorgis et al., 1996; Anda et al., 2009). Hence, the objective of this paper is to discern a methodology that is able to correctly value and decide about port capacity investment decisions under uncertainty and construct a framework to further develop this methodology. We review the relevant literature and risk factors in the next section, since all of these elements need to be taken into account in port capacity investment decisions.

As opposed to the NPV method, real options (RO) models offer a more appropriate method to value flexible investments under uncertainty and make better investment decisions, as is discussed in Section 3. To this end, RO models use stochastic calculus and dynamic programming to optimise an objective function (such as the value of the firm), including a random term with respect to the investment decision variables (Dixit & Pindyck, 1994). The disadvantage of the method are however its complexity, the need for data and parameter and function estimations. Its current applications to ports are limited. Some of the existing RO applications in a transportation context are discussed in Section 4. In order to allow building RO models to decide about port capacity investment decisions, building blocks and characteristics of general existing RO models relevant to the port context, are reviewed in Section 5. The insights from the reviews of both the port uncertainty and the RO modelling domain are combined in Section 6.1 in a port capacity investment RO modelling framework. This framework offers an overview that will support researchers and practitioners in model building, since insights in both the port context and RO models are indispensable for them. Section 6.2 uses the framework to elaborate a port capacity investment decision model under uncertainty. The final section concludes with the major findings of this review and presents some suggestions for future research.

2 Sources of uncertainty affecting port capacity investment decisions

Many sources of uncertainty are present in the port context. This section reviews the relevant port uncertainty-related literature in order to provide insights in the current state-of-the-art. Later on, these insights will be included in RO models.

The sources of uncertainty in a port can be classified under three categories: (i) the competitive position of a port in a global logistics chain, (ii) global evolutions in international trade and (iii) technological evolutions, increased environmental considerations and resulting changes in legislation. In order to link the sources of uncertainty to the actors in the entire logistics chain, Figure 1 represents the logistics chain. The different risks are grouped per activity in the logistics chain. Additionally, the actors per activity are displayed on top, to allow linking the risks at the bottom to the respective actors. The interaction of actors induces additional uncertainty and risks. Nonetheless, forwarders often intervene in this maritime logistics chain by coordinating different steps of the shipping process, resulting in the elimination of many direct contacts between shippers and different shipping lines (Meersman & Van de Voorde, 2014a). This might at times lead to a reduction of uncertainty. Finally, general and unforeseen uncertainties that can have an influence on investment projects, such as tsunamis, earthquakes or terrorist attacks, are not discussed in further detail in this paper.



Source: own composition, based on Meersman & Van de Voorde (2014a); Meersman et al. (2010); Vanelslander (2014); Vilko & Hallikas (2012); Cucchiella & Gastaldi (2006); Koetse & Rietveld (2012).

Figure 1: Actors and risks in the maritime logistics chain.

2.1 Competitive position of the port: global logistics chains

Ports are part of global logistics chains with a number of actors involved. These chains are multimodal, as it is necessary to switch between different transport modes (e.g., road, rail and maritime transport). This induces internal variability and risks to the significant demand and external risk, that are already present in the economic environment (Vilko & Hallikas, 2012). Decisions of one actor in the chain can have major implications for the other actors (Heaver, 2011; Slack & Frémont, 2005; Verhoeven, 2015). At first sight, they may seem insignificant but subsequently, they might cause a chain reaction creating bottlenecks that affect the competitive position of a port negatively (Panayides, 2006; Rodrigue & Notteboom, 2009; Van Der Horst &

De Langen, 2008). Variability moreover complicates the decisions taken by the different owners in the chain (Cucchiella & Gastaldi, 2006). Finding out the most vulnerable links in the chain can help to efficiently manage these chains wherein goods are to be transported and information is to be shared. In order to steer the chain, cooperation and communication are vital (Vilko & Hallikas, 2012).

In the port, many different intertwined actors come together and influence the decisions taken there (Verhoeven, 2015; Coppens et al., 2007). The relationships between these actors can be rather complex (Estache, 2001), as they might have different, conflicting objectives and an unequal distribution of power between them. This complicates specifying the objective functions of the port capacity investment decision makers (Xiao et al., 2012). As Van de Voorde & Vanelslander (2009) state for example, the concession policy are for the port authority one of the few instruments to express their negotiation power over TOC's. The negotiated concession fee needs to be taken into account in the objective functions. Moreover, shipping companies have strong decision power in the maritime chain too, since they decide the ports of call for large throughput volumes. Their organisational structure is changing towards more concentration (Kauppila et al., 2016). In addition, shipping lines may invest in dedicated terminals, in order to reduce waiting times by preventing being served on a first come, first served basis (Heaver et al., 2001). This reduction of port and hinterland congestion is an objective of both the shipping company and the TOC. As a result, the impact on port capacity needs to be considered (Strandenes, 2014; Meersman et al., 2010).

