Port capacity investments under uncertainty: The use of real options models

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"The best way to predict the future is to create it."
– Abraham Lincoln, 16th President of the United States

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Matteo Balliauw, Sint-Niklaas, 24 Februari 2020.

Abstract

Port operations are important for worldwide and regional trade and for the development of regions. Investments in port capacity are required to perform these activities. Port infrastructure and some superstructure investments involve large sums of money, are irreversible and involve a lot of uncertainty. In the literature, real options (RO) have been identified as a methodology to improve investment decisions with a flexible size and timing under uncertainty. Elements of existing RO models from other sectors, suited for port capacity investment analyses, are combined in a framework, together with specific port-economic characteristics. Based on this, new RO port models are constructed to meet this thesis' objective, which is to study how optimal port capacity investment decisions are influenced by different port- and project-related economic characteristics under uncertainty.

In the developed models, throughput level, timing and size of the investment are flexible. As an addition to the literature, the users' congestion costs are added to the RO models for port capacity investments. Next to a base case benchmark model, a second model adds the possibility of a partially or fully publicly owned port authority (PA), as well as the division of cash flows and activities in a landlord port model between the two investing actors: the PA and the port operator. A third model adds inter-port competition to the base case model: two new ports, competing in quantities, are constructed according to a Stackelberg leader-follower model. A final model considers port expansion of one service port, as well as the construction lead time.

If port customers are on average more waiting-time averse, new port investment projects need to be developed later, and their size needs to be larger as well. In the case of port expansion, such an investment should be made earlier, whereas the impact on size is limited. Uncertainty leads to later and larger investments. Increased public ownership leads to earlier and larger investments in new ports, whereas expansions projects are even more anticipated if the public share is larger. In landlord ports, the two investing actors can agree to follow the investment strategy that would be optimal under a service port configuration. Otherwise, the PA can use the concession fee to force the terminal operator to invest in the PA's optimum. Inter-port competition reduces the option value of waiting. This leads to earlier and smaller leader investment, compared with its unrestricted strategy. The follower however will invest later and more.

Dutch executive summary

De activiteiten die in een haven plaatsvinden, spelen een belangrijke rol om de wereldhandel en de regionale groei te ondersteunen. Om deze activiteiten uit te voeren, moet een haven investeren. Elementen zoals maritieme en hinterlandtoegang, infrastructuur en superstructuur moeten allemaal aanwezig zijn om de goederen te kunnen overslaan tussen maritiem en achterlandvervoer. De hoeveelheid goederen die in een bepaalde tijdsperiode behandeld kunnen worden, bepaalt de capaciteit van een haven. In deze thesis wordt er gefocust op containerhavens, en meer bepaald op de investeringen in containerinfrastructuur en delen van de superstructuur. Daarom wordt capaciteit in deze thesis uitgedrukt in (miljoenen) TEU per jaar.

De beschouwde investeringen in havencapaciteit zijn grootschalig, duren lang om te bouwen, kosten enorm veel geld en zijn onderhevig aan heel wat onzekerheden. Daartegenover staat dat de beslissingsnemers een aantal flexibele opties hebben om de investeringsbeslissing aan te passen, zoals het vrij beslissen over de timing en de grootte van de investering, een flexibel outputniveau en gefaseerde investeringen. De literatuur heeft uitgewezen dat de reële optie (RO) benadering zulke beslissingen verder kan optimaliseren onder onzekerheid. RO zijn daarom een ideale uitbreiding van de huidige benadering voor het berekenen van kosten en baten. Aangezien deze RO methode nog niet uitgebreid toegepast wordt binnen haveninvesteringsbeslissingen, worden in deze thesis RO modellen uitgewerkt voor het beslissen omtrent haveninvesteringen. Het doel is om hiermee te bestuderen hoe optimale investeringen in havencapaciteit onder onzekerheid beïnvloed worden door project- en havengerelateerde economische omstandigheden.

Het tweede hoofdstuk start met een overzicht van de verschillende bronnen van onzekerheid in een haven. Deze omvatten de interacties van actoren in de maritieme logistieke keten, de onzekere evolutie van de wereldhandel en de technologische veranderingen als gevolg van verschuivingen in ecologische en politieke prioriteiten. Vervolgens worden voorbeelden van RO toepassingen binnen de transportsector besproken. Ook niet-transportgerelateerde RO modellen met relevante elementen voor investeringen in havencapaciteit worden besproken en gebundeld in een raamwerk. Dit raamwerk bestaat uit verschillende elementen die in een RO model kunnen voorkomen, alsook specifieke haveneconomische elementen, zoals het type vraagfunctie, kostenfunctie, congestiekosten,

constructietijd, gefaseerd investeren, flexibel outputniveau, havenconcurrentie, investeringskosten, andere doelstellingen van het havenmanagement en de te optimaliseren variabelen in de investeringsbeslissing. Het raamwerk kan gebruikt worden om bestaande RO modellen te beoordelen en te plaatsen in de literatuur, alsook om nieuwe modellen mee op te stellen. De RO modellen zijn continue tijd en continue status modellen, in lijn met de theorie van Dixit & Pindyck (1994). Zij maken gebruik van stochastische calculus (het lemma van Itō en de Bellman vergelijking) om de investeringsbeslissing onder onzekerheid te optimaliseren.

Het eerste uitgewerkte model in deze thesis is een basismodel waarmee de volgende nieuwe modellen vergeleken kunnen worden. Deze benchmark behandelt de flexibele investering in de infrastructuur en superstructuur voor een nieuwe private haven, die door de eigenaar ook wordt uitgebaat naar het service havenmodel en waarbij havenconcurrentie buiten beschouwing gelaten wordt. In dit model zijn output, timing en grootte van de investering flexibel. De grootste toevoeging aan de literatuur bestaat erin dat in dit model de congestiekosten meegenomen zijn in een continue tijd en status model op basis van een geometrische Brownse beweging. Deze congestiekosten zijn een onontbeerlijk element in haveneconomie. De resultaten tonen aan dat investeringsprojecten in nieuwe havens voor havengebruikers die meer avers zijn voor wachttijd, beter later gebouwd worden en aldus groter in omvang zijn. Hetzelfde geldt bij stijgende onzekerheid. In groeimarkten leidt langer wachten tot de mogelijkheid om meer inkomsten te realiseren. Deze dienen ook als buffer tegen mogelijke negatieve schommelingen ten gevolge van deze onzekerheid. Grotere markten vereisen over het algemeen ook grotere investeringen, om aan de vraag te kunnen voldoen. Andere veranderingen die havenprojecten interessanter maken, zoals lagere kosten, hogere groeivoeten of lagere discontovoeten, leiden ook tot grotere of eerdere investeringen, of de combinatie van beide.

In Hoofdstuk 4 wordt het eerste model uitgebreid met twee elementen. Enerzijds is er de mogelijkheid dat publieke instanties de haven gedeeltelijk of volledig in eigendom hebben. Anderzijds wordt er een opdeling gemaakt tussen de haveneigenaar en de havenuitbater, naar het landlord havenmodel. De resultaten tonen aan dat de nieuwe haven sneller en groter gebouwd moet worden naarmate het publieke aandeelhouderschap toeneemt. Bovendien kunnen de havenuitbater en de haveneigenaar negotiëren om samen te investeren in een gelijke capaciteit. Zij kunnen ervoor kiezen om de optimale investeringsstrategie van een equivalente service haven te volgen. Door middel van de hoogte van de concessievergoeding kan de havenautoriteit de terminaluitbater ook dwingen om de optimale strategie van de havenautoriteit te volgen.

Hoofdstuk 5 breidt het basismodel uit met concurrentie tussen twee havenbesturen die kunnen investeren in een nieuwe haven volgens een Stackelberg leider-volger model. Na de investeringen vindt er Cournot hoeveelheidsconcurrentie plaats tussen de havens. De haven met investeringskostenvoordelen zal als eerste investeren. Afhankelijk van de grootte van de investering van deze leider en de grootte van de markt op dat moment zal de andere havenautoriteit, de volger, wachten om toe te treden met een investering, of meteen investeren. Wanneer de kostenverschillen tussen de havens klein zijn, zal de leider eerder dan het eigen optimum moeten investeren. Hoe groter de concurrentie, bijvoorbeeld door een nabijere ligging, hoe eerder deze leider dient te investeren en hoe kleiner de investering bijgevolg zal zijn. Concurrentie holt de optiewaarde van wachten namelijk uit. Het gevolg is wel dat de volger later zal investeren en in meer capaciteit.

Het laatste model vertrekt opnieuw vanuit het basismodel, maar houdt rekening met de constructietijd en de reeds aanwezige capaciteit voor het bestuderen van havenuitbreidingen. De constructietijd verhoogt enerzijds onzekerheid, omdat er tussen de beslissing en het effectieve moment van ingebruikname schommelingen in de vraag kunnen plaatsvinden. Bovendien is dit ook een periode waarin nog geen inkomsten gegenereerd worden uit het nieuwe project, wat de attractiviteit hiervan negatief beïnvloedt. De impact van de constructietijd op de optimale investeringsbeslissing is echter niet eenduidig. Het is daarentegen wel duidelijk dat de expansiebeslissing niet identiek is aan de investering in een nieuwe haven. Havenuitbreidingen voor klanten die een grotere aversie hebben voor wachttijden, zullen in dit geval niet later maar eerder plaatsvinden, omdat er een grotere incentive is om de reeds bestaande congestie te verminderen. De impact op de grootte is echter beperkt. Ook een toename van publieke eigendom zal de havenuitbreiding relatief gezien veel vroeger doen plaatsvinden.

Hoewel de theoretische modellen belangrijke inzichten verschaffen in de invloed van verschillende factoren op de optimale investeringsbeslissing, zijn RO modellen complex om toe te passen in de realiteit. Bovendien is de kost voor het schatten van parameters of het maken van kleine aanpassingen in het model om de realiteit beter weer te geven, vaak zeer hoog. De reden is dat hiervoor vaak externe econometristen ingehuurd moeten worden. Omdat de potentiële baten van het toepassen van RO mogelijk nog hoger zijn, wordt in deze thesis een blauwdruk van een algoritme uitgewerkt om RO in een vereenvoudigde versie toe te passen in havens. Uiteraard dienen de gemaakte veronderstellingen steeds goed voor ogen gehouden te worden. Verder onderzoek kan op basis van de ontwikkelde modellen en inzichten in deze thesis leiden tot nieuwe modellen om de assumpties realistischer en de modellen toepasbaarder te maken. Een voorbeeld hiervan is een model met gefaseerd investeren, waarbij expansie, constructietijd, congestiekosten en concurrentie nog steeds worden meegenomen.

English executive summary

Port activities are important to support world trade and regional development. To perform these activities, ports need to invest. Elements such as maritime and hinterland access, infrastructure and superstructure all need to be present to transfer goods between maritime and inland transportation. The quantity of goods that can be handled in a given time period determines a port's capacity. This thesis focuses on container ports, and more specifically investments in container infrastructure and parts of the superstructure. Therefore, capacity is expressed in (million) TEU per year.

The considered port capacity investments involve large sums of money, long construction lead times, are large-scaled and are subject to a lot of uncertainty. Decision makers however have a number of flexible options to adapt their decisions, such as flexible investment timing and size, flexible throughput levels over time and phased investments. Literature showed that a real options (RO) approach can further optimise such decisions under uncertainty. Hence, this approach is an ideal extension for cost-benefit analyses. Since the RO methodology has not been widely used for port investment decisions, new port RO models are developed in this thesis. The objective is to use them to study how optimal capacity investment decisions in ports are influenced by different port- and project-related economic characteristics under uncertainty.

The second chapter starts with an overview of different sources of uncertainty in a port. These include interactions between actors in the maritime logistics chain, the uncertain evolution of world trade and technological changes due to changing ecological and political priorities. Subsequently, examples of RO applications in the transport sector are discussed. Also non-transportation RO models with relevant elements for port capacity investments are discussed and combined in a framework. This framework consists of different potential RO models as well as specific port-economic elements, such as the type of demand function, cost function, congestion costs, time to build, phased investment, flexible throughput level, port competition, investment costs, other port management objectives and the decision variables that are to be optimised in the investment decision. The framework can be used to discuss existing RO models in the literature, as well as to develop new models. The RO models in this thesis are continuous-time continuous-state models, in line with the theory of Dixit & Pindyck (1994). They use stochastic calculus (Itô's Lemma and Bellman

equation) to optimise investment decisions under uncertainty.

The first model developed in this thesis is a base case to which subsequent, new models can be compared. This benchmark deals with a flexible investment in infrastructure and superstructure for a new private port operated by the owner, i.e., a service port. Port competition is left beyond this model's scope. Throughput, timing and size of the investment are flexible. This model's main addition to the literature is the inclusion of congestion costs in a continuous-time continuous-state RO model involving a geometric Brownian motion. These congestion costs are an indispensable element in port economics. The results show that investment projects in new ports for more waiting-time-averse customers are to be larger and built later. The same holds for increased uncertainty. In growth markets, waiting longer to invest yields larger revenue opportunities, which serve as a buffer against potential negative deviations due to the uncertainty. Larger markets in general also require larger investments, to accommodate the demand. Other changes in the economic environment making the port project more attractive, such as lower costs, higher growth rates and lower discount rates, also result in larger or sooner investments, or a combination of both.

In Chapter 4, the first model is extended with two elements. On the one hand, public entities can fully or partially own the port. On the other hand, the distinction between port owner and port operator is made, i.e., a landlord port. The results here show that an increase in public ownership optimally leads to sooner and larger investments. Moreover, the port operator and owner can negotiate to invest at the same time in the same amount of capacity. They can choose to implement the optimal investment decision of an equivalent service port. Through the size of the concession fee, the port authority can also force the terminal operator to follow the optimal investment strategy of the port authority.

Chapter 5 extends the base case model with port competition between two port authorities that can invest in a new port according to the Stackelberg leader follower model. After investment, Cournot quantity competition takes place between the ports. The cost-advantaged port will invest first. Depending on the investment size of the leader and the size of the market at that time, the other port authority, i.e., the follower, will wait to enter or invest right away. These situations are respectively known as entry deterrence or entry accommodation. When cost differences between the ports are small, preemption will force the leader to invest before the own unrestricted, optimal timing. The larger the port competition, e.g., due to the ports being situated closer to one another, the sooner the leader will invest, and the smaller the investment will be. The reason is that competition drives the option value of waiting down. As a consequence, the follower will invest later and in more capacity.

The final model adds time to build and the already existing capacity to the first model. Hence, it involves port expansions. Construction lead time increases uncertainty, as the market can change in the time between the investment decision and the generation of the first revenues. Moreover, revenues are foregone during this lead time, which reduces the project's attractiveness. The impact of time to build on the investment decision however is ambiguous. Oppositely, the results do show that optimal port expansion decisions differ from the decision to build a new port. Expansions for customers who are more waiting-time averse will not take place later, but earlier, due to the larger incentive to reduce the already existing congestion. The impact on size is however limited. Also an increase in public port ownership will lead to a much earlier investment in the case of expansion decisions.

Notwithstanding the ability of theoretical models to provide important insights into the impact of different factors on the optimal investment decisions, the complexity of RO models reduces its applicability in reality. Moreover, the cost of estimating parameters or changing model elements to increase realism can become very high, because it often involves hiring external econometricians. Since the potential gains of applying RO can be even higher, a blueprint of an algorithm to implement a simplified RO model in ports is developed in this thesis. Of course, the underlying assumptions always need to be taken into account. Further research can build on the models and insights developed in this thesis to develop new models that further relax the underlying assumptions, to increase applicability even more. As an example, a model including phased investment would be an interesting extension of this research.

Contents

List of figures

List of tables

List of abbreviations

CS .... Consumer surplus

FC .... Fixed cost

FTE .... Full-time equivalent

GBM .... Geometric Brownian motion

GDP .... Gross domestic product

GT .... Gross tonnage

ICT .... Information and communications technology

IRR .... Internal rate of return

NPV .... Net present value

NT .... Net tonnage

PA .... Port authority

PPP .... Public private partnership

RMSE .... Root-mean-square error

RO .... Real options

RQ .... Research question

TEU .... Twenty-foot equivalent unit

TOC .... Terminal operating company

Chapter 1

Introduction

The different activities performed in a port are important for society. In order to transfer cargo between maritime and inland transportation, port investments are required. These investments provide the throughput capacity of a port. However, such investments are very costly for the port and for society, and need to be as good and efficient as possible. The maximum benefits from the investment are sought after at minimal cost. Since such investments are complex, lumpy and subject to a lot of uncertainty, and because some options for flexible investment are available for the decision makers, current investment appraisal and decision making methods fall short. More accurate models and more profound insights into port capacity investment decisions are required, both in theory and in practice.

1.1 A background on ports, port actors and port organisation

Ports are the interface between maritime and hinterland transportation. The main port business, cargo handling, involves activities to transfer cargo between maritime and inland transportation, such as mooring, cargo moving, handling (in a strict sense) and storage, piloting, tugging, customs, etc. In this way, ports form an important link in maritime logistics chains between origins and destinations everywhere in the world (Haralambides, 2002; Meersman & Van de Voorde, 2014a). Ports, port actors and decisions made in a port should be studied accordingly in a logistics chain approach (Coppens et al., 2007).

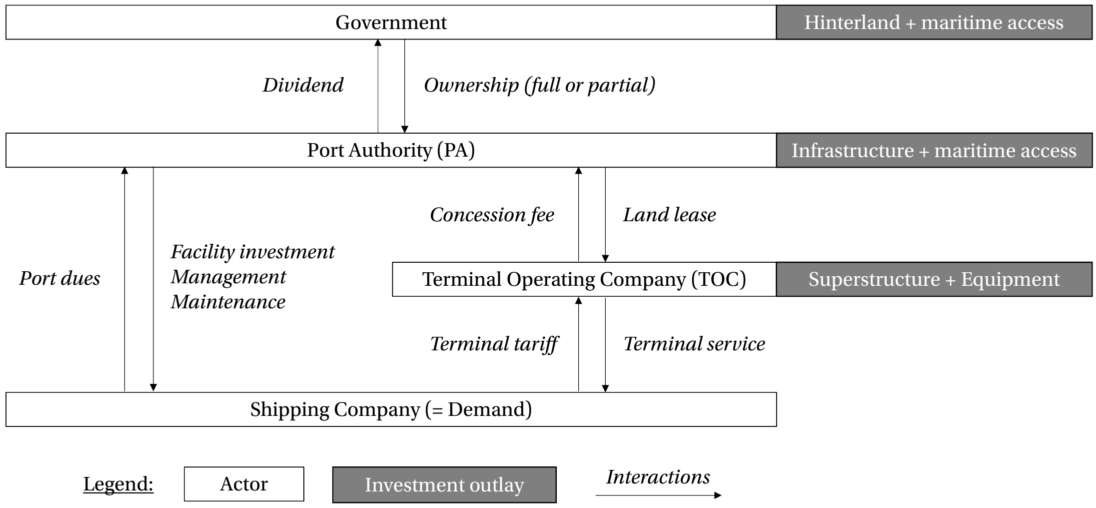
Ports are composed of many different intertwined actors influencing port decisions. Commonly, the most important actors are the port authority (PA) and the terminal operating company (TOC), but also the shipping companies and some smaller actors have an influence on the decisions taken in a port. Verhoeven (2015) identifies three important functions of a PA: landlord, regulator and in some cases operator of the port. Under the landlord function is comprised the daily management of the port; the maintenance of and investment in port infrastructure; and strategy, policy making and marketing. Additionally, the PA can act as a regulator, to ensure correct operations in the port. Finally, the PA may also operate the port and provide cargo throughput services itself. In that case, a port is classified as a *service port*.