The question could be raised whether port authorities aspire cost minimisation or profit maximisation, or even a different objective (Chang et al., 2012). The objectives of a port authority are influenced and complicated by their mixed ownership structure and competition inside and between ports (Cullinane et al., 2005). As Suykens & Van de Voorde (1998) indicate, not only private, but also public money plays an important role in port ownership. Xiao et al. (2012) define a multiple objective function to deal with the different actors in the port. Different weighted objectives are combined for the private and public actors involved. A private investor aims at maximising profit:

$$\pi = (p - c)q - c_h K, \tag{1}$$

with p the unit price, c the unit cost, q the output quantity, c_h the capital holding cost of one unit of capacity (to hold capacity in place, e.g. through maintenance) and K the total available capacity, which forms the upper bound of q. A local government looks at the sum of this profit and the spill-over effects (λq, with λ a constant scale factor) for the local economy. Finally, a central government additionally includes total consumer surplus in its value function. The objectives of the different actors are then weighted and summed in a global objective function which is to be maximised. Delay D, caused by congestion, is defined by a function of the capacity utilisation rate q/K: $D = \xi f(q/K)$, with ξ a constant scale factor. It is included in the analysis as a user cost. Xiao et al. (2012) find that a higher share of ownership for the private investor results in lower capacity investments and higher prices. Indeed, when positive spill-over effects of port business are not taken into account, capacity investment will be lower (Asteris et al., 2012).

The weights of the different objectives in this approach are defined by the share of ownership of the different parties in the port. This is a good first approximation when voting power is directly related to the shares of ownership of the different parties. In some ownership structures (e.g. majority share) or when dealing with dominating parties however, this approach might not be a correct representation of the decision making process. In such a case, only the objectives of the decision makers with influence need to be retained.

Also competition has an impact on the chain (Notteboom & Yap, 2012). Competition does not only exist within one chain but also between different chains. At first, the different actors in the chain might compete internally to have the power to influence the decisions made in the chain (Meersman & Van de Voorde, 2014b). Second, different TOC's and port authorities might compete to be part of a specific logistics chain. It is important to be part of the chain with the lowest generalised cost, because the goods are more likely to flow through this chain (Meersman & Van de Voorde, 2014a). This in turn leads to competition between different chains to actually have the lowest generalised cost and attract the highest possible throughput volumes. This competition induces extra uncertainty and risks in the port. To account for this competition between ports, many models use a competitive game with two or more ports (Zhuang et al., 2014; Xiao et al., 2012; Saeed & Larsen, 2010; Zhang, 2008).

2.2 Global evolutions in international trade

The amount of throughput handled in a port depends on international trade in three ways. First, the total amount of trade plays an important role, and is influenced by the macro environment (see Figure 1). Future levels of world trade flows are very uncertain and volatile, although they are expected to grow. Second, the geographical distribution of these trade flows can change, resulting in different routes for the ships. Finally, the composition of trade and the selected transport modes can change too, influencing amongst others containerisation rates. This uncertainty in global trade has a negative impact on forecast accuracy. Accurate forecasts estimating future port demand are required to obtain valuable outcomes of NPV analyses, since they cannot accurately account for uncertainty (Kauppila et al., 2016; Meersman & Van de Voorde, 2014b; Blonigen & Wilson, 2008; Jacks & Pendakur, 2010). Oppositely, RO models valuing flexibility have the advantage of being able to explicitly account for the uncertainty (De Neufville, 2016).

2.3 Technological change: environmental and legal uncertainties

Technological and environmental developments are another prominent macro environmental factor influencing the port. Asteris et al. (2012) describe ports as an industry facing numerous technological developments, internally as well as externally. Vessel size increases, new routes become available (e.g. through widening the Panama Canal, etc.) and the environmental impact of technology and the investment herein under uncertainty (e.g. LNG fuel) gain increasing attention (Kauppila et al., 2016; Verbruggen, 2008; Acciaro, 2014a,b). Koetse & Rietveld (2012) prove that climate change can add to the risk encompassed in transport infrastructure investments. Not only does transport induce climate change, there exists an influence of climate change on transportation as well. More extreme weather conditions can pose a problem to different transportation modes, even more than a change in the average condition. An interesting example in this context is the change in the sea level, complicating certain port activities. This in turn could result in a modal shift, altering the demand for certain types of transport infrastructure and hence imposing a higher demand variability and risk.

Since technological and environmental impacts, but also safety and security gain more interest, new legislations are constituted to protect the goods traded, the workers and the port environment (Harrald et al., 2004). Also the environmental impact of ports on climate change can be addressed by governments imposing additional legislation. Additionally, changes in labour regulations may induce additional risks (Barton & Turnbull, 2002).

3 Real options models to make better decisions under uncertainty

As opposed to the traditional valuation methods, RO models monetarily quantify the value of managerial flexibility to react to uncertainty in the best possible way. In this way, RO models do take the benefits of options of flexibility embedded in the project into account. Only when these options are included in project appraisal, the investment decision can be valued correctly. It is however important to point out that RO models should not be seen as a replacement for NPV with discounted cash flows. It is complementary to it, because the value of a project can be calculated as the static NPV value plus the value of the real options present (Hu & Zhang, 2015; Van Putten & MacMillan, 2004).

Port capacity investment analysis is a field where RO can be a very powerful methodology, as was already suggested by Juan et al. (2001) and Herder et al. (2011). RO show great potential to improve project valuation and decision making under uncertainty in large scale, complex, irreversible projects involving long planning and construction periods and influenced by technological shifts and opposing objectives of different stakeholders involved (de Neufville, 2003). Port infrastructure investment projects have these characteristics (Vanelslander, 2014). Moreover, the port environment itself is complex, as shown by the review in Section 2. As a result, the value of these projects can be increased by means of flexible size and timing of the investments through flexible options embedded in the project elaboration (Hull, 2012). Ports that want to excel in a dynamic world need to incorporate options to allow reacting flexibly to changes. RO models attribute value to such flexibility (Taneja, 2013; Van Putten & MacMillan, 2004). Moreover, uncertainty is considered an opportunity, not a threat, because managers can adapt their strategies to internal and external changes. Literature even indicates that higher demand uncertainty results in larger capacity investments (Dangl, 1999; Guthrie, 2012; Xiao et al., 2013).