In general, specific services such as tugging and piloting often remain under the responsibility of the PA (Meersman et al., 2015). Nevertheless, these special services have a relatively small impact on capacity. In some cases however, specialised providers operate these services under a concession agreement with the port, and earn a profit from this operation.

More frequently, the PA also grants a concession to provide the cargo throughput service to an external party, the TOC. The TOC obtains the right to exploit an area in the port, determined by a concession agreement, to service the ships and handle the cargo. The PA in this way outsources terminal operations to the TOC and in return earns a substantial revenue, the concession fee (Talley, 2009; G. W. Y. Wang & Pallis, 2014). Such a port is classified as a *landlord port*.[1] The landlord and service port models are historically the two main organisation typologies of a port.

The economic objectives of the PA and the TOC on both the operational and strategic level are strongly affected by their ownership structure. The PA can be owned publicly, privately or by a combination of both. The Anglo-Saxon Doctrine, stating that ports should be financially self-reliant, can be linked to private port ownership and striving for profit maximisation (Bennathan & Waters, 1979; Lee & Flynn, 2011). Public money is however very often involved in port projects throughout the world (e.g., public-private partnerships), because investments in port capacity involve large sums of money (Vanelslander, 2014). Meersman (2005) showed that in Europe the PA, whether or not corporatised, is frequently partly or fully publicly owned. In the Hamburg - Le Havre range for example, the ports of Antwerp and Rotterdam have this structure (Zachcial et al., 2006). The public PA invests and owns the infrastructure, but the superstructure and the equipment are both installed and exploited by TOCs. Under this Continental (European) Doctrine, ports are considered to be part of the social infrastructure. This is similar to the Asian Doctrine, where the central government involvement is however very high and where multiple ports are often developed centrally, possibly encompassing cross-subsidisation (Lee & Flynn, 2011). Oppositely, a TOC is most often a private party (Tsamboulas & Ballis, 2014; Estache & Trujillo, 2009), but it could in theory also be publicly owned (Lacoste & Douet, 2013). According to Heaver et al. (2001), competing private operators invigorate efficient terminal performance.

[1] This is in some literature distinguished from a tool port, where the superstructure and equipment are operated but not owned by the TOC (See e.g., Estache & Trujillo (2009)). Tool ports however are not frequently observed in reality and are not further discussed in this thesis. In financial terms, they could be modelled using a landlord port model, but replacing the TOC's investment cost by an additional rent paid to the PA in exchange for using the superstructure and equipment, which are both financed by the PA.



Source: Zachcial et al. (2006).

Figure 1.1: Revenue sources and investment outlays of the actors in a port.

For a PA, Suykens & Van de Voorde (1998), Tsamboulas & Ballis (2014) and Xiao et al. (2012) discern potentially conflicting objectives: profit maximisation, throughput maximisation as a driver of economic development, social welfare maximisation and minimisation of the generalised cost for the customers. When a PA is privately owned, it focuses on profit maximisation, whereas a public party has more attention for social welfare and throughput maximisation. In the case of mixed ownership, it could be a weighted combination of these different objectives. Additionally, a port is well aware of it being part of a maritime supply chain wherein the customers are waiting-time averse. When waiting time and the extra cost to shipping companies increase, the latter are more likely to call a competing port, in order to guarantee a supply chain with a lower generalised cost. The port takes this consideration into account and tries to reduce the waiting time and generalised cost for its customers. Hence, profit, throughput and welfare maximisation are not the only objectives of the PA. Oppositely, the TOC's only objective as a private company is maximisation of the individual company's profit (Tsamboulas & Ballis, 2014). These considerations are reflected in the capacity investment decision and at the daily operational level of both the PA and the TOC. They also have an impact on the concession fee strategy of the PA. The PA will set a different size and type of concession fee depending on the relative importance of the profit and throughput maximisation objectives in its strategy (Heaver et al., 2001).

Figure 1.1 shows the sources of income a TOC and a (partly) publicly owned PA receive in exchange for the specific services they offer to the different actors. Alderton (2008) and Meersman et al. (2015) state that different determinants make up the price of the port service. The price structure is not uniform over different ports and is often lacking transparency. For example, port dues, paid by the shipping companies to the PA, are very complex. They may depend on gross tonnage (GT), net tonnage (NT), destination in the port, number of locks passed, length of the ship, amount of cargo handled, time staying in the port, liner service or not, quantity reductions, etc. (Degroote, 2015; Port of Antwerp, 2017a). In exchange, the PA takes care of facility investment, management and maintenance in the port (Zachcial et al., 2006). The terminal tariff is set by the TOC and paid by the shipping companies for the handling of their transported goods. It may depend on the number of movements or the number of containers handled. In some cases, extra payments are received, e.g., for storing goods. Depending on the trade and time period considered, the relative importance of these extra payments in the TOC's total income is however rather limited, as they consist at most of 15% of total TOC revenue. Moreover, these extra services are not applied to all goods handled (Jenné, 2017). Also, the discussed concession fee paid by the TOC to the PA is included in Figure 1.1.

1.2 The economic importance of ports

Port activities facilitate international transportation of goods, international and regional trade, of which more than 80% is seaborne, and economic development of a region (Munim & Schramm, 2018). The economic impact of ports is hence broader than profit generation alone. The economic importance of the port sector is typically measured and quantified through its direct, indirect, induced and catalytic effects in terms of value added and employment. Value added is defined as the value that a port adds through its activities to the value of the used inputs. In this way, it is a quantification of a port's contribution to the gross domestic product (GDP) of a country or region. Employment expresses the average number of full-time equivalents (FTE) that are working in the sector during a financial year (van Gastel, 2016). Cooper & Smith (2005) and Oxford Economics (2015) state that direct effects, which constitute the primary impact, are generated by the firms situated within the port. According to Davis (1983), the secondary impact of ports consists of indirect and induced effects. Indirect effects are generated by the actors down the supply chains of the port firms. Induced effects are generated by the organisations that earn from the the employees of the firms generating direct and indirect effects spending their income. Finally, economic catalytic effects encompass other spillover benefits and consumer surplus resulting from the port activities, as they contribute to trade and long term productivity (Musso et al., 2006). The latter however are the most difficult to quantify. Next to the economic impact, port activities also make an important contribution to the tax income of a country (Benacchio et al., 2000; Oxford Economics, 2015). Finally, ports are also an engine allowing other national industries to grow, such as manufacturing, logistics and transportation (Benacchio et al., 2000).

A meta-analysis by Olaf Merk for OECD shows that, on average, 100 dollar of direct and indirect added value is created per tonne handled in the port. For containers, the average is 90 dollar per tonne, the minimum is 40 and the maximum is 150. As far as employment is concerned, one million tonnes lead on average to about 800 jobs (OECD, 2014). Notwithstanding the positive impact of ports on the economy, they also cause a number of negative effects and external costs. OECD (2014) mentions air, water and soil pollution, noise, waste production, an unpleasant visual impact, large land occupations and the creation of traffic congestion in the surroundings of the port.

A number of studies concentrating on individual countries and ports exist as well. In Belgium, the port of Antwerp is the major port in terms of value added. It generated between 10 (in 2012) and 11.5 billion euro (in 2017) of direct value added per year. It is followed by Ghent, Liège (an inland port), Zeebrugge, Brussels (a second inland port) and finally Ostend. In total, the direct effects generated by the Belgian ports ranged from 16.5 (in 2012) to 19.4 billion euro (in 2017), of which 4.4 to 4.8 billion euro were generated by the maritime cluster. This maritime cluster involves among other things cargo handling activities, shipping companies, shipping agents and forwarders. The cargo handling activities generated between 2 and 2.3 billion euro in the same years. Other, non-maritime port activities represented the majority of the direct value added: between 12 and 14.6 billion euro per year. The indirect effects ranged from 13.5 to 16 billion euro, again between 2012 and 2017. In total, Belgian ports generated between 30 and 35.3 billion euro per year in terms of direct and indirect value added. In 2016, the four Flemish seaports accounted for over 7% of the Belgian GDP, and more than 12% of the Flemish GDP. (Gueli et al., 2019; Merckx, 2018)

As far as employment is considered, Antwerp is still the largest port in Belgium, employing between 61 000 and 62 000 FTEs between 2012 and 2017. In total, the direct employment in the Belgian ports is slightly below 120 000 FTEs. Total employment is about 255 000 FTEs. The maritime cluster accounts for about 40 000 FTEs, of which about 20 000 FTEs perform activities related to cargo handling.

For the Netherlands, van der Lugt et al. (2018) estimated the direct added value of sea port activities at about 28 billion euro and the indirect added value at about 14.5 billion euro in 2017. As far as employment is considered, direct employment amounted to 184 000 FTEs and indirect employment to 166 000 FTEs. The port of Rotterdam accounts for almost half of the direct effects. When focusing on cargo activities, 5.9 billion out of a total of 7.2 billion euro added value is created within the Dutch port areas. 36 200 out of a total of 47 700 cargo related FTEs are working within the Dutch port areas.

In the UK, the direct value added of ports in 2015 was estimated by Cebr (2017) at 10.6 billion euro (1 GBP = 1.4 euro). The indirect value added for 2015 was 11.6 billion euro. Cebr (2017) also estimated the induced value added, estimated at 11.2 billion euro in 2015. In terms of employment, the direct, indirect and induced effect for the UK ports in 2015 amounted to 101 000, 319 000 and 276 000 jobs respectively (Cebr, 2017). These figures are in line with those of Oxford Economics (2015) for 2013.

In the USA, coastal seaport cargo activities are crucial for the economy. The direct business revenues generated by the port sector amounted to about 125 billion U.S. dollar in 2014. In total, when also importers' and exporters' activities are considered, seaport cargo activities accounted for 26% of the U.S. economy, as they generated about 4.6 trillion dollar in 2014. In terms of taxes, direct port sector activities resulted in about 8.2 billion dollar of income for the American government. The indirect and induced taxes amounted to about 33 billion dollar. As far as jobs are considered, about 542 000 direct, 372 000 indirect and 823 000 induced jobs are created within the port sector. (Martin Associates, 2015)

1.3 Investing in ports is indispensable

There are two main characteristics of good logistics performance of ports, namely low logistics costs and high reliability of the operations (Munim & Schramm, 2018). In order to perform port operations effectively and efficiently and generate added value in a port, investing to build new or expand existing ports is crucial. A port's ability to provide cargo throughput services is quantified in terms of its capacity. It is often expressed in twenty-foot equivalent units (TEU), tonnes or number of ships that can be handled per year. Next to building new capacity-increasing elements, capacity can also be increased through the optimisation of existing terminals (ESCAP, 2002; Kauppila et al., 2016). Each of these investment types will allow generating more throughput at better service levels (Musso et al., 2006). Since port capacity installed by investors increases the service level of the operators, the generalised cost in the logistics chain will fall, and also shippers and consumers will experience benefits from these investments. Musso et al. (2006) refer to this concept as a port investment chain.

Disposing of insufficient service capacity to handle cargo could involve congestion, leading to high logistics costs (Novaes et al., 2012). In a port, a service environment, and in transportation in general, it is even more important than in a production environment to dispose of the right amount of capacity, since the transport service is not storable (de Weille & Ray, 1974). Capacity that is not used at the actual time period cannot be stored and used in the next, as opposed to warehoused goods. Undercapacity cannot be covered either by unused outputs from a previous period. Since the demand for cargo throughput is uncertain and variability may become high, it might occur that moments of empty berths are followed by moments in which ships are waiting to be serviced at a berth that is currently occupied. In this way, congestion and waiting time might start to build up in the port from occupancy rates of about 50% of the theoretical design capacity, the maximum amount of throughput that can be handled by a port in a certain time period. Above 75% to 80%, waiting times increase more than linearly (Blauwens et al., 2016; Kauppila et al., 2016).

A mismatch between demand and capacity can result in periods of capacity scarcity or overcapacity. Without sufficient capacity, i.e., undercapacity, the port risks losing customers, throughput and profit due to the congestion building up. This results in a loss of social welfare in the form of lost consumer surplus. However, installing capacity comes at an investment cost, positively related to the amount of installed capacity. Hence installing too much capacity, i.e., overcapacity, poses a problem as well, as money is invested in capacity that is not used and that hence does not generate revenues. This gives rise to a trade-off between investing too much money in unused capacity and investing in too little capacity, which leads to higher user waiting costs and which might eventually lead to losing customers and profit (Meersman & Van de Voorde, 2014a). This capacity investment trade-off is even more complicated by the uncertainty in the port (Musso et al., 2006). As a result, installing the right amount of capacity at the right moment is crucial, as additional port capacity is required everywhere in the world (Vanelslander, 2014). Therefore, this thesis explores how ports can deal with this crucial trade-off between investment costs and internalised user waiting costs in port capacity investments under uncertainty.

In reality, overcapacity is often encountered. As a result of large investment sizes, high costs and long completion times of port capacity investment projects, it is more beneficial to initially install more capacity than needed in the first periods of use. If overcapacity is present, prices may be lowered to attain a desired capacity utilisation rate while awaiting demand increases for port services (Meersman et al., 2010; Xiao et al., 2013). Overcapacity may also exist in a port to reduce the attractiveness of a competitor's investment option, known in the literature as entry deterrence. Finally, (especially large) ships require overcapacity to reduce the probability of waiting at the dock (Huberts et al., 2015; Musso et al., 2006). The latter consideration demonstrates the importance of a joint analysis of the amount of available capacity, the amount and the timing of capacity expansions, the level of output and the output price, paid by the shipping company to the PA and the TOC (Strandenes, 2014). In case of undercapacity, congestion pricing could be applied to reduce utilisation rates and increase revenues, but the theoretical design capacity remains an upper limit to the port throughput (Zhang, 2007).

The previous discussion demonstrates that investing in port capacity is crucial, both in the long and in the short term. As Musso et al. (2006) argue, investing in port capacity allows increasing throughput at a moment that the demand for it becomes present. Due to increased port activities and resulting factor demand increases, different effects can be realised. Two effects are especially important in the short term: a direct profit for the owners of the investment and microeconomic benefits due to a reduction of generalised costs. Positive and negative macroeconomic effects in the long term involve economic growth and increased employment on the one hand and external costs on the other hand.

Long term

In the long term, consequences of port capacity shortages may involve freight delays and increased trade distances, leading to a growth slowdown of a region's GDP and worldwide trade. Maritime transportation on average is expected to more than quadruple between 2010 and 2050, although individual growth rates per port may differ and even become negative for some ports over a certain period of time. Consequently, the demand for cargo throughput services is growing, especially in the container segment, although this demand is also uncertain (De Langen et al., 2018). By 2030, container traffic related to international trade is expected to more than double, whereas by 2050, it is expected to become the threefold of current container traffic. As a result, additional port capacity is a prerequisite to accommodate the expected increases in worldwide maritime trade volumes. (Musso et al., 2006)

In reality, ports are aware of this necessity. Port capacity expansions that are planned until 2030 are expected to be sufficient to handle the additional trade volumes, except in South and Southeast Asia. If such capacity expansions are not installed however, freight delays are expected to increase with 48% by 2030 and with 84% by 2050. Moreover, due to the congestion that would arise as a result, trade distances could rise by 43% by 2030 and by 65% by 2050. (Kauppila et al., 2016)

Although maritime trade on average is expected to grow, some future evolutions in socio-economic factors may slow down or even reverse this growth. One important factor is the level of economic activity, as it has a strong, positive impact on the demand for transportation. In turn, this is influenced by economic cycles, investment decisions, demographics, political decisions, trade wars, geopolitical conflicts and technological evolutions (both in transportation and in other sectors) (Preston, 2001). Transportation of goods by drones and 3D-printing might both alter demand for maritime transportation, as transportation of raw materials might substitute (half) finished products, in turn having an impact on the transportation mode used. For ports, it is important to monitor these long-term evolutions, as they will impact the need for port capacity.

Short term

As a result of bottlenecks in the port and subsequent delays, shippers, forwarders and shipping lines incur a cost, i.e., the congestion cost, because for example goods may deteriorate or services might have to be rescheduled. Given the fact that cost competitiveness drives the shipping industry, the shipping companies will avoid such waiting costs as much as reasonably possible (Kauppila et al., 2016). As shown by Blauwens et al. (2016) and De Borger et al. (2008), the value of time for a ship waiting in the port can be high and makes up an important part of the generalised cost of the maritime logistics chain. Aversion to waiting moreover differs among users and among goods categories. The value of time can be estimated using stated or revealed preference experiments (De Jong, 2007; OECD, 2014). For example, liners shipping (white) reefer containers with food are more waiting-time averse than liners transporting containers with construction materials.

Sufficient capacity is needed in the short term. Congestion and its costs, resulting from capacity shortages, add an extra aspect to inter-port competition. Moreover, because the overlap of port hinterlands has increased over the last decades, inter-port competition has increased too (Musso et al., 2006). Such competition might lead to free, also called unused or idle, capacity in one port attracting throughput from a nearby congested port with high waiting times. This proves that the cost of congestion for the port customers needs to be considered by the port when studying the investment decision in additional capacity to decrease the probability of waiting and the resulting congestion costs (Macário, 2014).

Technological requirements

Small and fast capacity increases can be realised through the optimisation of terminal efficiency, e.g., through automation or a more efficient organisation of activities (Kauppila et al., 2016). Also extended opening hours can increase capacity. The environmental requirements for the maritime and port industry are expanding as well, in order to increase environmental sustainability through a reduced impact on the environment. To this end, ports may be obliged to invest in new noise and pollution reducing technologies (Kauppila et al., 2016).