An advantage of RO beyond its included flexibility and decision making realism, is the possibility of a stepwise elaboration of the mathematical model. Trigeorgis (2005) shows that RO can be approached as building blocks, where different options could be interrelated and interacting with each other. Some important options to be considered are: the option to expand the project, possibly in stages; the option to defer (timing flexibility); the option to switch to other activities or good types handled; the option to adapt output levels; and the option to fully shut down operations. Such RO models are often expanded. In an initial stage, only one firm might be considered. In a following stage of the research, the model might be extended for example to more firms operating under competition (Aguerrevere, 2003; Xiao et al., 2013).

4 Real options in the transportation literature

Real options have been applied to many transportation investments, because they can deal very well with managerial flexibility under different sources of uncertainty. Those noted here relate to the maritime sector, to other modes and to environmental projects. When transportation infrastructure is financed by the public government, the social welfare function has to be maximised, complicating the analysis because now different variables have an impact on the value of the project (Szymanski, 1991). Chow & Regan (2010) exemplify this when applying RO to transportation network investments. Tibben-Lembke & Rogers (2006) in their paper show how financial options could be adopted as transportation options to hedge logistical contracts. Also in aviation, RO have been applied. Hu & Zhang (2015) for example have analysed airline investment decisions, whereas Xiao et al. (2013) and Xiao et al. (2017) have investigated airport expansion decisions under uncertainty. Interesting lessons with respect to the maritime and port context can be drawn from this field of study.

There have been many applications of RO to maritime investments. Bendall & Stent (2003), Bendall & Stent (2005), Bendall & Stent (2007) and Dikos (2008) show how investing in a new ship or maritime technology can incorporate an option value. Bjerksund & Ekern (1995) discuss the value of mean-reverting cash flows through contingent claim analysis, applied to time charters in shipping. Sødal (2006) and Balliauw (2017) use RO to study entry and exit decisions in shipping markets. Rau & Spinler (2017), as an extension of Rau & Spinler (2016), discuss the performance of RO modelling in a cooperative container shipping game concerning alliances. Moreover Sødal et al. (2008) use RO to value the option to switch operations in combination carriers. These examples confirm that RO models offer a good approach to valuing volatile and capital-intensive projects as in the maritime business (Kakimoto & Seneviratne, 2000a).

RO analysis has been used to evaluate alternative technologies dealing with environmental issues (Kim et al., 2009; Koetse & Rietveld, 2012). RO is well suited to dealing with the uncertainty associated with climate change and the effectiveness of technological innovations (Acciaro, 2014a). RO demonstrates the option value in postponing the technological investments. However, adapting to climate change during regular maintenance or retrofitting could be beneficial pro-active actions (Cullinane & Bergqvist, 2014).

5 Real options models to analyse port capacity investment decisions

This section's review of RO models in the literature is the basis for developing models suitable to the specific, complex port context with its considerable uncertainties. In order to model investment decisions as realistically as possible, without relying on too many simplifying assumptions, the relevant decision variables need to be included in the port model. Nevertheless, some variables need to be kept exogenous in order to have a solvable model with sufficient explanatory power. The included decision variables alter the outcomes of the model and the impact of uncertainty. For example, considering timing and size of an investment together could be more realistic in some cases and would lead to results that differ from models with only one single decision variable.

5.1 The basic RO model of Dangl and its extensions

An initial RO model to decide about the size and timing of capacity investments is available in Dangl (1999). His continuous time and continuous state model starts from the inverse demand curve

$$p(t) = X(t) - Bq(t), \tag{2}$$

with the following variables defined at time t: $p(t)$ the price, $X(t)$ the demand shift parameter that follows a Geometric Brownian Motion (GBM), B the inclination of the curve and $q(t)$ the output quantity. The increment of a GBM is defined by $\mathrm{d}X(t) = \mu X(t)\mathrm{d}t + \sigma X(t)\mathrm{d}Z(t)$, with μ the drift parameter, σ the volatility (a measurement of uncertainty) and Z a standard Wiener process. For convergence of the model, it is required that the risk-free discount rate $r > \mu$ (Dixit & Pindyck, 1994). For the sake of clarity, we further on omit the time-dependency in our notation, e.g. p instead of $p(t)$.

Dangl (1999) in his paper models a flexible firm, since the firm can choose its optimal output level, as long as it satisfies $q = min\{q^{opt}, K\}$, as opposed to a non-flexible firm, with $q \in \{0, K\}$. Ports are typical examples of flexible firms, as operating at full capacity is in general an exception. According to Hagspiel et al. (2016), a flexible firm will invest more than a non-flexible firm, proving that flexibility adds value to the firm.

The cost of investment is given by

$$I = \gamma K^{\varepsilon}, \tag{3}$$

with γ a constant scale factor, K the total capacity and $\varepsilon < 1$ to indicate economies of scale in investment outlays and to exclude infinitesimal expansion, which would have an infinite cost under the current specification. The profit π is equal to

$$\pi = (p - c(K))q, \tag{4}$$

where $c(K)$ is the average operational cost, being dependent of the size of the available capacity K. This function is a reduced version of the profit function used by Xiao et al. (2012) in Equation (1) for a port environment. Maximisation of this profit will lead to the optimal output q^{opt} at each point in time, given X and K. Subsequently, Dangl (1999) maximises the value of the firm, given by the integral of the discounted expected future profit streams minus the investment cost. This forms the input of the option value maximisation. By using dynamic programming, an optimal investment strategy (X_T, K) is found. It indicates the optimal timing, based on an investment threshold for the demand shift parameter, and the optimal amount of capacity. The main conclusion of the model is that an increase in uncertainty will lead to investing more, but later.