Investing in safety measures to protect the port from adverse effects of climate change, such as rising sea levels, might be appropriate (K. Wang & Zhang, 2018). Due to spillover effects, investing early in climate change adaptations increases social welfare under uncertainty (Randrianarisoa & Zhang, 2019). In addition, investing in new, advanced information systems could enhance the exchange of information in port communities. In turn, operations in the logistics chain could be managed and coordinated in a better way. This is important, because disposing of correct information is at least as important as the cargo delivery itself for customers and transportation companies (ESCAP, 2002).

Finally, increasing average and maximum ship size as a result of liners further exploiting economies of scale and specific newly developed engines for large ships also have an impact on the need for port investments (ESCAP, 2002; Kauppila et al., 2016; Musso et al., 2006). Ports that want to accommodate these larger ships have different capacity requirements and need to adapt their operations. For example, access channels and berths need to be deeper, quays need to be longer and stronger, cargo storage areas need to be larger, cranes need to be larger (Kauppila et al., 2016), tugs need to be stronger and ship passages (such as channels, locks, turning points, etc.) need to be wider (Sys et al., 2008). Hence, it is important for port capacity investment decision makers to also take the investment decisions of ship owners into account.

1.4 Throughput capacity of a port

In order to discuss port capacity and the investment herein, it is important to first study in detail the different definitions of capacity and its constituting elements. The theoretical design capacity measures the maximum amount of cargo a port can handle (i.e., throughput) on a sustained basis over a predetermined time period, e.g., one year (Dekker, 2005). It is opposed to the commercial capacity of a port, which expresses the maximum amount of throughput that can be realised on a sustained basis at a predetermined service level (Kauppila et al., 2016; Rashed, 2016). This service level is often defined by the TOC. Hence in practice, commercial capacity does not exceed 75% of the theoretical design capacity, since waiting times start to increase sharply from such occupancy rates (Kauppila et al., 2016). Both capacity definitions are often expressed in TEU, tonnes or number of ships per year.

In this thesis, the focus is on the theoretical design capacity for two reasons. First, this definition is independent of the service level that a specific TOC wants to achieve. In that way, consistent comparisons of capacity between different ports and terminals are possible. Second, this approach does not necessarily exclude high occupancy rates and resulting waiting times in ports. This is a prerequisite to be able to analyse the economic impact of congestion on port investment decisions.

Capacity is determined by a complex interaction of different elements like infrastructure and superstructure, and is often approached from an operational perspective (Novaes et al., 2012). The capacity in a port in a certain time period is influenced by different constituting parts. These components are discussed in the following subsection. Subsequently, it is pointed out that all these parts need to be well adjusted to one another. A lack of alignment of only one component may already reduce capacity significantly, as capacity is very sensitive to bottlenecks (De Langen et al., 2018).

1.4.1 The determinants of capacity

In port capacity literature, different overviews of the constituting elements of port capacity are available. The overview here is composed from a capacity investment perspective (Alderton, 2008; Dekker, 2005; De Langen et al., 2018; Kia et al., 2000; Maloni & Jackson, 2005; Meersman & Van de Voorde, 2014a; Musso et al., 2006; Vanelslander, 2014; Zachcial et al., 2006):

- **Maritime access:** Locks, lights, buoys, channels and breakwaters;
- **Port infrastructure:** Berths, docks, basins, internal connections, storage areas and quay walls;
- **Port superstructure and equipment:** Paving,[2] lighting, gates, fences, sheds, build-

[2]Some sources classify paving under infrastructure (plus), others classify it under superstructure. This also depends on which actor invests in it. Here it is decided to classify it under superstructure, as for example in the port of Antwerp, paving is to be provided by the terminal operator.

ings, offices, cranes, pipes, warehouses, straddle or gantry carriers and ICT. These elements are strongly influenced by available technology;

- **Labour and operations:** Port workers, administrative staff, customs, working hours, labour organisation and division, stacking process, division between empty and full containers;[3]
- **Hinterland access:** Road, rail and inland navigation connections.

Not only the presence and amount of these different elements, but also their maintenance define the theoretical capacity (Alderton, 2008). Without maintenance, many of these elements may deteriorate, reducing their productivity and capacity. Additionally, a port's design capacity is limited by the element or elements with the lowest capacity, which can be seen as the bottleneck(s). The importance of this holistic approach is highlighted by Kauppila et al. (2016).[4]

1.4.2 Port actors influence capacity as well

The different, intertwined actors in a port influence the aforementioned elements of port capacity to handle the goods (De Langen et al., 2018). Figure 1.2 shows where the stakeholders from the maritime chain have an impact on capacity. First, there are the customers of the port: the shipping companies. They bring the goods to the port, through the maritime access provided by the port authority and governments. The port's throughput is not only limited by its own capacity, but also by the total capacity of the shipping companies calling at this port (Maloni & Jackson, 2005). Ports will not handle more goods than what the ships can carry.

Subsequently in the port, the PA and the TOC have the decision power over port infrastructure, superstructure and equipment investment. This is explained in detail in Section 1.4.3. Moreover, they organise labour by hiring port workers (Maloni & Jackson, 2005). This represents the majority of the variable costs of throughput. Additionally, both the number of pilots and the number of tugboat operators influence capacity.

[3]The amount of labour is considered as a flexible input. Increasing working time or the number of workers has a positive impact on port capacity. Also the way labour is organised, operations are coordinated and equipment and available technology are managed, determine the productivity and capacity of a port.

[4]An example clarifies this statement. Suppose that annually 10 million TEU could enter the port (maritime access capacity) and could also be handled (port infrastructure, superstructure and equipment capacity), but that only 8 million TEU could leave the port, because there is not sufficient hinterland access capacity (roads, railways and inland waterways). In this case, the design capacity of the port is only 8 million TEU and is limited by the hinterland access, which is the bottleneck. The capacity of the port can be expanded to 10 million by increasing hinterland accessibility in order to be able to ship the additional 2 million TEU into the hinterland. In that case, the bottleneck disappears. If the port subsequently wants to increase its capacity to 15 million TEU, this can be achieved by increasing all the aforementioned constituting elements of capacity by 5 million TEU.

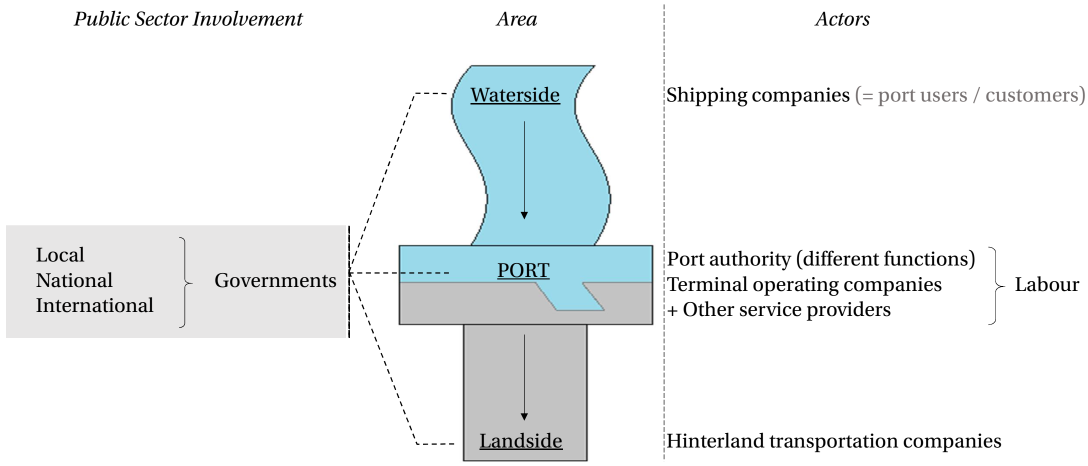


Figure 1.2: Maritime chain actors influencing capacity.

The last actors in Figure 1.2 are the hinterland companies, using road, rail and inland waterways connecting the port with the hinterland. These connections are often partly provided by the port authority and partly by the government. Hinterland companies or connections being unable to move the goods out of the port before new goods arrive, or move the goods into the port before the ship leaves, may cause congestion within the port, leading to a capacity reduction as well (De Borger et al., 2008).

1.4.3 The capacity investment decision making process in the port

Different decision makers interact in port capacity investment decisions. This results in a complex decision making process, which varies with the type of port studied (Meersman, 2005). When the PA of an active port experiences congestion building up at the current infrastructure, when operational efficiency cannot be further increased and when the congestion pricing mechanism cannot be (further) exploited in a profitable way, the PA considers the infrastructure to be a bottleneck. Hence, the responsible government(s), possibly in collaboration with the PA, start(s) to develop plans for the investment in additional infrastructure (e.g., a new dock). If there is no port in place yet in a region, plans to build a new port are developed when sufficient maritime traffic to or from the region under consideration is expected to justify the construction of this new port (Novaes et al., 2012; Ward, 2015). If the port is a private service port, the decision making process is less complicated than for a public landlord port.

In the case of a private service port, there is one single actor which both installs and operates the infrastructure, superstructure and equipment. Hence all revenues and costs are on its account. Since profit maximisation is the objective, such a port needs to compare all expected revenues and costs. When sufficient profit, compared to the weighted average cost of capital, is expected so that it is better to invest rather than to wait longer, the port will decide to go ahead with the project and install the new capacity. Subsequently, it will receive all revenues, which include port dues and terminal handling charges.

However, due to the large scale of port infrastructure projects, a part of or the entire investment is very often funded with public money. In many cases, such as the port of Napier in New Zealand, service ports are partly or fully publicly owned. In such cases, not only profit will matter, but all welfare effects will be considered. As opposed to the private owner, a public owner is interested in the total throughput and employment as well. Not only direct economic effects are considered in the cost benefit analyses or economic impact studies. Also indirect and induced effects require attention. However, some other effects, such as the catalytic effects, are considered as well, although they are difficult to quantify in monetary terms. For a government, it matters that total benefits outweigh the costs (Musso et al., 2006).

Before, when governments decided on port investment projects, a lot of projects were funded on a first come, first served basis, as governments had sufficient money. Large amounts of money were invested in the development of ports by these governments (Haralambides, 2002). Nowadays, this is no longer the case. The scarce resources are allocated to projects with the best business cases, which optimise the objectives of the funder. Different business cases enter in competition with one another for the (public) money. In 2015, for example, the Flemish government decided to expand the container capacity of the Port of Antwerp, to avoid liners losing time due to congestion in the port (RebelGroup Advisory Belgium, 2015). This decision is only the first of four steps in the process. Different alternatives need to be considered and studied in detail in the second phase. The addition of a new dock, Saeftinghedok, is only one of the nine possible scenarios discussed in 2019. The outcome of this second phase is a preferred scenario, which needs to be developed in full in the third planning phase. With the project decision made in that third phase, the execution can be realised in the final, fourth phase. The time-consuming construction works however need to be as efficient as possible (Flemish Government, 2019).

In a landlord port, such as the port of Antwerp, the investment process is complicated by the involvement of multiple actors. In this case, the (often) partly or fully publicly owned PA is not the only actor deciding about future capacity. Also the TOC has a role to play. Since the PA and the TOC have different revenues and costs (see Figure 1.1), their optimal investment decision will differ as well. Additionally, in the case the PA is publicly owned and the TOC privately, the PA and the TOC would even have different and in some cases opposing objectives, i.e., welfare versus profit maximisation (Musso et al., 2006). The decision making process would comprise two decisions. The PA would first have to decide on and install the infrastructure. When deciding about the investment however, it could be beneficial to previously consult potential TOCs about their development plans (Port of Vancouver, 2015). After completion of the infrastructure, the PA can grant the TOC with the most attractive project the concession agreement. This TOC subsequently installs the superstructure and equipment. Hence, the timing of the TOC's investment cannot be before the PA's investment, nor can the capacity exceed the capacity installed by the PA. After completion of the terminal, the TOC can operate the terminal and handle the cargo. Nevertheless, the PA should already take into account the available information about the expected revenues from the future concession agreement, i.e., the concession fee paid by the TOC, when deciding about the infrastructure in the first step. This information is available to a port's PA to the extent that it disposes of the necessary information about the terminal operators already active in the port. The concession fee is an important revenue for the PA that allows recovering investment costs (Haralambides, 2002).

1.5 The cost of port investments

Investing in ports involves large sums of money. Not only the development of the land is costly, also the land itself has a high value. Land used for port activities is situated close to the water, and hence has a high opportunity cost due to a wide variety of valuable other potential destinations for the land (Haralambides, 2002). This section discusses the required investment budgets and the effectively made port investment outlays in different countries.

According to Merckx (2018), the Flemish region invested 415 million euro in its ports in 2017, of which slightly more than 60% was needed for maritime access works. Of the 69 million euro invested in Antwerp, the majority involved maintenance and renovation works. Gueli et al. (2019) show that in the Belgian ports, the direct investments amounted to 4.8 billion euro in 2017. Almost half of it was invested in Antwerp. The total maritime investments amounted to 1.9 billion euro, of which 0.9 accounted for cargo handling related investments, 0.3 for port construction activities and the remainder for shipping companies and other maritime activities. In 2003, when the new Deurganckdok project was nearing its completion, the investment of the Flemish region in Antwerp was at its highest point at 170 million euro. In 2004, 160 million euro were invested (Merckx, 2018). The total cost of the Deurganckdok, constructed between 1995 (initial study work) and 2006, was 670 million euro (Vanelslander, 2014). Quay wall construction and dredging accounted for the majority of the costs (almost 75%). At the same time, these were also the cost drivers causing the largest cost overruns. In total, cost overruns amounted to about 230 million euro. According to Freddy Aerts, head of the Maritime Access Division of the Flemish government, construction of the new Saeftinghedok is expected to cost between 0.9 and 1.5 billion euro.

In Rotterdam in the Netherlands as well, an important expansion took place between 2004 and 2013. The new facilities at Maasvlakte 2 have been installed in phases, at a total cost of 2.9 billion euro (Port Consultants Rotterdam, 2018). According to Vanelslander (2014), the list of future port infrastructure investments in Europe is small. However, according to a survey of De Langen et al. (2018) and their subsequent extrapolations, investments of about 50 billion euro are needed in the European ports in the period 2018-2027.

As far as port investments are considered, there are important differences among geographical regions. Based on estimated trade volumes using a four step model approach, Kauppila et al. (2016) state that the need for additional capacity is the largest in Asia and Africa. In Africa, economic growth is supported by an increase in port projects, especially in the northern and western regions (Vanelslander, 2014). Large investments are taking place in Asia and the Pacific region. According to ESCAP (2002), between 2001 and 2011, 400 additional berths were needed, corresponding to an investment need of about 27 billion U.S. dollar. In India, the government planned to invest 12 billion U.S. dollar in its ports over the period 2012-2017, mainly in new terminals, expansions and navigation channels. Between 2010 and 2020, a total of 66 billion U.S. dollar is anticipated in India, of which the majority is to be funded privately. Also in China, where many ports are financed by the central government (Lee & Flynn, 2011), and in Singapore, large sums of money are invested in the ports (Vanelslander, 2014).

American ports are constantly seeking to expand their capacity as well (OECD, 2019). According to Vanelslander (2014), the major American ports had planned to invest about 8.5 billion dollar between 2012 and 2017, mainly in container terminals and dredging. However, investments of more than 30 billion dollar would be needed by 2020 to remain competitive. Therefore, the U.S. government provides, as part of the FAST programme, 4.5 billion dollar of funding over five years for a number of port projects (ASCE, 2019). Moreover, U.S. ports are planning to invest about 155 billion dollar between 2016 and 2020, mainly for expansion, maintenance and innovations.

In Latin America, the majority of port investments are taking place in Brazil. Between 2010 and 2013, the government invested about 6.4 billion U.S. dollar, especially in new ports, port expansions and port upgrades. Next to Brazil, also projects in Mexico, Chile and Peru are developed. Finally, also the Middle East, a small region disposing of a lot of capital, further develops its port infrastructure. (Vanelslander, 2014)

1.6 Characteristics of port capacity investments

Each port worldwide is organised, funded and built in a different way. Even every port investment project is different (Wiegmans & Behdani, 2018). Such investments can take the shape of a greenfield project, if no previous port exists in that place; a port expansion project, if e.g., a new dock and terminals are installed in an existing port; or an upgrade of existing facilities, e.g., by installing more efficient cranes based on new technologies.[5]

Port capacity investments have some peculiar characteristics. First of all, they are sub-

[5]In the literature, the following synonyms are sometimes respectively encountered for these three type of projects: greenfield port (see Chapters 3-5), greenfield expansion project (within an existing port: see Chapter 6) and brownfield (expansion) project. The latter type is beyond the scope of this thesis.

ject to a lot of uncertainty, resulting from many sources. Moreover, investing in the large elements of capacity involves large sums of money and sunk costs. These projects also take a lot of time to be completed, the so-called lead time. This lead time can easily exceed five years. This results in large gaps between investment outlays and revenues. Very often, this lead time increases due to slow planning and (political) decision making (Kauppila et al., 2016; Musso et al., 2006). On the other hand, the lifetime of these elements is extremely long (Musso et al., 2006). Examples of such large capacity elements include maritime access, hinterland access, port infrastructure and to a lesser extent some port superstructure elements and equipment, such as paving, buildings, warehouses, cranes and pipelines. Some of these capacity investments are also irreversible, including maritime access, hinterland access, port infrastructure and again some superstructure elements and equipment, such as paving, lighting, specific buildings and specific equipment that cannot be used at other terminals or for other activities (Musso et al., 2006). Moreover, infrastructure projects have a long expected economic life during which they generate revenues. In this light, maintenance is crucial to guarantee this extended economic life. Finally, due to the large scale of infrastructure investments, they are often funded with public money. All of these specific characteristics have an important impact on the decision making process and are taken into account in this thesis. (Vanelslander, 2014; Wiegmans & Behdani, 2018)

1.7 Research objective and scope

It has been discussed that ports have an important economic impact and that well-thought-out investments in port capacity are indispensable. However, analysing and deciding about these investments is complex, since many actors and objectives are involved in an uncertain environment. The available literature does not provide clear theoretical insights into the factors that influence port capacity investment decisions under uncertainty. The literature does not provide practical guidelines for applications of such insights and developed models accounting for uncertainty either. As a result, the objective of this thesis is to study how optimal capacity investment decisions of ports under uncertainty are influenced by different port- and project-related economic characteristics. This objective is reflected in this thesis' main research question: How are optimal port capacity investment decisions influenced by changes in economic, port- and project-related characteristics, both theoretically and in practice?