Bar-Ilan & Strange (1999) analyse the difference between lumpy and incremental investments. They confirm the findings of Dangl (1999), but only for lumpy investments, namely that uncertainty delays the investment and increases its size. Lumpy investments are defined by two properties: combinable investments and the presence of adjustment costs. Investments in port capacity are combinable, since adding a dock increases capacity. Moreover, there are adjustment costs in public infrastructure, such as planning costs (Szymanski, 1991). It is exactly those costs that lead to the presence of economies of scale in the size of investment. So indeed, investing in port capacity is considered lumpy, as adding a dock means increasing capacity by a big leap.

An extension to the model of Dangl (1999) is provided by Hagspiel et al. (2016), who adds a capital holding cost $c_h K$ to the cost function of Dangl (1999). The resulting profit function is similar to the one of Xiao et al. (2012) in Equation (1). However the typical port congestion and delays are still omitted. The new profit function is given by

$$\pi = (p - c(K))q - c_h K. \tag{5}$$

5.2 Inclusion of port expansion in the model

A slightly different continuous time and state model to analyse the impact of economies of scale on the investment decision is presented by Guthrie (2012). It takes into account a firm that can undertake subsequent capacity expansion investments. For a port, this could be by means of adding a dock. The inverse demand curve used in this model is not linear, but has a constant price elasticity of demand $(-1/a)$. It is given by

$$p(t) = X(t)q^{-a}, \tag{6}$$

with $X(t)$ again following a GBM, that could be adapted for risk-aversion by subtracting a risk premium.

The investment cost function I is given by

$$I = \Delta q^{\varepsilon}, \tag{7}$$

with $\varepsilon < 1$, leading to economies of scale and preventing infinitesimal capital expansions. This investment cost function is similar to the one of Dangl (1999), although Guthrie (2012) sets γ to 1 and uses for K the amount of capacity expansion Δq, hence being the difference between the new and previously installed capacity. Output in this case is always set at maximum capacity, because $a < 1$ makes this the optimal decision in every circumstance. This is equivalent to the non-flexible firm of Hagspiel et al. (2016). Another element that is included in the model, is depreciation: $dq = -\zeta q dt$, with ζ the depreciation rate. The objective function is the market value of the firm and is to be maximised.

The outcome of maximising the firm's market value is a set of three decisions $(\hat{y}_0, \kappa, \hat{y}_b)$. $\hat{y}_0$ defines the initial capacity investment. κ and $\hat{y}_b$ define the subsequent capacity expansion strategy. κ is the scale of each expansion (related to the current capacity level) and $\hat{y}_b$ is the return on assets-threshold indicating the investment timing. It is calculated as $pq/q^{\varepsilon} = q^{1-a-\varepsilon}x$, where q^{ε} is the replacement costs of the assets in place. It is noteworthy to indicate that investing will decrease the actual value for $\hat{y}_b$ through an increase of q.

The main conclusion of Guthrie (2012) is similar to the findings of Dangl (1999). Guthrie (2012) confirms that increased uncertainty will lead to larger investment outlays that are in turn less frequent.

5.3 The impact of time to build

As opposed to the previous model, Aguerrevere (2003) includes time to build in his RO model of capacity expansions. He uses the same demand curve as Dangl (1999). Aguerrevere (2003) uses the demand function to explicitly study the resulting pricing decision for a chosen output-level of a non-storable product. However, his cost function is different: $c(q) = c_1 q + \frac{1}{2}c_2 q^2$, with q being flexible, but limited by the operational capacity available. As a result of flexible output, this model considers overinvestment in capacity less harmful than underinvestment. Indeed, there is an imbalance between the two sides of risk, as the capacity investment decision in combination with flexibility has to be considered rather as a determination of the maximal output threshold.

The investment cost in this model is given by Equation (3), with ε set to 1. This however excludes economies of scale in the investment size decision, leaving infinitesimal investments possible under this cost function specification (Dangl, 1999). However, such investments are not realistic in port capacity expansion, as they are characterised as large-scaled. A fixed investment cost should still be included in the function, as a preliminary study and a negotiation process with different parties involve a cost as well.

Time to build is modelled through three functions: $O(t)$ represents the amount of capacity present at time t, $N(t)$ is the amount of capacity that is under construction with lead time θ and $K(t)$, the committed capacity, is the sum of the previous two. $K(t)$ is non-decreasing over time, because of investment irreversibility and the omission of depreciation in the model.

An important insight of Aguerrevere (2003) is that capacity investments increase with uncertainty when time to build is included in the model. The same logic applies when the time lag increases. The results explain why expansion takes place even when current capacity is not fully used. It also turns out that when capacity is fully used, the pricing behaviour as a result of increased demand will be entirely different. The price will rise much more following a demand increase than in the case when capacity is not fully used. As a result, a model like that of Aguerrevere (2003) could be used to quantify congestion pricing, which could be an important contribution to understanding the complex pricing strategy of a port.

5.4 Installing the project in stages

Building a new dock can be realised in different steps and should not necessarily be completed at once. A well-known example is Maasvlakte 2 in Rotterdam, where the water basin and part of the terminals were realised in the first stage. In the second stage, the rest of the terminals can be build, but only when the additional capacity is required. Also the port of Antwerp is considering expansion. Therefore, it considers digging a first phase of the Saeftinghedock and develop the terminals around it (Timperman, 2017). When additional capacity is needed, the second phase can be installed, by further expanding this dock and its terminals.

An important advantage of the phased investment approach can be a shorter lead time to add extra capacity, because part of the project has already been realised. The downside of such a project however is that in general, a premium has to be paid in terms of a higher total investment cost. Stage 1 has an investment cost I_{s_1}, whereas Stage 2 involves I_{s_2} and realising the project at once costs I_l. Hence in reality, $I_{s_1} + I_{s_2} > I_l$ will hold.

A model that confronts lumpy and stepwise investment is provided by Chronopoulos et al. (2017). They confirm the findings of Kort et al. (2010) who work with exogenous capacities and who calculate a maximum cost premium $(I_{s_1} + I_{s_2})/I_l > 1$ for which phased investment is more profitable. Chronopoulos et al. (2017) however state that if the capacity of the project is determined ex-ante, lumpy investment is better under a high price uncertainty. If the final capacity is not fixed, stepwise investment leads to a higher value and more capacity will be installed.

5.5 Game-theoretic approaches

Most of the previous models only consider the investment decision of one monopoly entity. In reality however there is competition between ports and even within ports to attract cargo flows (Meersman et al., 2010). The preference of shipping goods to Western-Europe for instance through the port of Rotterdam or the port of Antwerp will be determined by the cost and the service provided by the port (i.e. transit time, the frequency of service for container lines, the amount of congestion, etc.), but also by switching costs (determined by existing contracts, the presence of liner-owned terminals and the speed of new information availability) (Veldman & Bückmann, 2003). The ports in the Hamburg-Le Havre range should hence not be considered monopoly ports. They are in competition for the same market or hinterland, like for example in De Borger et al. (2008). In this regard, Pallis et al. (2008) and Saeed & Larsen (2010) look at port negotiations as a game. Because entities in the public sector can also be included in the analysis, sufficient transparency can be assumed. As a result, information asymmetry should not necessarily be included in the game.

When game theory is involved in the analysis, individual value functions have to be derived and the type of game has to be decided on. Dynamic programming can then be used to find the optimal decision (Dixit & Pindyck, 1994; Azevedo & Paxson, 2014; Huberts et al., 2015). Huisman & Kort (2015) discuss a model that analyses the initial investment decision of a leader and a follower firm. In a duopoly setting, they use a multiplicative inverse demand function given by

$$p = X(1 - BQ), \tag{8}$$

where X follows again a GBM and Q represents the total market output. This function is a special case of the one introduced by Dixit & Pindyck (1994). The authors find that in this case, overinvestment of the leader forces the follower to invest later and in less capacity. However, this model is not directly applicable to a competitive port setting. An important implication of this model is that the maximal output is limited to $1/B$ in order to prevent negative prices. This demand function could serve as a good first approximation. A linear demand function would be better suited to analyse a market wherein potential demand growth is possible. However, more sophisticated functions and their applicability should also be considered when developing the model.

Another important limitation of the model of Huisman & Kort (2015) lies in the number of competitors involved. As shown by Veldman & Bückmann (2003), in the Hamburg-Le Havre range, five ports are in competition. For this reason, modelling the port as an oligopoly, rather than as a duopoly could be a better alternative. Some examples are given by Azevedo & Paxson (2014). Aguerrevere (2009) finds in his model with an exogenously determined number of firms in the industry that with more companies in the market, the option to expand is exercised earlier. In order to analyse an n-firm game, Grenadier (2002) uses a constant elasticity demand function, equivalent to the one used by Guthrie (2012) in Equation (6). It is shown that the value of waiting is negatively correlated to the amount of competition, as a result of preemptive strategies. As stated before, competition between ports is not the only competitive element in the analysis of port capacity investments. Potentially conflicting interests in combination with a number of aligned objectives of the actors involved in the maritime logistics chain require a much more complex analysis in a new port investment model too.

Since ports are heterogeneous, this should be translated into asymmetric firms in an RO game model. Firms or ports could differ in terms of investment costs, revenues or production costs (Azevedo & Paxson, 2014). In addition, ports also offer products or services that are not identical. Kamoto & Okawa (2014) present an RO model that allows for product differentiation, more specifically in an innovative environment with a leader and follower entrant. Their inverse demand function of firm i is an extended version of the one used by Huisman & Kort (2015), since it involves a correction for the output of the other firms j, weighted by the amount of product similarity. The inverse demand function, is given by

$$p_i = X(1 - q_i - \delta q_j), \tag{9}$$

with $\delta \in [0, 1]$ the differentiation parameter, taking the value of 1 in the case of perfect substitution and 0 in the case of perfect complementarity. By assuming a variable production cost of zero, the model of Kamoto & Okawa (2014) does not include scale effects, which however do play an important role in infrastructure and cargo handling in ports (Tovar et al., 2007).

5.6 Alternative uncertainty processes: cyclicality and changes in legislation

RO models frequently use a GBM as the stochastic process expressing uncertainty, also in transportation (Li & Cai, 2017; Lindsey & De Palma, 2014). This non-negative process allows uncertainty and drift to be set by two independent parameters, and its mathematical complexity is relatively limited (Schöne, 2014). However, as Dixit & Pindyck (1994) also indicate, alternatives exist to model different market patterns. Maritime markets typically follow a cyclical pattern, with cycles lasting about eight to ten quarters (Stopford, 2009; Paflioti et al., 2015).