In this thesis, the focus is on port investment decisions providing throughput capacity for cargo handling activities at berths, including loading and unloading ships. Other activities, such as ship facilitation (e.g., bunkering, ship building and repair), passenger cruises and industrial activity, are left beyond the scope of this thesis.[6] To this end, the assumption

[6]The other activities could be included in an extension of the presented models by considering their relevant income, costs and actors.

is made that the maritime and hinterland access capacity elements are sufficiently present in the port and do not present a capacity bottleneck. They do not influence the considered investment decision. Such a focus on a single functional area has also been adopted by De Borger et al. (2008), who studied the investment in port hinterland capacity. It is also followed by de Weille & Ray (1974), who assume that berths are the bottleneck in order to study berth investments. In this way, this bottleneck selection methodology allows increasing or decreasing the scope of cargo handling capacity investment decisions to the necessary elements with their specific characteristics, revenues and costs.

The models developed in this thesis focus on the large-scale, irreversible infrastructure investments made by the port authority. However, also the subsequent superstructure investment decision of the terminal operating company is identified as a crucial influencing element of a port's throughput capacity, as the TOC handles the goods. Accordingly, the superstructure is also considered in the models of this thesis.[7] Although the degree of irreversibility is considered to be lower, costly transportation of cranes and their specific design, the fixed character of paving, lightning, offices and buildings for storage, next to the large scale and long construction lead times, make the use of RO models also relevant for this type of investments. As a result, smaller and reversible capacity investments such as hiring additional pilots to compensate for a deficit, are left beyond the scope of this thesis.

Both infrastructure and superstructure investments are subject to a lot of uncertainty. In this thesis, the focus is on the macro level of uncertainty: demand uncertainty. The different types of uncertainty are further elaborated in Chapter 2. The implications of focusing on demand uncertainty in this thesis' models are clarified in Chapter 3. There are also some important differences between infrastructure and superstructure projects. Table 1.1 provides a synthesising overview of the characteristics of port infrastructure and superstructure. It is apparent that superstructure consists of a typical private investment of which all cash in- and outflows relate to the deciding actor (TOC). The investment is justified by an expected profit, generated by users paying tariffs to the TOC. Superstructure has a relatively short lifetime. This is opposed to the infrastructure, which has to be built before the superstructure can be developed. Infrastructure has a longer lifetime, but has no specific users. It is decided upon and funded by the PA receiving port dues and rents such as concession fees, but the government is often involved as well. For the latter, next to profit, also market share and welfare matter. These differences need to be taken into account in the investment analyses.

Since containers represent an important segment of seaborne trade, as they accounted for 45% of worldwide traffic in 2010 measured in tonnes (Kauppila et al., 2016), the developed models in this thesis focus on the investment in container ports. The advantages are

[7]Hence, in this thesis, the infrastructure, superstructure and equipment elements of capacity are assumed to be bottlenecks, all with an equal initial level of capacity (zero for a new port or the current capacity when expansion is studied). This approach is deemed realistic for lumpy investments (e.g., adding an entire new dock).

Table 1.1: Comparison between the characteristics of infrastructure and superstructure.

	Infrastructure	**Superstructure**
Users	Non user-specific	User-specific
Financing	Government, PA	Enterprise (i.e., TOC)
Revenues	Port dues, rents	Terminal tariff
Lifetime	Long (25-50 years)	Short (5-25 years)
Deciding actors	Government, PA	Enterprise (i.e., TOC)
Decision variables	Profit, market share, welfare	Profit

Source: own composition, based on Vanelslander (2014) and National Port Council (2001).

that a lot of container data is available, and that the uniformity of the containers leads to similar handling activities and infrastructure and superstructure requirements all over the world, making the developed models more generally applicable. Oppositely, it is more difficult to estimate average aversion to waiting for the different containers shipped. Since containers may carry diverse cargo types, the time sensitivity of containers may differ. Hence, the aversion to waiting is less clear-cut. Only general distinctions are easier to made, for example between reefer containers, which in general are highly time-dependent and other, regular containers. In this light, aversion to waiting for containers needs to be considered as an average value, as opposed to bulk cargo, where the type of cargo and hence waiting time aversion is clearer.

Since the focus is on containers, TEU is chosen as the unit of measurement of the goods handled in the port. According to Kauppila et al. (2016), the current container capacity in the major ports worldwide exceeds 500 M TEU per year. Although the analyses focus on container ports, the presented approach and models can be translated to ports handling other goods. To this end, another unit of throughput needs to be selected, and if applicable, specific characteristics of the cargo handling activities, infrastructure and superstructure need to be taken into account as well. The theoretical findings moreover remain qualitatively valid, independent of the unit of throughput used.

1.8 Research approach: advantages and limitations of investment analysis and decision making with real options models

The amount of capacity in which a port invests, is often determined by a net present value (NPV) or internal rate of return (IRR) approach in a cost benefit analysis that considers all relevant welfare effects, represented in monetary terms (Centraal Planbureau, 2001). However, port infrastructure and superstructure investment decisions consist of a number of flexible options to deal with different sources of uncertainty (e.g., the option to postpone the investment or to develop a new terminal in phases). These options bear an option value, which is overlooked by these traditional methods when applied to large-scale, irreversible investments under uncertainty. As a result, such traditional approaches can be very wrong when deciding about port infrastructure and superstructure projects (Dixit & Pindyck, 1994).

Real options (RO) have been identified as a more accurate approach than singular NPV or IRR to support the specific type of investment decisions under consideration in this thesis (Dixit & Pindyck, 1994). In Chapter 2, this is discussed in more detail. An important advantage of this methodology when modelled in continuous time and continuous state is that the investment decision's resulting profits and other benefits can be optimised with respect to the investment size and the crucial timing decision, given the large uncertainty present (Kauppila et al., 2016). However, currently available RO models are not able to fully incorporate the most important specific characteristics of ports and their capacity investment decisions, such as the impact of (increasing) congestion costs, the different actors involved in the decision making process, inter-port competition, time to build and the amount of existing capacity (Benacchio et al., 2000). As a result, detailed insights into the impact of these characteristics on ports' optimal investment decisions are not available in the literature.

Since the main objective of this thesis is to examine and formalise the impact of port- and project-related economic characteristics on the optimal capacity investment decision of a port, port-specific RO models are developed in this thesis. These models take some of the specific port and project characteristics into account. The complex economic reality is translated into mathematical investment decision making models. The data to calibrate the economic model parameters are based on existing port projects. The findings will allow port managers to better understand required reactions to changes in the economic environment within their investment strategy, an important added value of this thesis. Subsequently, econometrics and additional conversions are required to translate the theoretical RO models into specific, applicable port investment decision variables such as the optimal timing and size of the investment. This analysis moreover allows explicitly quantifying the added value of using RO for port investment decisions.

Modelling the correct patterns for the different uncertain variables in continuous-time continuous-state models is however the most difficult, and hence most costly aspect of real options modelling. A model always represents reality in a simplified way. As a model is always used for a specific purpose, simplifying assumptions on less important elements for this purpose, or regarding tractability, complexity and solubility are always adopted when translating reality into mathematical models (Provost & Fawcett, 2013). These assumptions may relate to the values of parameters, the shape of processes or even the number of uncertain variables that are considered.

In practice, both the demand (price) and supply (cost) side are uncertain. However, in RO models, often one side is modelled as and hence assumed to be deterministic. Without this, additional assumptions are needed about the interaction between both uncertain variables and simulations might be needed to solve the models. Moreover, it proves difficult to account for behavioural reactions to new decisions and policies in forecasts (Meersman & Van de Voorde, 2019). Finally, reality encompasses important unknown unknowns, uncertainty nobody has ever thought about (Thanopoulou & Strandenes, 2017). They also have an impact on the correctness of forecasts and parameter estimations and hence the applicability of the developed models. Notwithstanding these challenges and limitations, with acceptable parameters values and reasonable patterns for the uncertain variables at hand, investors and their externally hired econometricians should be able to implement the scientific insights from this thesis in their investment strategy. Nevertheless, caution is necessary when interpreting and using this thesis' findings in practice. To this end, the assumptions underlying each of the models, limited as much as possible to make the models as realistic as possible, are summarised in Table 1.2. The assumptions are discussed in greater detail and extended with some chapter-specific assumptions in the relevant chapters.

1.9 Structure of the thesis and research sub-questions

The thesis is divided into eight chapters in order to deal with a number of sub-questions derived from the main research question: How are optimal port capacity investment decisions influenced by changes in economic, port- and project-related characteristics, both theoretically and in practice?

The next chapter, Chapter 2, further builds on and extends the available literature on port uncertainties and RO models by formulating an answer to the sub-question: Why and how are RO suited to evaluate and decide on port capacity investments? Answering this question leads to uncovering the issues present in currently used methods and the sources which cause them. Subsequently, RO are explored in detail as an appropriate methodology to study flexible port capacity investment decisions under uncertainty. This chapter adds to the body of knowledge by developing an original framework to analyse port investments under uncertainty with practical implications, as advocated by Musso et al. (2006).

In Chapter 3, the first port RO model of this thesis is developed to deal with a one-shot or once-and-for-all investment in a new port, fully operated and owned by one actor: the privately owned port authority. This base case model, the benchmark for the subsequent chapters, allows answering two sub-questions: What is the impact of the degree of waiting-time aversion of port customers on a port's optimal capacity investment decision in a new private service port under uncertainty without competition? and What is the impact of the amount of uncertainty on a port's optimal capacity investment decision in a new private service port without competition? From a theoretical point of view, the answer to the first question extends the current state-of-the-art. In practice, only a few ports in the United

Table 1.2: Overview of the next chapters' model assumptions.

	3. Base case	**4. Multiple actors**	**5. Inter-port competition**	**6. Time to build in port expansion**
Project type?	New port	New port	New ports	Port expansion
Capacity constraint?	Hard constraint	Hard constraint	Soft constraint	Soft constraint
Port type?	Private service port*	Public and/or private, service* or landlord port**	Public and/or private service ports*	Public and/or private service port*
Port competition?	No (1 port in model)	No (1 port in model)	Duopoly: Stackelberg and Cournot competition	No (1 port in model)
Time to build?	Not considered	Not considered	Not considered	Included in the model
Phased investment?	Project installed at once: available after completion	Project installed at once: available after completion	Project installed at once: available after completion	Project installed at once: available after completion
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, which evolve with the market (i.c., increasing) 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)			

*: Owned and operated by one single actor.

**: Owned by the PA, operated by one TOC (actor differs from the PA).

***: 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 TOC). Focus on lumpy investment in port infrastructure and irreversible elements of superstructure.

Kingdom and in New Zealand can to some extent be classified under the private service port model (Turpin, 2013). Moreover, this model is especially useful for the development of new private service ports in developing regions, such as Africa, where port competition is moreover limited. Port competition is also limited on relatively small islands. In Sardinia for example, the port of Cagliari is the only substantial container port. Nevertheless, since in reality the majority of ports are landlord ports, in which public money is involved, the model of Chapter 3 requires some extensions in the subsequent chapters.

Chapter 4 studies the investment in one new port that can also be partly or fully publicly owned and where two investing actors are considered (TOC and PA). The majority of newly developed ports adheres to this structure (Turpin, 2013), see e.g., the port of Gioia Tauro in Italy during its development phase (Genco et al., 2012, p. 10) and the port of Luanda in Angola (Porto de Luanda, 2018), with one PA and one TOC and without competition from nearby ports. The developed game allows answering the sub-questions: How are the investment decisions of the PA and the TOC in new port capacity influenced by each other's decisions under uncertainty without competition? and How are the investment decisions influenced by public PA ownership under uncertainty without competition? This innovative way of modelling different port actors under uncertainty adds to the body of knowledge, as it allows discerning the impact of different concession fee strategies on port investment decisions.

Competition from nearby ports has an impact on a port's investment decision too. If a nearby port invests earlier in additional capacity to alleviate congestion, the port that did not yet invest in new capacity may remain congested. Due to the waiting-time aversion of the customers, they might leave the congested port and move cargo to another port. As a result, expanding the port might no longer be required or profitable. A consequence might be that the congested port foregoes a lot of throughput and revenue. This is an important reason why competition between ports pushes them to anticipate their infrastructure investment when compared with a monopolistic case. These considerations have been disregarded in the first two models. For this reason, those strategies of preemption and entry deterrence are studied in Chapter 5. A second port, which will enter the market by installing a new port too, is added to the first model. Since ports are heterogeneous and for instance encounter different investment costs, one of the two can have an investment cost advantage, which leads to it becoming the leader in the investment timing game, unless the leader's capacity decision allows the follower to invest simultaneously (Pawlina & Kort, 2006). The sub-question answered in this chapter is: What impact does inter-port competition have on the investment decision of both the leader's and the follower's new port under uncertainty? Here, the scope is limited to service ports again, as the aggregate optimum from a landlord port can be obtained by optimising a service port model. However, the PA in this model can be owned privately, publicly or by a combination of both. Hence, this model is especially suited to study the investment decision in two new competing service ports, e.g., in New Zealand. From a theoretical point of view, Chapter 5 adds theoretical insights to the port investment literature considering congestion, competition and uncertainty in a more realistic model that allows jointly analysing the timing and size of the port investment decisions.

Port expansion and time to build have not been considered in the previous chapters. However, the majority of port capacity investment projects involve expansion projects, and take considerable time to be completed. Examples include the extensions of the port of Antwerp or the port of Rotterdam with new docks. In Chapter 6, the first service port model is extended with these two important characteristics of port capacity investment projects. In this already active service port, where competition is again left beyond the scope to focus on the unrestricted investment decision, the following sub-questions are answered: What is the impact of time to build on the optimal capacity investment decision under uncertainty without competition? and What is the impact of existing capacity on the optimal capacity investment decision under uncertainty without competition? Here, (greenfield) expansion, with new docks added to an existing port, is considered.[8] The results of this chapter show that the previous findings do not necessarily hold for expansion projects. Since time to build plays an important role in the considered port investment projects, these new insights are very relevant for practical applications too.

Another element that has not been considered in these models, is phased investment. The investment in Maasvlakte 2 in the port of Rotterdam involved such a phased investment option. Although port expansion is already one step closer to reality than a one-shot investment, considering phased investment in the RO model would involve another increase in realism. Nevertheless, as is explained in Section 2.4.4, this involves a considerably different modelling approach, for which this is left for follow-up research.

In each of the model chapters, sensitivity and robustness of the previous findings with respect to the added characteristics are included. Moreover, extensive numerical simulations are also provided to guarantee the robustness of the results. The interrelatedness of these chapters is displayed graphically in Figure 1.3, as a guide for the reader to the next chapters. Each of the developed models is based on some underlying assumptions, which are relaxed in subsequent chapters to add realism to the models. Port managers may gain insights and benefit from the model with the assumptions closest to their own situation. However, when their situation requires the combination of multiple models, insights of the different chapters need to be combined.[9] Also mathematical elements of these models can be combined in a new RO model, as is shown in Chapter 2.

In order to be able to implement the theoretical findings of these model chapters, a blueprint of a practical tool is developed in Chapter 7. This provides a first step to implement the findings of this thesis in real-life port capacity investment decisions. Moreover, a

[8] This is opposed to brownfield (expansion) projects.

[9] For example, the derivation of the PA and TOC's individual investment optima and the impact of a competing port are derived from the different models in Chapters 4 and 5. These insights can be applied to an optimal port expansion decision of one service port, derived from Chapter 6's model.

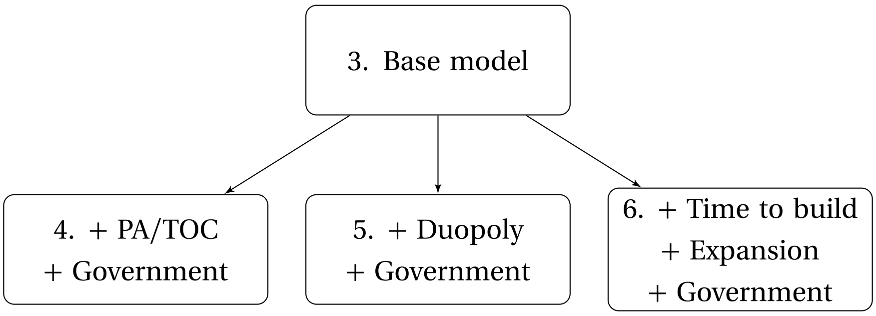


Figure 1.3: Overview of the relationships between the different RO models in the different chapters of this thesis.

critical reflection on the potential gains and costs of implementing RO is provided. In this chapter the sub-questions answered are: (RQ 7.1) How can the developed RO models be implemented in reality? and (RQ 7.2) What are the potential gains and costs of this approach, compared with currently used approaches? An overview of all research sub-questions, related to this thesis' research question (RQ) is shown in Table 1.3.

The final Chapter 8 brings the answers to the sub-questions together in order to answer the main research question. Moreover, the added value, implications and limitations of this research are linked to these answers. This finally allows conceiving potential avenues for future research.

Table 1.3: Overview of this thesis' research question and sub-questions.

RESEARCH QUESTION: How are optimal port capacity investment decisions influenced by changes in economic, port- and project-related characteristics, both theoretically and in practice?

Literature Review	**Chapter 2 sub-questions:**	
	RQ 2.1	Why and how are RO suited to evaluate and decide on port capacity investments?
New Ports	**Chapter 3 sub-questions:**	
	RQ 3.1	What is the impact of the degree of waiting-time aversion of port customers on a port's optimal capacity investment decision in a new private service port under uncertainty without competition?
	RQ 3.2	What is the impact of the amount of uncertainty on a port's optimal capacity investment decision in a new private service port without competition?
	Chapter 4 sub-questions:	
	RQ 4.1	How are the investment decisions of the PA and the TOC in new port capacity influenced by each other's decisions under uncertainty without competition?
	RQ 4.2	How are the investment decisions influenced by public PA ownership under uncertainty without competition?
	Chapter 5 sub-questions:	
	RQ 5.1	What impact does inter-port competition have on the investment decision of both the leader's and the follower's new port under uncertainty?
Port Expansion	**Chapter 6 sub-questions:**	
	RQ 6.1	What is the impact of time to build on the optimal capacity investment decision under uncertainty without competition?
	RQ 6.2	What is the impact of existing capacity on the optimal capacity investment decision under uncertainty without competition?
Implementation	**Chapter 7 sub-questions:**	
	RQ 7.1	How can the developed RO models be implemented in reality?
	RQ 7.2	What are the potential gains and costs of this approach, compared with currently used approaches?

Chapter 2

Towards improved port capacity investment decisions under uncertainty

Port capacity investment decisions involve considerable uncertainty for the investing port actors, such as port authorities (PA), 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, uncertainty and managerial flexibility are not fully taken into account in traditional valuation methods such as net present value (NPV) and internal rate of return (IRR) analyses, which are often used in cost-benefit analyses (Trigeorgis, 1996; Anda et al., 2009). As Dixit & Pindyck (1994) noted, 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 flexibility to postpone investment to a better moment, 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.