Ruiz-Aliseda & Wu (2012) built an RO model analysing the entry and exit decisions in such cyclical markets. Balliauw (2017) applied this model to study entry and exit decisions in shipping markets. To model cyclical markets, the traditionally used GBM is replaced by a discrete-time Markov process, defined by

$$d\pi = \alpha(t)\pi \mathrm{d}t, \tag{10}$$

with π the instantaneous profit at time t, and α the growth (α_1) or decline (α_2) rate. The probabilities of going from a growth phase to a decline phase and vice-versa are given by

$$\begin{cases} P(\alpha(t+\mathrm{d}t) = \alpha_2 | \alpha(t) = \alpha_1) = \psi_1 \mathrm{d}t + o(\mathrm{d}t), \\ P(\alpha(t+\mathrm{d}t) = \alpha_1 | \alpha(t) = \alpha_2) = \psi_2 \mathrm{d}t + o(\mathrm{d}t). \end{cases} \tag{11}$$

Whereas a GBM is used to model a process showing a positive, negative or zero trend with some random variations, the Markov process can model different states in one model (e.g. growth and recession phases). Because of this, it is expected that capacity investments will be lower under this approach, since overcapacity in times of recession has a high cost.

Alternatively, Poisson or Jump processes are often used in models in order to represent the possibility of sudden changes, for example following a newly available technology in R&D or new legislation (Weeds, 2002; Dixit & Pindyck, 1994). In this case, the sudden change, called the event, results in a jump. Such a stochastic process is written as a Poisson differential equation:

$$\mathrm{d}x = f(x,t)\mathrm{d}t + g(x,t)\mathrm{d}J, \tag{12}$$

with $f\mathrm{d}t$ the non random evolution over time, g also a known function and $\mathrm{d}J$ the increment of the Poisson process:

$$\mathrm{d}J = \begin{cases} 0, & \text{probability } 1 - \nu \mathrm{d}t, \\ u, & \text{probability } \nu \mathrm{d}t. \end{cases} \tag{13}$$

Here, u is the size of the jump caused by the event and ν the main arrival rate of the event.

6 Towards a real options application in ports

Elements of RO models that could be adapted for use in a port environment have been linked to each other and to the port environment. The objective hereof is to enhance port capacity investment decisions through our framework offering guidelines to build new RO models. This framework is applied in Section 6.2.

6.1 A framework to enhance port capacity investment decisions

The framework in Figure 2 combines the insights from the port uncertainty and RO models reviews. This framework visualises the different choices of components to be made when building a new model to decide on port capacity investments. First of all, decisions are to be made about the demand function for the output (i.c. port throughput). The mathematical specification of the function and the way of including uncertainty in this function need to be considered. Possible alternatives include a GBM, a Markov process, a Poisson process, a binomial process (Smit, 2003), a uniform distribution (Xiao et al., 2013), a mean reverting process (Dixit & Pindyck, 1994) or a vector autoregressive (VAR) process (Huisman et al., 2007). When more than one port needs to be considered, the inverse demand function should reflect competition between ports, with or without differentiated products.

A cost function for producing the output has to be selected as well. This function could be linear, quadratic or even of a higher degree in q. Besides a capacity-dependent variable cost, a capital holding cost could be added to the function. When a capital holding cost is included, investments to maintain the level of capacity are already accounted for. In that case, depreciation should not be included in the model. Next to the profit, also other benefits matter and could be included in the analysis. Different objectives can be combined by means of a weighted sum of these objectives. The sum of discounted profits and other benefits in each period of time minus the cost of investment together determine the value of the project. Other than the investment cost function of Dangl (1999), also a polynomial specification could be used, for example a higher order term to account for a limit to the project size. The value of the port authority's project is the objective that needs to be maximised. A slightly different approach is maximising the market value of the port authority, as a function of the ROA (Guthrie, 2012).