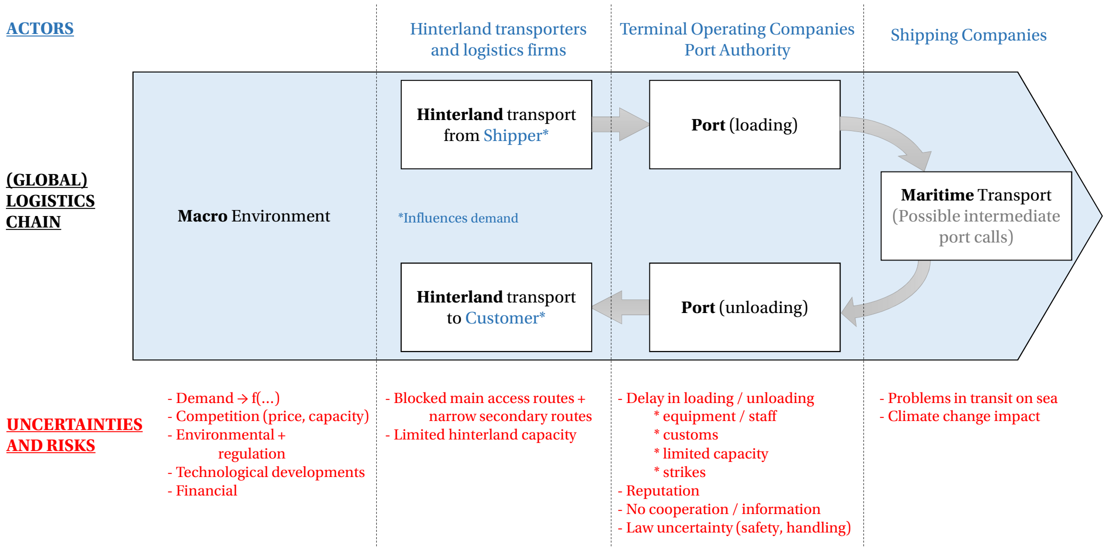
As opposed to the traditional valuation methods, real options (RO) models offer a more appropriate method to evaluate flexible investments under uncertainty and make better investment decisions. RO models monetarily quantify the value of managerial flexibility to react to uncertainty in the best possible way. T. Wang & De Neufville (2005) discern two different types of real options. RO 'on' projects relate to the correct valuation of flexible investment opportunities. RO 'in' projects and the related models take the benefits of options of flexibility embedded in the specific project into account. Only when all relevant options of flexibility are included 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 (such as the value of the firm), including a random term related to an investment decision variable (Dixit & Pindyck, 1994). It is however important to point out that RO models should not necessarily 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 plus the value of the real options present (Hu & Zhang, 2015; Van Putten & MacMillan, 2004). The disadvantages of the RO approach are however its complexity, the need for even more data and parameter and function estimations. Its current applications to ports are limited.

The objective of this chapter is to discern a methodology that is able to correctly value and to enhance port capacity investment decisions under uncertainty. This is translated into the following research sub-question: (RQ 2.1) Why and how are RO suited to evaluate and decide on port capacity investments? The answers to this question are brought together by constructing a framework to further develop the RO methodology in a port context.

This chapter consists of six sections. In the next section, the relevant literature on uncertainties and risk factors is reviewed, since all of these elements have an impact on port capacity investment decisions. Some of the existing RO applications in a transportation context are discussed in Section 2.3. In order to allow building RO models to decide on port capacity investment decisions, building blocks and characteristics of general existing RO models relevant to the port context, are reviewed in Section 2.4. The insights from the reviews of both the port uncertainty and the RO modelling domain are combined in Section 2.5.1 in a port capacity investment RO modelling framework. This framework offers an overview that will support the RO model building for port capacity investment decisions in the remainder of this thesis. Section 2.5.2 uses the framework to elaborate a port capacity investment decision model under uncertainty. The final section concludes with the major findings of this chapter and makes the link to the next chapters, which contain the actual models. These RO models are based on the framework. The underlying assumptions are based on the information from this chapter and the previous one.

2.1 Sources of uncertainty and risk in the port context

Many sources of uncertainty and risk are present in the port context. Although the concepts uncertainty and risk are sometimes used interchangeably, they are different. Many scientists have debated on the difference, often starting from the seminal work of Knight (1921). Knight (1921) argues that uncertainty is related to an unknown probability of outcome, whereas risk is linked to a known distribution of outcomes. Moreover, discussions about risk are often related to the potential loss and its insurability (Langlois & Cosgel, 1993).



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 2.1: Actors, uncertainties and risks in the maritime logistics chain.

Meyer & Reniers (2016) use the risk definition of ISO 31000:2009, which points out that uncertainty has a positive or negative effect on one's objectives. In this way, the amount of and exposure to negative uncertainty can lead to not achieving objectives and hence incurring losses. This is defined as negative risk, which is the focus of this chapter. However, there are also positive uncertainties which may lead to (better) realising objectives and gains. In this chapter, when the outcome can be positive or negative, this is referred to as an uncertainty.

The sources of uncertainty and risk in a port can be classified in 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 and risk to the actors in the entire logistics chain, Figure 2.1 represents the logistics chain. The different uncertainties and risks are grouped per activity in the logistics chain. Additionally, the actors per activity are displayed on top, to allow linking the uncertainties and 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. Moreover, it should be noted that many other activities bearing risks are performed in the port at the operational level and are not included in Figure 2.1, such as mooring, tugging and piloting (Blomme, 2014). 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 chapter either.

2.1.1 Competitive position of the port: global logistics chains

Ports are part of global logistics chains with a number of actors involved. The chain can be divided in three sections: maritime transportation, transferring cargo from sea to inland transportation in the port and hinterland transportation (Kapros, 2014). Maritime logistics chains are well-oiled machines (Van de Voorde & Vanelslander, 2014). Hence, for a port to be competitive, its connectivity in the transportation chain is vital (Jia et al., 2017). Such 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 risk in the demand for different transportation modes (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) identify port authorities, the government, shipping companies, terminal operating companies, shippers, integrators, forwarders, other logistics and transportation firms, brokers, customers at destination, production firms, project teams, regions and banks. The relationships between these actors can be rather complex (Estache, 2001), as they might have different, conflicting objectives. For example, a shipper wants to minimise the generalised transportation cost or the entire production cost,[1] including the port price and waiting time in a port, whereas a shipping company wants to maximise profits or its market share and a terminal operator wants to maximise its profit by reducing concession prices and increasing handling prices. The port authority in turn wants to ascertain the competitive position of the port. In addition, the port authority requires a sufficient business and/or welfare ROI to be generated in the port (Meersman & Van de Voorde, 2014a; Y.-T. Chang et al., 2012).

The complexity of the relationships between these actors, which hampers a correct specification of the objective functions of the port capacity investment decision makers (Xiao et al., 2012), is reinforced by the unequal distribution of power between them. As Van de Voorde & Vanelslander (2009) state for example, the concession policy is for the port authority one of the few instruments to express their negotiation power over TOCs. The negotiated concession fee needs to be taken into account in the objective functions. Moreover, shipping companies have a lot of decision power in the maritime chain too, since they

[1] Depending on the shipper's specific activities and cost function.

decide on 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 the shipping company, as well as the PA 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 (Y.-T. Chang et al., 2012). The objectives of port authorities are influenced and complicated by their mixed ownership structures and competition inside and between ports (Cullinane et al., 2005). In some cases, they could be captured by a multiple objective function. As Suykens & Van de Voorde (1998) indicate, not only private, but also public money plays an important role in port ownership. This leads to the consideration of social welfare. Xiao et al. (2012) define such 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. Together, they can realise the objectives of both parties, which are profitability for the private actors and social welfare for the public actor (Musso et al., 2006). A private investor aims at maximising profit:

$$\pi = (p - c)q - c_h K, \tag{2.1}$$

with p the unit price, c the unit cost, q the output quantity, c_h the capacity (or 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 considers the sum of this profit and the spillover effects for the local economy, λq, with λ a constant scale factor. 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. The delay D, caused by congestion, is defined by a function of the capacity utilisation rate q/K:

$$D = f(q/K). \tag{2.2}$$

Delay is included in the analysis of Xiao et al. (2012) 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 spillover effects of port business are not taken into account, capacity investment will be smaller (Asteris et al., 2012).

The weights of the different objectives in the approach of Xiao et al. (2012) 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., a majority shareholder or public-private partnerships) 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. A second limitation of the approach of Xiao et al. (2012) encompasses the omission of demand variability.

Competition has an impact on the chain as well (Notteboom & Yap, 2012). Competition between ports increased over the last decades, because captive market areas became less incontestable, increasing the overlap of hinterlands of the ports (Musso et al., 2006). Competition does not only exist within one chain, but also between different chains. 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 TOCs 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 additional uncertainty and risk 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).

2.1.2 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 2.1). Future levels of world trade flows are very uncertain and volatile, although they are expected to grow, leading to an increase in goods shipped over seas (UNCTAD, 2015). Second, the geographical distribution of these trade flows can change, resulting in different routes for the ships. Third, the composition of trade and the selected transport modes can change too, influencing among other things 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 the latter cannot correctly 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 account for the uncertainty (de Neufville, 2016). This is because RO explicitly model uncertainty and account for it in the calculations based on stochastic calculus. Nevertheless, the more exact the forecast of demand, the more accurate the outcome of the RO analysis will be too.

2.1.3 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, the North Sea Route to Asia, 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 uncertainty and risk encompassed in transport infrastructure investments. Next to transport inducing climate change, there also exists an influence of climate change on transportation. 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 eventually result in modal shifts for regional and global goods transportation, altering the demand for some types of transport infrastructure and increasing demand variability. All of these technological innovations and environmental impacts, in combination with the aforementioned variable economic demand, add to the already present port uncertainty.

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. Furthermore, changes in labour regulations may induce additional uncertainty (Barton & Turnbull, 2002). An example of typical port labour regulations are laws organising which workers may perform which type of work in a port area.

2.2 Real options models for better decisions under uncertainty

Port capacity investment analysis is a field where RO can be a very powerful methodology, as was already suggested by Juan et al. (2002) 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, which are influenced by technological shifts and opposing objectives of different stakeholders involved (de Neufville, 2003). A lot of port infrastructure investment projects have these characteristics, as was discussed in Section 1.6. Moreover, the port environment itself is complex, as it is characterised by competition and uncertainty (see Section 2.1), especially because ports form a link in the maritime logistics chain, involving intertwined actors with possibly conflicting objectives (Heaver et al., 2001; Meersman & Van de Voorde, 2014a).

As a result, the value of port projects can be increased by means of flexible size and timing of the investments and 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 as 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 goods categories 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 (Xiao et al., 2013).

In order to explore in more detail how RO can improve port capacity decision making, some previously elaborated RO applications in a transportation context are first identified in the next section. Afterwards, the focus is narrowed down to a port context.

2.3 Real options in the transportation sector

Real options have been applied to many transportation investments, because they can deal very well with managerial flexibility under different sources of uncertainty. The models discussed in this section relate to the maritime sector, to other modes and to environmental projects. When transportation infrastructure is funded by the public government, the social welfare function has to be maximised, complicating the analysis, because now more 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) show how financial options could be adopted as transportation options to hedge logistical contracts.

Real options have amongst others been used in toll road investment analyses (Ashuri et al., 2011). In aviation too, RO have been applied. Hu & Zhang (2015) for example have analysed airline investment decisions. A lot of interesting and relevant work about airport infrastructure investments under uncertainty is available (Smit, 2003; Zhang & Zhang, 2003, 2006; Xiao et al., 2013, 2017). As there are some similarities between ports and airports, these papers allow drawing useful conclusions to be considered in the port context. Xiao et al. (2017) for example find that for an airport it is important to buy enough reserve capacity to expand at a later moment. When uncertainty increases, the option value is higher, explaining this need to invest in reserve capacity. This finding may prove important for ports as well. Nevertheless, there are some important differences between the described context for ports and airports. These differences should be correctly taken into account before transferring results from one sector to another.

A first important similarity is that airport capacity expansion is lumpy and involves a long lead time as well. Moreover, a lack of sufficient infrastructure, compared to demand, leads to capacity shortages in both ports and airports. When there are not enough runways, terminals or gates in an airport, delays will occur as well. Third, also in the airport, multiple actors interact. However, their interactions are different, especially when maritime transportation of goods is compared to passenger air transportation. This leads to a first distinction. As far as maritime transportation of goods is considered, the shipping line effectuates the transportation and decides through which ports the goods are shipped. In practice, these will be the ports with the lowest generalised cost. In passenger air transportation, the airline effectuates the transportation, but it are the passengers who choose the airline and decide on the origin and destination airport. This important transportation decision making difference should also be expressed in the specific models for ports and airports. Moreover, price transparency is higher in passenger transportation than in goods transportation (Onghena, 2013). A second difference is linked to the investment decision making process. Notwithstanding the more complex transportation decision making process, the investment decision making process in the airport involves fewer actors. The airport holding company is often the main actor deciding about the investment in new capacity. In a landlord port however, both the TOC and the PA have an impact on this investment decision. A final important distinction is related to the concessions in ports and airports. While concessions in ports are often related to the provision of products or services linked to the transported goods, concessions in airports are also related to the generation of non-aeronautical or commercial revenues from e.g., retail and real estate. As shown by Gillen (2011), airports are two-sided platforms, providing both aeronautical and non-aeronautical services to airlines and passengers.

There have been many applications of RO to maritime investments as well. Bendall & Stent (2003, 2005, 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. This is because projects in the maritime business are characterised by financial risks, as revenues are uncertain and situated in the distant future (Kakimoto & Seneviratne, 2000a). As a result and because the market environment changes continuously towards more integration (Bergantino & Veenstra, 2002), accurate forecasts are also indispensable in maritime economics (Meersman et al., 1997).

RO analysis has been used to evaluate alternative technologies dealing with environmental issues as well (Kim et al., 2009; Koetse & Rietveld, 2012). RO are well suited to deal with the uncertainty associated with climate change and the effectiveness of technological innovations (Acciaro, 2014a). RO demonstrate 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).

2.4 Real options models from a port perspective

Herder et al. (2011) already showed that real options can be used in ports to decide on the optimal timing and size of a capacity project, including flexibility in terms of investment in and use of the infrastructure and to open the option of postponement and abandonment. This section contains a critical overview of existing RO models to analyse decisions with a number of similar characteristics. The advantages and drawbacks of the models and their constituting building blocks are discussed in light of inclusion in a new port investment RO model. This model has to take the specific, complex port context into account. An overview of models to find the optimal size and timing of investment projects is supported by the work of Huberts et al. (2015) and also includes game-theoretic approaches. This is followed by the discussion of a model incorporating cyclicality, because demand in maritime markets is cyclical. In ports, such growth cycles are estimated to have a duration of 8 to 10 quarters (Paflioti et al., 2015; Stopford, 2009).

Novaes et al. (2012) analysed the development of terminals and berths under demand uncertainty and economies of scale in a developing country. In that paper, capacity is considered as a hard constraint and relevant insights from queuing theory are taken into account. Although engineering approaches are relevant for port capacity investment decisions, they should always be supported by economic considerations, such as revenues and costs generated by the project. This is lacking for example in Kia et al. (2002) and Noritake & Kimura (1983). Chen & Liu (2016) and Chen et al. (2017) in their analyses of port infrastructure investments prove that uncertainty alters the investment decision a lot and needs to be included in the port capacity investment analysis, as well as congestion costs. Although the latter two papers consider uncertainty, as modelled by a uniform distribution, it is possible to go one step further by taking an uncertain process that allows modelling expected growth (drift) and uncertainty independently. K. Wang & Zhang (2018) apply RO to the investment in abatement technology to reduce the impact of natural disasters, resulting from climate change, in a port with inter and intra-port competition. To this end, they assume the probability of the event of a disaster following some ambiguous probability density function and hence being unknown ex-ante, but known after the investment decision (Knight, 1921). This Knightian uncertainty is compared to a Poisson jump to model the uncertain occurrence of the event (see Section 2.4.6 for a discussion of Poisson or jump processes).

This section's review of RO models in the literature is the basis for developing new models suitable to the specific, complex port context with its considerable uncertainties and demand characteristics. 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.

2.4.1 The basic real options model of Dangl and its extensions

An initial RO model to decide on the size and timing of capacity investments is available in Dangl (1999). His continuous-time continuous-state model starts from the linear (in Q) additive (in X) inverse demand function

$$p(t) = X(t) - Bq(t), \tag{2.3}$$

with the following variables defined at time t: $p(t)$ the price, $X(t)$ the demand shift parameter, intercept or reservation price that follows a geometric Brownian motion (GBM), B the (negative) slope and $q(t)$ the output quantity. The increment of a GBM is defined by

$$\mathrm{d}X(t) = \mu X(t)\mathrm{d}t + \sigma X(t)\mathrm{d}Z(t), \tag{2.4}$$

with μ the drift (a measurement of growth) 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). Although the rate of uncertainty, σ, can vary in practice, it is assumed fixed in RO models based on a GBM. Instead of imposing uncertainty on the uncertainty parameter, decision makers are advised to re-evaluate RO models as soon as changes in one of the parameters are suspected. As far as the GBM is concerned, Marathe & Ryan (2005) already empirically showed that the GBM is a good process to model demand for established services such as the number of passengers in airline transportation. Additionally, Lindsey & De Palma (2014) highlight the frequent use of a GBM in a transportation context.

In ports there are two possible ways to deal with capacity shortage: investing in additional capacity or increasing the output price (Xiao et al., 2012). As a result, it is important in a port context to jointly analyse the output price and quantity through a demand function when studying capacity investments (Aguerrevere, 2003; Vanelslander, 2014). Of course, the use of a demand function in the models assumes sufficient price transparency for the customers in the market for the considered port activities, which is not necessarily true in practice, as the price is set by a number of actors (Meersman et al., 2015). For the sake of clarity, time dependencies are omitted in the remaining formulae in this chapter, e.g., p instead of $p(t)$.

Dangl (1999) models a flexible firm, since the firm can choose its output level, as long as it satisfies

$$q = \min\left\{q^{opt}, K\right\}, \tag{2.5}$$

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 (Rashed, 2016). 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

$$I = \gamma K^{\varepsilon}, \tag{2.6}$$

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 a relatively high cost under the current specification. Profit is equal to

$$\pi = (p - c(K))q, \tag{2.7}$$

where $c(K)$ is the average operational cost, being dependent on the installed capacity K. In the numerical calculations of Dangl (1999) however, c is assumed constant. Equation (2.7) is a reduced version of the profit function used by Xiao et al. (2012) in Equation (2.1) 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 discounted investment cost. This forms the input of the option value maximisation. By using dynamic programming, an optimal investment strategy (X_T, K) is found. The first element indicates the optimal timing, expressed as an investment threshold for the demand shift parameter. As soon as $X(t)$ reaches this threshold for the first time from below, or if X is initially above this threshold, investment takes place. The second element indicates the optimal amount of capacity of the investment.

The main conclusion of Dangl (1999) is that an increase in uncertainty will lead to investing in more capacity, 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). Exactly those costs 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 large leap (Kauppila et al., 2016). It is not possible to extend a dock's capacity just by a few TEU per year through infrastructure investments (Musso et al., 2006).

An extension to the model of Dangl (1999) is provided by Hagspiel et al. (2016), who add a capacity 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 (2.1). However, the typical (port) congestion and delays are still omitted. The new profit function is given by

$$\pi = (p - c(K))q - c_h K. \tag{2.8}$$

2.4.2 Inclusion of port expansion in the model

A slightly different continuous-time continuous-state model to analyse the impact of scale economies 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 achieved by means of adding multiple docks, one after another. The inverse demand curve used in this model is not linear additive, but has a constant price elasticity of demand ($-1/a$). It is given by

$$p(t) = X(t)q(t)^{-a}, \tag{2.9}$$

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

$$I = \left(\Delta q\right)^{\varepsilon}, \tag{2.10}$$

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 substitutes K by the amount of capacity expansion Δq, which is the difference between the new and previously installed capacity. Output in this case is always set at maximum capacity, i.e., output inflexibility, because $a < 1$ makes this the optimal decision in every circumstance. This is related to the non-flexible firm of Hagspiel et al. (2016), where output was also equal to full capacity, or zero. Another element that is included in the model, is depreciation:

$$\mathrm{d}q = -\zeta q \mathrm{d}t, \tag{2.11}$$

with ζ the depreciation rate. The objective function is the market value of the firm and is to be maximised. It is calculated as the integral of the discounted net operating incomes minus the sum of the discounted capital investment costs. In addition, the expansion decision is analysed in terms of scaling up the existing capacity by a scale factor κ. This is possible because of the homogeneity of the objective function.

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. The return on assets is calculated as

$$y = pq/q^{\varepsilon} = q^{1-a-\varepsilon}X, \tag{2.12}$$

where q^{ε} is the replacement cost of the assets in place. It is noteworthy to indicate that investing will decrease the actual value for $\hat{y}_b$ again through an increase in q.

The main conclusion of Guthrie (2012) is in line with the findings of Dangl (1999): increased uncertainty will lead to larger investment outlays that are in turn less frequent. Next to output inflexibility, another limitation of the model is that capacity expansion is assumed to be realised instantaneously, which is not in line with the long lead times incurred in port infrastructure construction.

2.4.3 The impact of time to build

Aguerrevere (2003) includes time to build in his RO model of capacity expansions, a project characteristic that was not included in the previously discussed models. 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. This could be useful in a port to shed some additional light on the complicated port pricing decision.

Aguerrevere (2003) uses an operational cost function that differs from the one of Dangl (1999):

$$c(q) = c_1 q + \frac{1}{2} c_2 q^2, \tag{2.13}$$

with q being flexible, but limited by the available operational capacity. As a result of flexible output, this model considers overinvestment in capacity less harmful than underinvestment, which is a direct application of the inequality of Jensen (1906). Indeed, there is an imbalance between the two sides of uncertainty, as the capacity investment decision in combination with flexibility rather has to be considered as a determination of the maximum output threshold.

The investment cost in this model is given by Equation (2.6), with ε set to 1. 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 under full capacity utilisation than in a case where capacity is not fully used. This is a consequence of the limit that capacity places on throughput levels. 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.

2.4.4 Installing the project in stages

Building a new dock can be realised in different steps and should not necessarily be completed at once. This approach allows reducing the lumpy character of port investments, since the capacity can be installed in phases, and then also be brought into use gradually (Kauppila et al., 2016). A well-known example of the implementation of such a real option 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 built, 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 Saeftinghedok and developing 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 (relative) cost premium $(I_{s_1} + I_{s_2})/I_l > 1$ for which phased investment is more profitable. Chronopoulos et al. (2017) state that if the capacity of the project is determined ex-ante, lumpy investment is better under a high price uncertainty. However, if the final capacity is not fixed, stepwise investment leads to a higher value and more capacity will be installed.

2.4.5 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), since the logistics chain with the lowest generalised cost will be selected. 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 as 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), Saeed & Larsen (2010) and Van de Voorde & Vanelslander (2014) describe port negotiations as a game. Sufficient transparency can be assumed, because entities in the public sector can also be included in the analysis. As a result, information asymmetry should not necessarily be included in the game.

When insights from industrial organisation are added to the models and a game-theoretic approach is chosen, individual value functions have to be derived and the type of game has to be chosen. Dynamic programming can then be used to find the optimal decision (Dixit & Pindyck, 1994; Azevedo & Paxson, 2014; Chevalier-Roignant et al., 2011; 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 linear (in Q), multiplicative (in X), inverse demand function given by

$$p = X(1 - BQ), \tag{2.14}$$

where X again follows 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 maximum output is limited to $1/B$ in order to prevent negative prices. This demand function could serve as a good first approximation. A linear (in Q), additive (in X) inverse demand function would however be better suited to analyse a market wherein potential demand growth is possible. Nevertheless, more sophisticated functions and their applicability could also be considered when developing port investment models.

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 ports in an oligopoly, rather than in 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, as its value is eroded by the presence of competitors. 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 (2.9). 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 operational costs (Azevedo & Paxson, 2014). In addition, ports offer products or services that are not identical (e.g., different service levels or hinterland distances). 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 related to the one used by Huisman & Kort (2015). A correction is applied for the output of the other firm j, weighted by the amount of product similarity. The inverse demand function is given by

$$p_i = X\left(1 - q_i - \delta q_j\right), \tag{2.15}$$

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. If more than two ports are competing in the market, Equation (2.15) could be extended to

$$p_i = X\left(1 - q_i - \delta \sum_{j \neq i} q_j\right), \tag{2.16}$$

with an equal product differentiation between the considered ports or to a more complex situation

$$p_i = X\left(1 - q_i - \sum_{j \neq i} \delta_j q_j\right), \tag{2.17}$$

with different diversifications between the services of the considered ports. Adding the latter asymmetry between the ports might however complicate the calculations too much, so that more complex solution techniques such as agent based modelling might be needed.

The models discussed above involve firms that were not yet active in the market and have to decide on their first investment size and timing. However, practically every port is already active and has made one or more capacity investments in the past. For this reason, a realistic port model should allow for ports to be not only a new market entrant, but also an incumbent with previously installed capacity. Also in such a case, it would be interesting to analyse which port would invest first (preemption), and when they would invest again (Huberts et al., 2015).

2.4.6 Alternative uncertainty processes to model cyclicality and changes in legislation

RO models frequently use a GBM as the stochastic process expressing uncertainty (Li & Cai, 2017). This non-negative process allows uncertainty and drift to be set by two independent parameters, and its mathematical complexity is relatively limited (Schöne, 2014). Moreover, Marathe & Ryan (2005) and Lindsey & De Palma (2014) already proved the suitability of this process in a transportation context. 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, like maritime markets are. 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

$$\mathrm{d}\pi = \alpha(t)\pi\,\mathrm{d}t, \tag{2.18}$$

with π the instantaneous profit at time t, and α equalling the growth rate (α_g) when the industry is in a growth phase, or the decline rate (α_d) when the industry is in a decline phase. The probabilities of going from the initial phase to the second phase and of the inverse transition are given by

$$\begin{cases} P\left(\alpha(t+\mathrm{d}t)=\alpha_2 | \alpha(t)=\alpha_1\right)=\psi_1 \mathrm{d}t+o(\mathrm{d}t), \\ P\left(\alpha(t+\mathrm{d}t)=\alpha_1 | \alpha(t)=\alpha_2\right)=\psi_2 \mathrm{d}t+o(\mathrm{d}t). \end{cases} \tag{2.19}$$

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). As a result, the presented Markov model can take into account periods of decline, as opposed to many economic models assuming only a growth trend. Because of this, it is expected that capacity investments will be lower under this approach, since overcapacity in times of recession has a higher cost. Substituting the GBM by a cyclical Markov process offers a worthwhile approach to study the impact of this alternative stochastic market demand process on the decisions made in the port.

Alternatively, Poisson or jump processes are often used in models in order to represent the possibility of sudden changes or events, for example following a newly available technology in R&D or a new legislation (K. Wang & Zhang, 2018; 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:

$$\mathrm{d}x = f(x,t)\mathrm{d}t + g(x,t)\mathrm{d}J, \tag{2.20}$$

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:

$$\mathrm{d}J = \begin{cases} 0, & \text{probability } 1 - \nu \mathrm{d}t, \\ u, & \text{probability } \nu \mathrm{d}t. \end{cases} \tag{2.21}$$

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

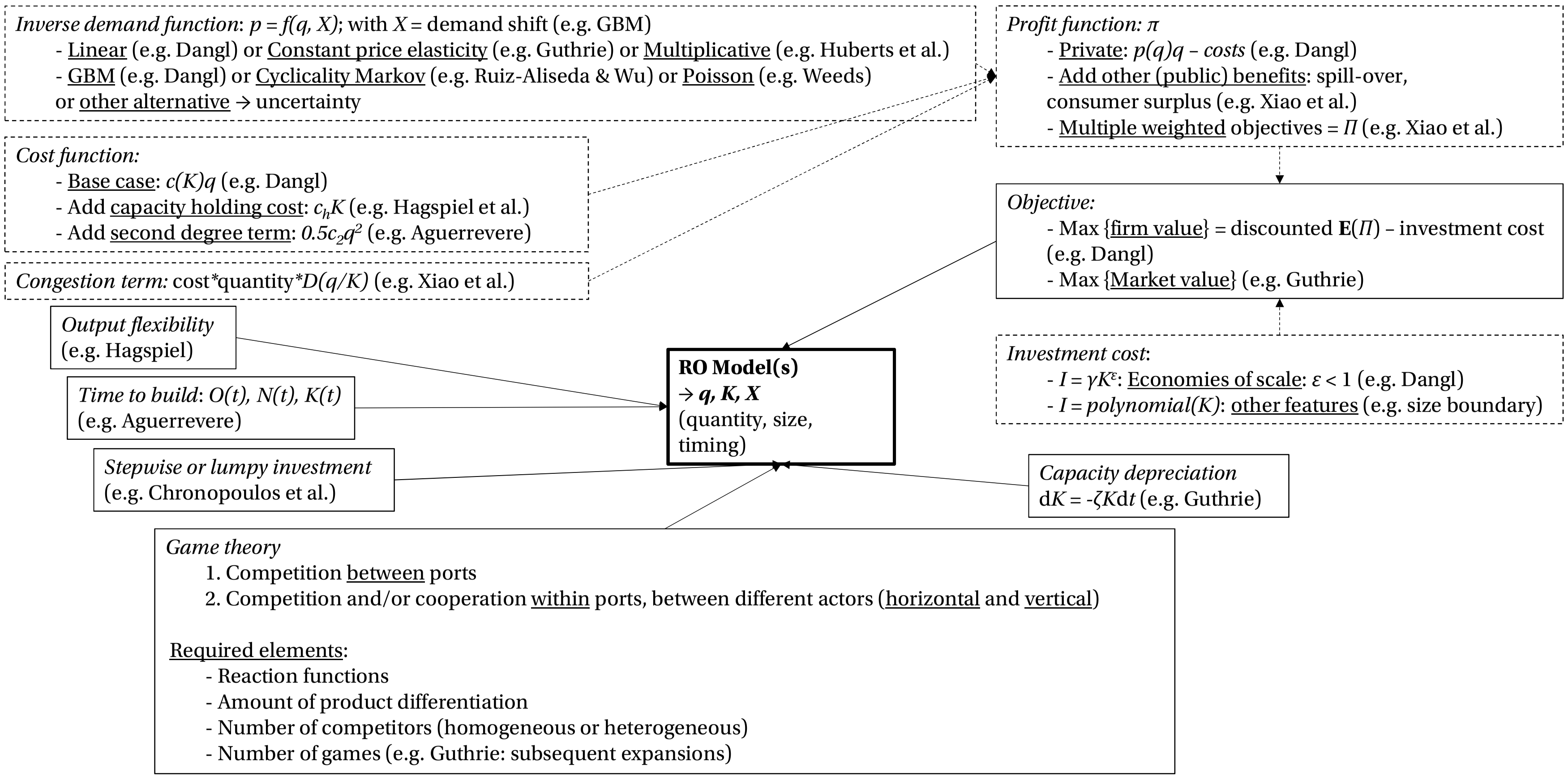
2.5 Towards a real options application in ports

Elements of RO models that could be used in a port environment were examined in the previous section, identifying some of their important characteristics. In this section, the different models and their characteristics are linked to each other within the port environment, with the objective of effectively improving port capacity investment decisions. This section first presents a framework that will lead to enhanced port capacity investment decisions. The framework is then applied in Section 2.5.2.

2.5.1 A framework to enhance port capacity investment decisions

The framework in Figure 2.2 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. In this figure, the dashed blocks together constitute the building block 'objective'. 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., 2013). The inverse demand function should also account for the cost of congestion (Xiao et al., 2012). 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 a linear, quadratic or even higher-order function of q. Besides a capacity-dependent variable cost, a capacity holding cost could be added to the function. When a capacity 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 (e.g., spillover effects or consumer surplus). 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



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 2.2: Comprehensive framework of RO models and their components.

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 (e.g., because of limited space and the subsequent need of expropriation). The value of the port authority's project is the objective that needs to be maximised through the flexible investment. A slightly different approach is maximising the market value of the port authority, as a function of the return on assets (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.

2.5.2 Applying the framework to improve port capacity investment decisions

In order to illustrate a potential application of the framework, the investment decision of a port in new capacity is analysed. A port that wants to maximise the revenues consisting of the sum of port dues and terminal handling prices is considered. In such a port, the value of the firm comprises the combined objectives of the port authority and the operators of the port (Meersman et al., 2015; Strandenes & Marlow, 2000). Those two actors may coincide in one enterprise, like in the private port of Felixstowe, owned by the port operator Hutchison Port Holdings (Juhel et al., 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, which only become available after investment, is composed of the revenue (pq) minus the operational cost (a linear function in this initial setting) and the capacity holding cost (see Figure 2.2). 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. The opportunity cost of waiting, namely foregone profits before the investment takes place, is also reflected in the objective function through the discounting of the profit stream to the moment of investment. These considerations result in the following system of equations, which can be optimised through dynamic programming (Dixit & Pindyck, 1994):

$$
\begin{cases}
\max_{T,K}\left\{\mathbf{E}\int_0^{+\infty} e^{-r(T+t)}\pi(T+t)\mathrm{d}t - e^{-rT}I(K)\right\}, & \\
\pi(t)=0, & t<T,\\
\pi(t)=(p(t)-c)q(t)-c_hK, & t\geqslant T,\\
p(t)=p(\underset{+}{X(t)},\underset{-}{q(t)},\underset{-}{D(t)}), & \\
\mathrm{d}X(t)=\mu X(t)\mathrm{d}t+\sigma X(t)\mathrm{d}Z(t), & \\
D(t)=D\big(\underset{+}{q(t)/K}\big), & \\
0\leqslant q(t)\leqslant K, & \\
I(K)=\gamma K^{\varepsilon}. &
\end{cases}
\tag{2.22}
$$

System (2.22) 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 and is related to the size of the market. Since congestion can result in a loss of potential demand (Jansson & Shneerson, 1982), the demand and congestion level are endogenised in the 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 occupancy or utilisation rate q/K and the amount of delay D is visualised in the delay curve in Figure 2.3. According to Kauppila et al. (2016), such a delay curve is a good approach when modelling at port level. To derive a good equation for the delay curve, insights from queuing theory can be used (Novaes et al., 2012). Also computer simulations (e.g., enterprise dynamics) can be used to further estimate the impact of operations on capacity (Kia et al., 2002). Additionally, System (2.22) specifies that the upper limit to throughput is defined by the theoretical design capacity, K. Producing no output ($q = 0$) is also possible. The cost of investment I is initially based on the specification of Dangl (1999). With $\varepsilon < 1$, economies of scale in investment costs can be included in order to prevent infinitesimal investment. When capacity expansions are studied, K has to be replaced by ΔK in the investment cost function.

In infrastructure investment projects, demand and revenues are often overestimated, whereas costs are frequently underestimated. Both could reduce the value of a project significantly. For this reason, the inclusion of uncertainty both on the demand and cost side of the model is suggested (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 mathematical tractability of the model (Huisman et al., 2013). As a result, Monte-Carlo simulations might be needed. Tsamboulas & Kapros (2003) for example apply Monte-Carlo simulations to the investment decision in freight villages under uncertainty.

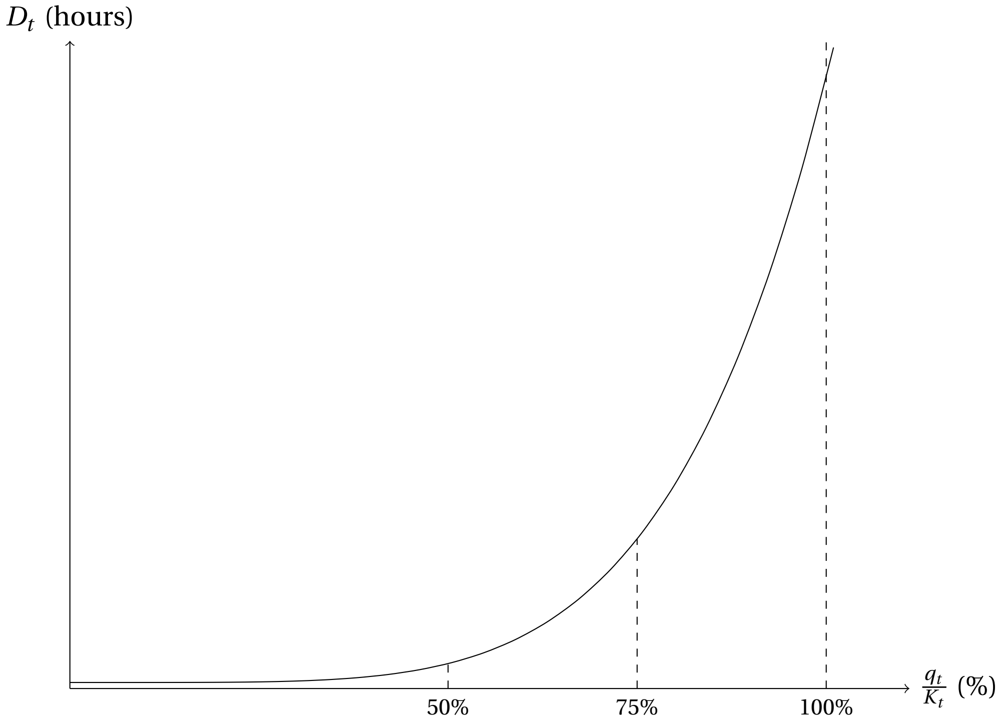


Figure 2.3: Delay curve illustrating the positive relationship between the port occupancy rate and the amount of delay.