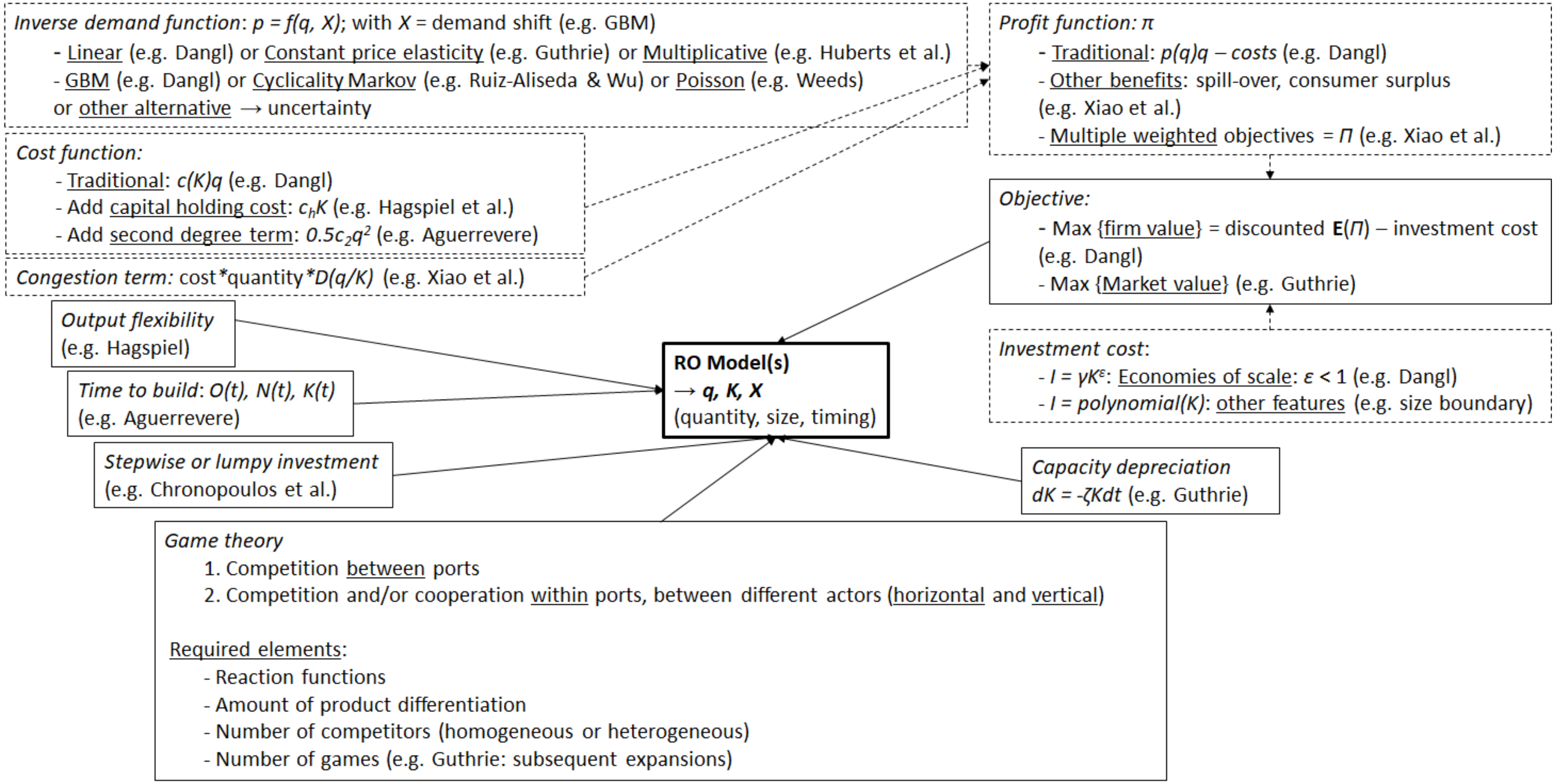
Other components that could be included are time to build, depreciation (when there is no capacity holding cost) and output flexibility. Finally, single-firm models can be expanded to game-theoretic models with more than one firm. The most appropriate specification will depend on a number of factors, such as the port characteristics, uncertainties and the research objectives. The presented framework should support the selection of the best building blocks when developing new port capacity investment models (Trigeorgis, 2005). The framework will also help better understanding, categorising and comparing existing RO models.

6.2 Applying the framework

In order to illustrate a potential application of our framework, we analyse the investment decision of a port in new theoretical design capacity. We start from a port that wants to maximise the revenues consisting of the sum of port dues and terminal handling prices. In such a port, the value of the firm comprises the combined objectives of the port authority and operators of the port (Meersman et al., 2015; Strandenes & Marlow, 2000). Those two parties may coincide in one enterprise, like in the private port of Felixstowe, owned by the port operator Hutchison Port Holdings (World Bank & PPIAF, 2007). This single entity wants to maximise the stream of discounted profits minus the investment cost with respect to the investment timing (T) and the capacity (K). The stream of profits is composed by the revenue (pq) minus the operational cost (a linear function in this initial setting) and the capital holding cost (see Figure 2). In the profit function, the concession payments are cancelled out, because this is an internal transfer from the TOC to the port authority and should not be considered here. This results in the following system of equations, which can be optimised through dynamic programming (Dixit & Pindyck, 1994):

$$\begin{cases} \max_{T,K}\{\mathbb{E}\int_0^{+\infty} e^{-r(T+t)}\pi(T+t)\mathrm{d}t - e^{-rT}I\}, \\ \pi = (p-c)q - c_h K, \\ p = p(\underset{+}{X}, \underset{-}{q}, \underset{-}{D}), \\ \mathrm{d}X(t) = \mu X(t)\mathrm{d}t + \sigma X(t)\mathrm{d}Z(t), \\ D = D(\underset{+}{\tfrac{q}{K}}), \\ 0 \leqslant q \leqslant K, \\ I = \gamma K^{\varepsilon}. \end{cases} \tag{14}$$

System (14) indicates that the price p from the inverse demand function is negatively related to the throughput quantity q and delay D and that it is positively related to a random shift parameter X. This parameter follows a GBM. Because congestion can result in a loss of potential demand (Jansson & Shneerson, 1982), the demand and congestion level are endogenised in our model. When congestion and delay increase, the customers' willingness to pay decreases, because they will incur the additional costs caused by congestion and delays. A possible shape of the positive relationship between the amount of waiting time delays D and the occupancy or utilisation rate q/K is visualised in Figure 3. D_1 and D_2 are two constants that are to be estimated empirically, using insights from queuing theory (Novaes et al., 2012). Additionally, output is limited by capacity. Producing no output $q = 0$ is also possible. The cost of investment I is initially based on the specification of Dangl (1999). When capacity expansions are studied, K has to be replaced by ΔK in the investment cost function.



Source: own composition, based on Huberts et al. (2015); Xiao et al. (2012); Dangl (1999); Hagspiel et al. (2016); Guthrie (2012); Aguerrevere (2003); Ruiz-Aliseda & Wu (2012); Weeds (2002); Chronopoulos et al. (2017).

Figure 2: Comprehensive framework of RO models and its components.

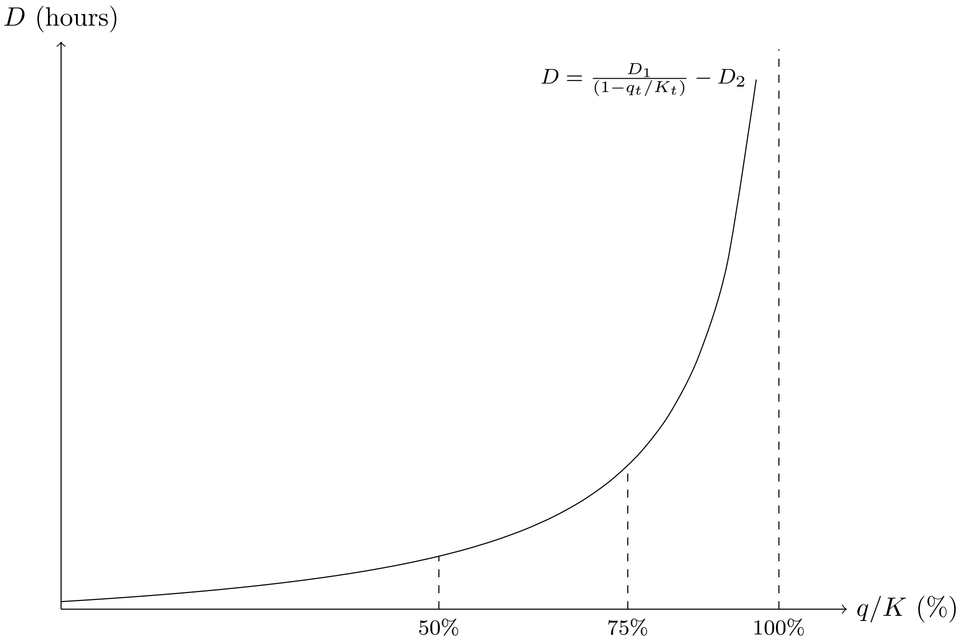


Figure 3: Positive relationship between delay and occupancy rate.

In infrastructure investment projects, demand and revenues are often overestimated, whereas costs are frequently underestimated. The latter could reduce the value of a project significantly. For this reason, we would like to suggest the inclusion of uncertainty both on the demand and cost side of the model (Van Putten & MacMillan, 2004). The latter could result in the inclusion of an additional state variable, with its own uncertainty. This would however complicate the analysis considerably, because the interaction between both distributions has to be included. This will in turn reduce the tractability of the model (Huisman et al., 2007). As a result, Monte-Carlo simulations might be needed.

The presented model from System (14) can be used to calculate an optimal investment threshold for X (expected to be reached at time T), the amount of capacity K and the throughput quantity q for a port. When building new RO models however, one always has to keep in mind the solution technique as well. A frequently used technique to solve RO models is dynamic programming. This technique is explained by Dixit & Pindyck (1994). However, often no analytical expression can be derived for the optimal values of some decision variables. Nevertheless, numerical solutions can be calculated and allow drawing conclusions on the dynamics of the model (Aguerrevere, 2003; Guthrie, 2012). In some cases, the optimum might also be approached by a good heuristic algorithm, but it does not guarantee reaching the actual optimum. Azevedo & Paxson (2014) provide such an example in RO games. Cucchiella & Gastaldi (2006) also use a software package to solve their RO model. The RO analysis might also be simplified by a binomial tree approach (Hu & Zhang, 2015) or a Monte-Carlo simulation to estimate some parameters involving processes characterised by uncertainty (Anda et al., 2009). Even spreadsheet approaches are available (de Neufville, 2006). This shows that the trade-off between the complexity and realism of the model on the one hand and the feasibility of the solution technique on the other hand, should be well considered when building RO models.

7 Conclusions

It is very important for a port to install the right amount of capacity, since undercapacity leads to congestion and waiting costs for the port users, while persistent overcapacity means that unnecessary investments and capital costs are incurred not only by the port authorities and private investors, but often also by the society. However, it is not easy to determine the optimal size of investments in port capacity, because a great deal of uncertainty has to be taken into account, especially because it often concerns large scale irreversible investment projects.

As ports are nodes in often long and complex logistics chains, they are subject to a wide range of uncertainties. It is necessary to account for the complex relationships between the maritime logistics chain actors, as well as uncertainty resulting from changes in global trade, technology, environmental factors, and the legal framework. Applying the traditional NPV in such a complex situation will in general lead to the wrong investment decision. In this case, RO models are a better alternative, since they specifically take into account the value of managerial flexibility under uncertainty. However, introducing all the different sources of uncertainty ports are facing in a RO model is not straightforward.

Starting from a review of these uncertainties and of the available RO models, we set up a framework which will help to categorise and apply RO models for port capacity investments taking into account the complex environment ports are operating in. Future RO models should include the relevant characteristics of the port or ports studied. This could for instance be achieved by selecting the most suited components from the presented framework. The port RO models can be expanded even further, with major or minor additions, in order to include more and more of the complex relationships between the actors in the maritime logistics chain. This however requires an increasing number of assumptions about the specification of the underlying stochastic processes and their interactions; and the estimates of their variances. Moreover, RO models are only applicable in a limited range of parameter settings, because of convergence conditions. Due to the complex mathematics of RO, the main challenge will remain to find the right balance between on the one hand having an acceptable and reliable representation of the port environment and on the other hand ending up with a tractable RO-based model.

Acknowledgements

This work was supported by the Research Foundation Flanders (FWO) under a PhD Grant. The authors would like to thank Trevor Heaver, Siri Pettersen Strandenes, Peter Kort and the participants of various conferences for their valuable comments to previous versions of this paper.

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