The presented model from System (2.22) can be used to calculate an optimal investment threshold for X (expected to be reached at time T), the amount of capacity K, the optimal throughput quantity q and price p 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). Often however, no analytical expression can be derived for the optimal values of some decision variables. Nevertheless, numerical solutions can be calculated and they 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 global optimum. Azevedo & Paxson (2014) provide such an example in RO games. Cucchiella & Gastaldi (2006) also use a software package to solve their RO model. Furthermore, the RO analysis might 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 simplifying 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.

2.6 Conclusion of this chapter

It is very important for a port to install the right amount of capacity when making lumpy investments. On the one hand, undercapacity leads to congestion and waiting costs for the port users. On the other hand, 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 substantial amount 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 method 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 an RO model is not straightforward.

Starting from a review of these uncertainties and of the available RO models, a framework has been set up in order to help categorising and applying RO models for port capacity investments decisions, taking into account the complex environment ports are operating in. New RO port models should include the relevant characteristics of the port or ports studied. This could for instance be achieved by selecting the most suitable components from the presented framework. The port RO models can be expanded even further, with major or minor additions, in order to include even more of the complex relationships between the actors in the maritime logistics chain. This however requires an increasing number of assumptions about the specifications 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 be 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 solvable RO model.

In order to improve the performance of investment decision making models in transportation, ex-post analyses of these models are advised (Mackie & Preston, 1998), with the careful attention for correct parameter estimations (Azevedo & Paxson, 2014). For this purpose, case studies are an excellent approach in the subsequent stage of this research in order to verify and fine-tune the developed models. Already completed projects might be useful, as data confidentiality might be less critical. It is however necessary to possess information about the entire decision process, including all the alternatives and final decisions. When these data are lacking, other finished projects might allow making valid estimates of missing data and obtaining information about the different parties involved in the project.

This chapter is only the first step in evolving towards better port capacity investment decisions. In the following chapters, new port RO models are developed in order to study the impact of different typical port characteristics on the investment decision and take investment decisions with embedded options of flexibility. These different models contain components from the developed framework, taking into account the relevant characteristics of the port(s) studied. The next chapter deals with a private port owner that wants to invest in and operate a new port. To this end, a linear additive inverse demand curve with a GBM is selected. For the cost function, the traditional first-order function of throughput is retained, to which a capacity holding cost is added. This leads to the private port profit function. Combined with a polynomial investment cost function, the project value is to be maximised. To this model, output flexibility is added. In subsequent chapters, the model is expanded gradually. From Chapter 4 on, other public benefits are also considered by publicly owned ports. Moreover, in that chapter, game theoretic considerations within the port are explored, since the port authority and terminal operating company need to take the port capacity investment decision together in a landlord port. In Chapter 5, competition between two ports is considered in a duopoly. Finally, in Chapter 6, time to build is added to the model and port expansions are considered. A synthesising overview of how the models of each chapter relate to one another has been provided in Figure 1.3. An overview of their underlying assumptions has been shown in Table 1.2. These overviews can be interpreted in combination with the framework in Figure 2.2 to enhance insight into the differences and the applicability to different situations. They moreover offer the reader a guide to the next chapters. For port managers, they help to select the most appropriate model or combination of models to support the investment decision in the own port. These are the models with the most reliable assumptions, compared to the case at hand.

Chapter 3

The impact of congestion and uncertainty on a new private port's capacity investment

As port infrastructure capacity investments are irreversible, subject to many sources of uncertainty and involve large sums of money, the real options (RO) approach to investment was chosen in the previous chapter to help determine the optimal amount of capacity for this type of investment projects and the ideal moment to invest. The basic principle is that potential investors monitor information about costs and returns as it becomes available, and make the investment as soon as the cost of deferring the project is greater than the expected value of the information gained by postponing investment (Bernanke, 1983). Decisions about the timing of this type of port investment are related to decisions about the optimal capacity of infrastructure with flexible throughput. Pindyck (1988) examined this issue in the context of incremental investment decisions, while Dangl (1999) considered investments in which there was only one opportunity to choose the maximum capacity. The latter approach is more suitable for analysing port infrastructure investments, as large-scale port infrastructure projects are often lumpy once-and-for-all decisions (Bar-Ilan & Strange, 1999). Hence, this latter approach is also used in this thesis.

As discussed in the previous chapters, ports are affected by environmental issues on the one hand, and cause a number of negative external effects themselves on the other hand (Benacchio et al., 2000). In this chapter, the focus is on the impact of the aversion to waiting time of the shipping companies using the port's capacity on the investment decision. This waiting time generates delays involving considerable costs (Novaes et al., 2012). As pointed out in Chapter 1, aversion to waiting time and resulting congestion costs differ among users and goods categories. From queuing theory, it is known that waiting time in ports generally begins to increase as infrastructure occupancy rates pass 50% and that it is the result of uncertainty regarding the distribution of ship arrivals at a terminal with a given theoretical capacity (Blauwens et al., 2016). Installing a larger port would lead to less waiting time and less congestion when the same amount of throughput is handled. As a result, travel times would be shorter, since capacity serves as a buffer against waiting time that is caused by future demand growth. This is of measurable value to shippers. Yet, previous studies have shown that investment in more capacity attracts additional traffic and throughput, offsetting part of this capacity investment benefit (Zhang, 2007; Wan et al., 2013). What remains unclear however is how the investment decision in a new port is influenced by port users' average aversion to waiting time.

In this chapter, the investment in a new container port in a growth market under uncertainty is studied. The considered port is operated by one single actor which also owns the port. In the considered region, only one significant port is assumed, leaving port competition beyond the scope of this chapter. Two once-and-for-all decisions have to be made: the size of the port and when to build it. The analysis takes into account that next to the capacity decision in the first (investment) stage, the port can flexibly adapt its price level in the second (operational) stage to influence throughput and port occupancy. The approach omitting competition moreover allows focusing on the impact of congestion and uncertainty on an individual port's investment decision. Such investment decisions are relevant in growing developing countries with a lot of uncertainty. Examples include the greenfield container ports in Manaus and Porto Central (both in Brazil) and north of Izmir (in Turkey), as well as port development in African countries (Vanelslander, 2014; Ward, 2015).

This chapter sheds light on how the cost of congestion for port users affects the optimal investment in new port infrastructure under demand uncertainty. To this end, a real options approach is used. The proposed approach to congestion costs allows differentiating between projects involving goods categories and shippers with different waiting-time aversions. The RO methodology in this chapter represents a more accurate continuous-time continuous-state model for ports to decide on their optimal investment strategies, compared with models omitting congestion and the costs it involves (Dangl, 1999; Hagspiel et al., 2016; Novaes et al., 2012). Moreover, uncertainty is modelled through a geometric Brownian motion, which allows analysing the impact of economic growth and uncertainty independently of one another.

As was shown in the previous chapter, many sources of uncertainty impact demand, such as trade uncertainty and the different maritime logistics chain actors' uncertain decisions, which are exogenous for a port. Although here the scope of uncertainty is limited to the macro level, also a number of micro-level uncertainties, such as disasters, technological, legal and political uncertainty exist. They are however left beyond the scope of this thesis, since they involve a different modelling approach. Nevertheless, other research is available that studies the impact of these sources of uncertainty on port investment decisions. Randrianarisoa & Zhang (2019) study the impact of climate change on port investment decisions under uncertainty. Also K. Wang & Zhang (2018) study the impact of natural disaster risk on port adaptation investments to reduce potential damage. They use Knightian uncertainty and Poisson jumps to model uncertainty. Moreover, other port investment types are concerned. As a result, ports' policies need to be supported by a combination of both types of research. It could be interesting to study in future research how different sources of uncertainty and investment types can be combined in one decision making model.

The structure of this chapter is as follows. The next section deals with the economic context considered in this chapter and explains the methodology used to identify the optimal size and timing of the (new) port capacity investment decision under uncertainty. Section 3.2 explains the selection of the parameters used for the numerical application of the model to a new port, since analytical solutions are not obtainable. In Section 3.3, the value calculation of an investment project under uncertainty is elaborated. In Section 3.4 the optimal size and timing of the investment decision are derived and the impact of congestion and uncertainty on the decision is quantified. A sensitivity analysis in Section 3.5 shows how the investment decision depends on the various economic parameter values. The final section presents the conclusion of this chapter.

3.1 Economic setting and methodology

In this chapter, a profit-maximising private port with flexible throughput, operated and owned by one single actor, is considered. Figure 3.1 illustrates the revenue sources and investment outlays of the considered single port actor. This port authority (PA) has the option to invest in a new port. The PA must take a lumpy once-and-for-all decision regarding the maximum capacity of the new port and the timing of the investment. However, the port's customers are averse to waiting, which implies additional costs for them. Hence, the first sub-question to be answered in this chapter is: (RQ 3.1) What is the impact of the degree of waiting-time aversion of port customers on a port's optimal capacity investment decision in a new private service port under uncertainty without competition? Since the port experiences a random but growing demand, the second sub-question is: (RQ 3.2) What is the impact of the amount of uncertainty on a port's optimal capacity investment decision in a new private service port without competition?

The assumed price transparency gives rise to the following linear additive inverse demand function for the port at time t:

$$\rho(t) = X(t) - Bq(t), \tag{3.1}$$

with $\rho(t)$ the gross willingness to pay,[1] $q(t)$ the throughput, $X(t)$ the value of an exogenous demand shift parameter at time t, sometimes also called the reservation price, and B the (negative) slope of the inverse demand curve. Throughput is measured in terms of

[1] Synonyms used in the literature are generalised cost or full price.

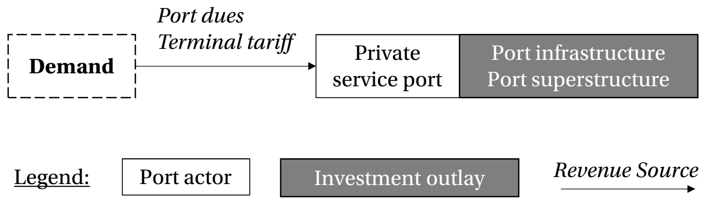


Figure 3.1: Revenue sources and investment outlays of the single actor (PA) in the considered private service port.

container TEU. It is assumed here that the theoretical design capacity of the new port, K, puts an upper limit to the throughput that can be handled. As such it is assumed that $0 \leqslant q(t) \leqslant K$ and as a consequence the capacity utilisation rate $q(t)/K$ is constrained between zero and one. Hence, exceptional cases where realised throughput $q(t)$ temporarily exceeds K at peak moments are disregarded in this chapter (Luo et al., 2010).[2]

Demand uncertainty is introduced in the model through random shifts of the demand function. These are introduced by a random process for $X(t)$ which is assumed to follow a geometric Brownian motion:

$$\mathrm{d}X(t) = \mu X(t)\mathrm{d}t + \sigma X(t)\mathrm{d}Z(t), \tag{3.2}$$

which is specified by parameters μ (expected drift in demand shift) and σ (variability) and with Z a standard Wiener process. A GBM is often used to model uncertainty, because both drift and variability are included in the random process as independent parameters. The implementation of this approach is however new in the context of port capacity investment decisions under congestion. Chen & Liu (2016) for example use a uniform distribution to model demand uncertainty in a port. Another advantage is that with an initial value of $X(t=0) > 0$, the variable $X(t)$ always remains positive, even if expected drift is negative (Dixit & Pindyck, 1994). Here, the focus is on a base case with a positive drift μ, reflecting economic growth and growing international trade (UNCTAD, 2015). In such a case, demand shifts at the rate of μ, on average, but over certain time intervals, growth may be higher, lower or even negative due to the uncertainty, as shown in Figure 3.2. This simulated figure displays a possible evolution of demand for throughput in a port in a growth market. This approach of a positive growth rate is common in real options models (see e.g., Dixit & Pindyck (1994), Dangl (1999) and Hagspiel et al. (2016)), but is not a necessary condition for finding a solution. For the sake of readability, the (t)-dependencies will be omitted in the following equations.

According to Strandenes & Marlow (2000) and Xiao et al. (2012), the gross willingness to pay of customers is the sum of the unit price of services at the port (p) and the unit cost of

[2]This assumption is relaxed in Chapters 5-6. In Chapter 6, a comparison between the two approaches shows that the impact of this assumption on the optimal investment decisions is negligible.

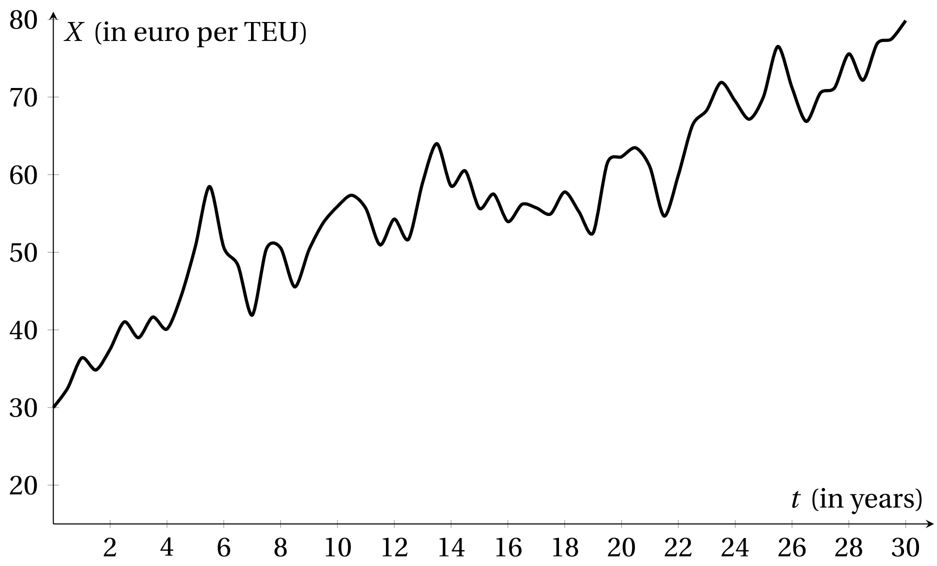


Figure 3.2: Sample evolution of demand shift parameter X following a GBM, with $X(t=0)=30$ euro per TEU, $\mu=0.015$ and $\sigma=0.1$.

congestion the users incur:

$$\rho = p + AX\frac{q}{K^2}. \tag{3.3}$$

Hence, p can be rewritten as:

$$p = X - Bq - AX\frac{q}{K^2}, \tag{3.4}$$

with the final term the unit cost of congestion which reduces the customer's gross willingness to pay. Total congestion cost TCC equals $AX(q/K)^2$, an own specification based on queuing theory insights from other authors (De Borger & Van Dender, 2006; Yuen et al., 2008; Xiao et al., 2012; Zhang & Zhang, 2006; Chen & Liu, 2016).[3] In the unit congestion cost term, the capacity utilisation rate is a proxy indicator for the amount of congestion and delays.

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, as previously discussed, queuing theory learns 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). To this end, Zhang & Zhang (2006) use a specification where delay depends on a scale factor *times* $q/[K(K-q)]$. This specification is based on estimates from steady-state queuing theory, with the underlying assumption of Poisson distributed arrivals (Lave & DeSalvo, 1968). It satisfies four conditions (Zhang & Zhang, 2006):

$$\frac{\partial D}{\partial q} > 0, \frac{\partial D}{\partial K} < 0, \frac{\partial^2 D}{\partial q^2} > 0, \frac{\partial^2 D}{\partial q \partial K} < 0. \tag{3.5}$$

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

These conditions imply that higher throughput and lower capacity lead to an increase in congestion and that these effects are stronger when congestion is already high.

The condition $\partial^2 D/\partial q^2 > 0$ however does not hold for the linear specification on the one hand. On the other hand, the disadvantage of the specification of Zhang & Zhang (2006) is that delays, and hence costs as well after a multiplication with a monetary scale factor, are infinitely high at full occupancy. This is not the case 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 (3.5), whereas full occupancy would not ex-ante be excluded. However, the exact, analytical optimisations performed in the remainder of this thesis would become too complicated under such a specification of the delay function, due to the consideration of quantity flexibility.[4] A second-order dependency would also already be more realistic than the first-order relationship, and would also satisfy the required conditions, but would still complicate the calculations too much. Therefore, a proxy for q is required, which can then replace the factor q^1 in q^2. The uncertain reservation price, X, is positively correlated with the optimal throughput at any point in time. This explains why q^2 is replaced by Xq, using X as a proxy for q. The advantage of this approach where congestion costs are linked to the state of the market is discussed further on in this section, using Equation (3.8).

In the next step, delays are translated into costs through the monetary scale factor A (Xiao et al., 2012). The parameter A depends on the port users and goods categories involved (Yuen et al., 2008). The monetary scale factor (A) is an expression of the value of time (De Jong, 2007) and is lower for shipping companies that transport goods which are less urgently needed or less impacted by time (e.g., wood compared with perishables or critical machine components) and for shipping companies with less stringent sailing schemes. In such cases, congestion poses less of a problem for the port user. However, different individual liners that will use the new capacity might have different values of time. Therefore, A should be interpreted as the average value of time of the new capacity's users. Moreover, A is fixed over time in this RO model. Therefore, including X in the congestion cost function has the advantage that the excess growth of X compared to the growth of q can account for rising values of time in the future (De Jong, 2007). Moreover, the customer base of a port is relatively stable over time, because container liners became less footloose (Verhoeven, 2015; Heaver et al., 2001). Hence, the assumption of a fixed average scale factor A per project is reasonable. Nevertheless, the value for A may differ between projects with different users. It is exactly this approach that allows illustrating the effect of different waiting-time aversions of users on the timing and size of the investment in a new port, through the variation of A in the analysis.

[4]The maximisation of profit, which is the first optimisation, with respect to the optimal quantity would then involve a sixth order function to be maximised. Even a second-order dependency on occupancy would involve a third-order function in this optimisation.

It can be derived from the previous expressions that in order to reduce or avoid congestion, ports can choose two strategies. On the one hand, they can charge higher prices. Congestion, ceteris paribus, reduces the willingness to pay of users. When there is more waiting time for the same amount of throughput, the aversion to waiting of the customers will lead to the port having to charge a lower price if it wants to retain all of these customers. As a result, handling the same amount of throughput for customers with the same willingness to pay, leads to lower revenues if congestion is higher (i.c., due to less capacity), because the users' additional waiting costs are part of their generalised costs. Equivalently, customers have a willingness to pay in order to avoid congestion. Hence, charging a higher price will lead to a lower throughput level, as a result of the negative slope of the demand curve, and less congestion, which in turn tempers the throughput reduction and might increase port revenues. This mechanism is known in the literature as congestion pricing. However, to implement this in a good way, the port needs to accurately measure instantaneous port occupancy rates at every moment in time. Moreover, the congestion pricing approach is especially useful in the short term. On the other hand, ports can accommodate the additional demand by investing in more capacity. Since this latter approach takes more time, this is only feasible in the long term. The investment approach will be preferred when the effect of the throughput increase will outweigh the previously discussed price effect following from the specific price elasticities of the port users.

Optimising both instantaneous profit and these discounted profits over time, in relation to investment outlays, includes the potential strategy of congestion pricing in the model. Prices will be set at the level that is most profitable for the port under consideration and will depend amongst others on the willingness to pay of the users and the actual value for the aversion to waiting, A, leading to an instantaneous optimal level of congestion. At a certain point in time however, investing becomes more profitable than further increasing prices and reducing throughput, and will then be the preferred option.

The total operational cost function of the port is given by

$$TC_O(q) = c\,q, \tag{3.6}$$

where c is the constant marginal operational cost, like it was used by Haralambides (2002). In the literature, no consensus exists about the presence of economies or diseconomies of scale in port operations. S. Chang (1978) for example encounters constant scale economies, whereas Reker et al. (1990) find diseconomies of scale, as opposed to the economies of scale of Tongzon (1993).[5] Due to the ambiguity in the literature, a simple linear production function is reasonable in this model.[6] The instantaneous port profit, π, can now be calculated

[5] For a comprehensive overview, see the literature review of Tovar et al. (2007, p. 210).

[6] A practical example justifies this specification. The available employees can handle one or more extra units of throughput, a typical case of economies of scale. However if even more additional throughput is to be handled, a new employee needs to be hired, leading to a sudden cost leap (diseconomies of scale). Moreover, the linear cost function approach is in line with other real options models such as Dangl (1999). Altering the specification of TC_O would however not substantially complicate the remainder of the analysis. For example, a second-order term as in Chapter 2 could be added if it increases realism for a specific case.

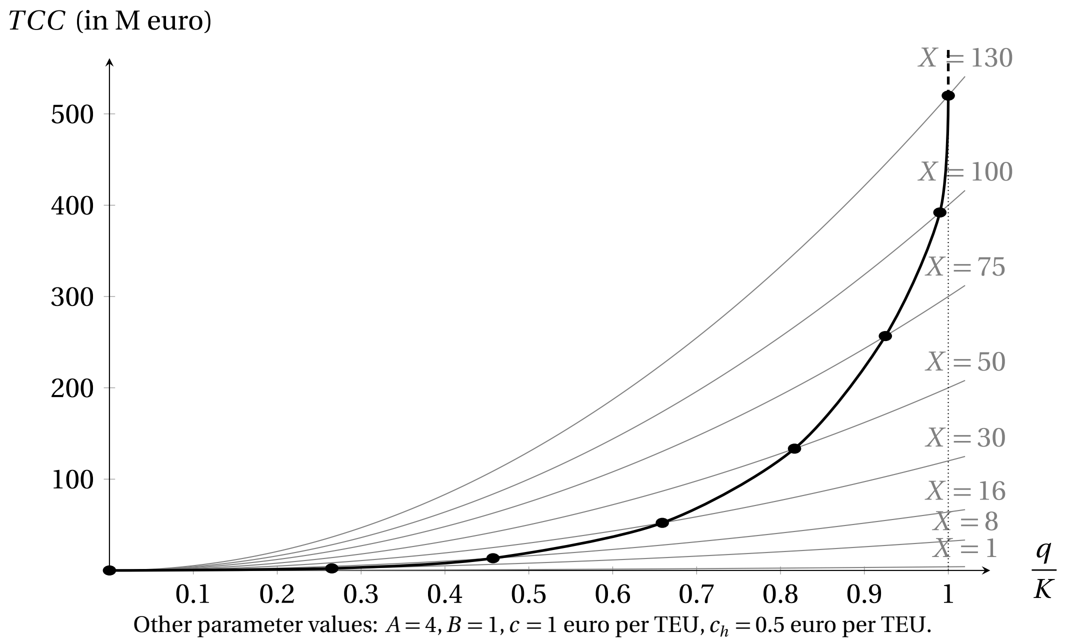


Figure 3.3: Realised total congestion cost function with installed capacity $K = 10$ million TEU per year.

as

$$\pi(X, K, q) = p(q)q - cq - c_h K, \tag{3.7}$$

total revenue minus operational costs (TC_O) and $c_h K$, the total cost to hold the capacity in place, for example through maintenance.

The optimal throughput $q^{opt}(X, K)$ for given X and capacity level K is the result of maximising profit π with respect to throughput q. This leads to the following total congestion cost TCC dependent on given X and K:

$$TCC(X, K) = AX\left(\frac{q^{opt}(X, K)}{K}\right)^2. \tag{3.8}$$

It is represented by the black curve in Figure 3.3 for the fixed port capacity level K of 10 million TEU per year.

Figure 3.3 hence demonstrates that including X in the congestion cost allows for an exponential realisation of the total congestion cost function, as observed in Figure 3.3. It moreover satisfies the conditions of Zhang & Zhang (2006) and it leads to a good approximation of the discussed queuing theory insights and reality, in which congestion and delays begin to emerge once an occupancy rate of approximately 50% is exceeded and increase substantially beyond 75% to 80% (Kauppila et al., 2016; Memos, 2004; Leachman & Jula, 2011; Novaes et al., 2012; Blauwens et al., 2016). The grey lines in Figure 3.3 are the quadratic total congestion cost functions that correspond to given values for the factor X and the variable throughput (q). Subsequently, a $q^{opt}(X, K)$ corresponds to each factor X and the fixed capacity level K. This q^{opt} divided by K results in the optimal occupancy rate.

These are marked on their corresponding congestion cost curves by black dots. Connecting those dots results in the realised total congestion cost function, shown in black, which has an exponential shape similar to the one of Leachman & Jula (2011). This is the case because the impact of X on the total congestion cost is twofold. On the one hand, an increase in X shifts the demand function upwards.[7] On the other hand, an increase in X leads to a higher occupancy rate and also to more delays.[8] As a consequence, the missed fraction of the potential demand grows more than linearly (Blauwens et al., 2016).

The investment cost $I(K)$ of installing a new port of size K is independent of the investment timing and is given by the following function:[9]

$$I(K) = FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_3 K^3 + \gamma_4 K^4, \tag{3.9}$$

where FC_I is the fixed investment cost, resulting among other things from a preliminary feasibility study. The cost of the investment grows with size K. Installing a larger dock involves more dredging activities and installing more quay walls and paving. This is reflected by a positive first-order term. General RO literature (Dangl, 1999; Hagspiel et al., 2016) and port literature (Haralambides, 2002) indicate the existence of economies of scale in the investment size. Investment costs increase less than proportionally with an increase in project size. This is reflected by the negative second-order term. Additionally, waterfront land is very costly (Haralambides, 2002). The available land for port infrastructure is limited. A larger investment than the available land would, for instance, imply expropriating houses, which is very costly. Therefore, a fourth-order term is added to the investment cost, reflecting an investment size boundary with a very sharp cost increase. Although a third-order term could also be used to model this boundary, the advantage of a fourth-order polynomial (with the third-order term omitted, $\gamma_3 = 0$) is that the function is not symmetric about the inflection point. Hence, the proposed mathematical specification does not impose that the economies of scale need to follow the same functional shape as the investment size boundary.

The previous considerations are taken into account by selecting appropriate values for the γ's in Equation (3.9), see Section 3.2. An example is already given in Figure 3.4. This investment cost function is compared with the dashed line representing the investment cost function of Dangl (1999):

$$I_{\text{Dangl}} = \gamma K^{\varepsilon}, \tag{3.10}$$

with the $\varepsilon < 1$ expressing the economies of scale in the investment size and without a size boundary. It is similar over the first part of its domain, but only the specification of this

[7] In the example, this leads to an upward shift in the grey curve. The impact on the congestion cost can easily be verified by considering a case in which q already equals K. With an increase in X, the occupancy rate would remain constant at $1(= K/K)$, but more potential demand would be foregone. The model accounts for this mathematically by multiplying the occupancy rate with X.

[8] The black dots move to the right.

[9] As Haralambides (2002) and Musso et al. (2006) highlighted, port investments are lumpy. This leads to discontinuous jumps in expansion paths of ports. Nevertheless, the cost of one individual investment project as a function of its size can reasonably be modelled as a continuous function.

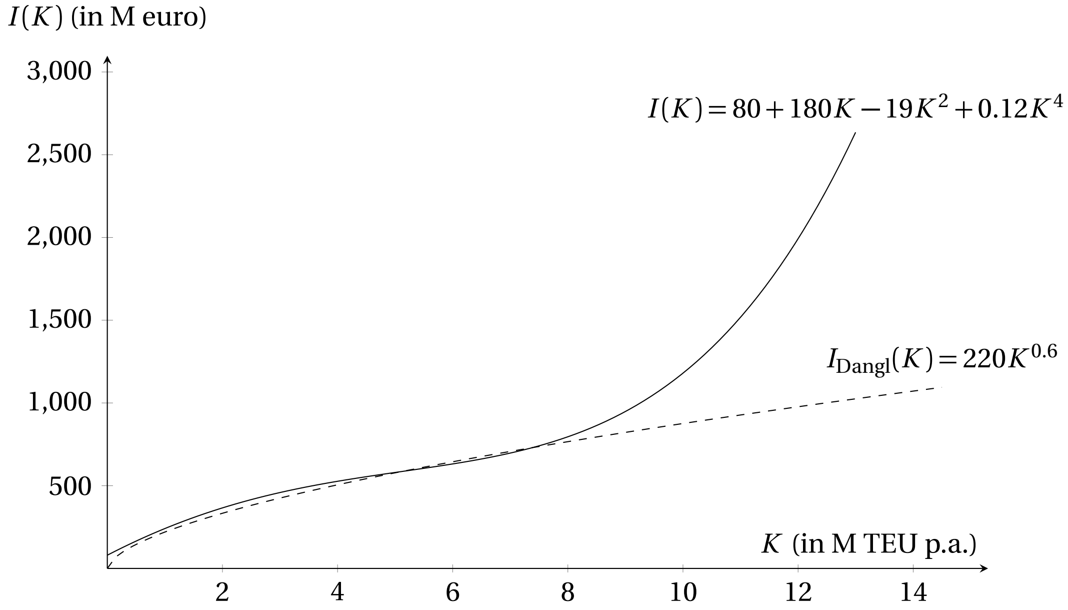


Figure 3.4: Total investment cost functions with and without a maximum boundary.

chapter's model then displays the required sharp cost increase reflecting the investment size boundary. This required shape is obtained when the γ's adhere the condition: $|\gamma_1| > |\gamma_2| > |\gamma_4|$. Although it could have been a possible alternative to just add a fourth-order term to I_{Dangl}, the advantage of the proposed function is that the shape is more flexible (especially over the first part of its domain) and that it is easier to estimate empirically using linear estimation techniques.

Additionally, it is important to point out that in practice, the shape and height of the investment cost function depend to a large extent on the characteristics of the project, such as the geographical situation, the production technology to be used, etc. The mathematical specification of the investment cost function needs to be considered as a translation of the reality into a model. In practice, it is necessary for the deciding actor to have a good insight into the different possible sizes of the project and the respective investment costs. The two most important aspects are the correct cost estimation for each size and the first-order derivative with respect to size, to express correct cost increases between different project sizes. To meet these requirements, for each case, different more or less equivalent functional specifications can be used. The exact functional shape will barely impact the investment decision, as long as the height and first-order derivative are sufficiently reflecting reality.

Given the discussed economic setting, the decision is to be made when and how much to invest. The former means to decide on the critical value X_T of the demand shift parameter for which it becomes optimal to invest, instead of waiting. This implies that investment will take place as soon as X reaches this threshold for the first time from below, as illustrated in Figure 3.5 at $T = 4.65$. Hence, a higher threshold value corresponds to investing

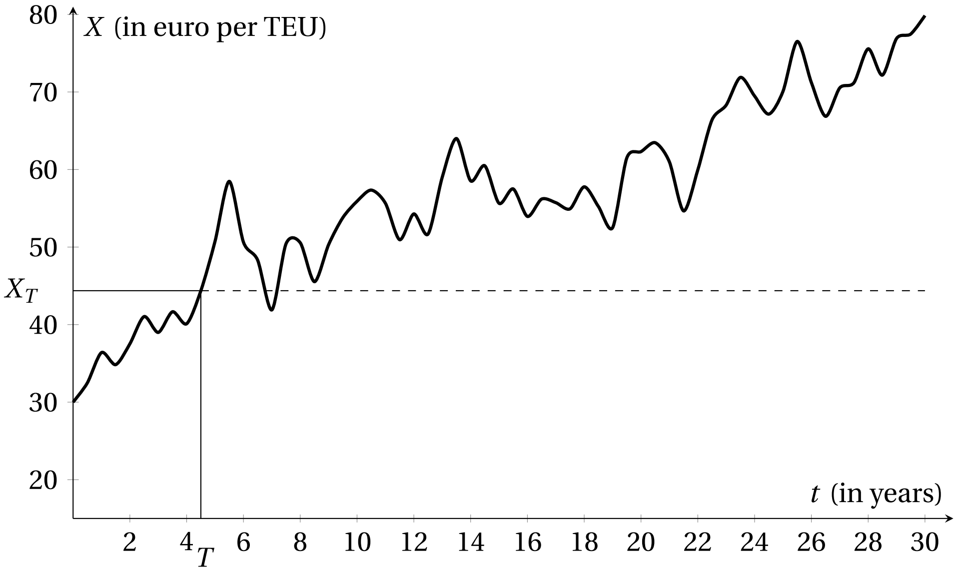


Figure 3.5: Relationship between the optimal investment timing and the threshold for demand shift parameter X following a GBM, with $X(t=0)=30$, $\mu=0.015$ and $\sigma=0.1$.

later. If $X(t=0)$ however exceeds X_T, investment takes place right away. At the moment of investing, also the optimal size of the capacity K has to be determined. As long as the demand shift parameter X remains below X_T, it is better to wait and keep the option open. Therefore, this region $X < X_T$ is called the *waiting region*. In this region, for $t < T$ such that $X(t) < X_T$, the value of the option is given by

$$F(X|X < X_T) = \mathrm{e}^{-r\mathrm{d}t}\,\mathbf{E}[F(X) + \mathrm{d}F(X)]. \tag{3.11}$$

At the moment (T) the demand shift parameters X equals X_T for the first time, the demand is sufficiently high to make it optimal to invest. In this *investment region* $X \geqslant X_T$, the value of the option becomes equal to the return of the investment. This return will depend on the demand at the moment of investment (as determined by X) and the installed capacity K. This capacity will be chosen such that the return of the investment is maximised. This implies that for $t \geqslant T$ where $X(t) \geqslant X_T$, the value of the option is given by

$$F(X|X \geqslant X_T) = \max_K [V(X,K) - I(K)], \tag{3.12}$$

with V the project value. This project value equals the present value of the annual profits (or losses) resulting from the project after it has been installed.

The model can be summarised as follows. The objective function for the investment maximises the expected future discounted profit stream minus the investment outlay of the project with respect to the timing T, where $X(t=T) = X_T$, and the capacity K (Huberts et al., 2015). If $X(t=0) < X_T$ so that it is not optimal to invest from the beginning, this investment problem objective function is given by

$$\max_{T\geqslant 0, K\geqslant 0} \mathbf{E}\left\{[V(X_T,K) - I(K)]\mathrm{e}^{-rT} | X(t=0) = X\right\}, \tag{3.13}$$

with the value of the investment project, which is assumed to have an infinite life time due to maintenance outlays:

$$V = \mathbf{E}\int_0^\infty \max_q\{\pi(T+\tau)\}e^{-r\tau}\,d\tau, \tag{3.14}$$

the (inverse) demand function where X is following a GBM determined by drift μ and variability σ, specified as follows:

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

the total cost function

$$TC = cq + c_h K$$

and the investment cost function

$$I = FC + \gamma_1 K - \gamma_2 K^2 + \gamma_3 K^3 + \gamma_4 K^4.$$

The next section determines numerical values for the model parameters, which are needed to calculate numerical solutions, since analytical solutions are not attainable.[10]

3.2 Parameter calibration of a hypothetical numerical example

In order to illustrate the working of the model and calculate solutions for the remainder of this thesis, the theoretical model is applied to the investment decision about a dock of about 8 to 14 million TEU. In this chapter, this dock is to be installed in a region where no port is active yet. The parameters are calibrated using data of projects such as Deurganckdok or Saeftinghedok in the port of Antwerp (Port of Antwerp, 2016; Vanelslander, 2014) and Maasvlakte 2 in the port of Rotterdam (Zuidgeest, 2009) in the Hamburg - Le Havre range in Western Europe. The derived parameters in this chapter will be retained in the next chapters.[11] Through this numerical approach, the impact of these parameters on the optimal investment decision can be derived. Moreover, outcomes of the different models in the different chapters are better comparable.

Given the investment costs discussed in Section 1.5, the cost of the investment in a new port, $I(K)$, is expected to be between one and three billion euro, depending on the size of the investment. In the example, throughput (q) and capacity (K) are expressed in million TEU per year, while price p and costs $c(=1)$ are in euro per TEU and $c_h(=0.5)$ in euro per TEU per year (Vergauwen, 2010; Meersman & Van de Voorde, 2014b; Vanelslander, 2014).

[10]This is due to the factor X not appearing in each term of the profit function. Hence, the solution for the optimal throughput, the resulting expression for the optimal profit and the expression for V become so complicated that the optimal solution for the option value cannot be expressed analytically.

[11]Additional parameters for the following models in the next chapters will be discussed when they are introduced for the first time.

Since sufficient data to accurately estimate parameter B are not available for this thesis, this parameter is normalised to 1. This is a common approach in RO models, see e.g., Dangl (1999). The impact of a change in B is analysed in the sensitivity analysis in Section 3.5. Profit is calculated in million euro. The investment cost $I(K)$ is also expressed in million euro. The values for drift ($\mu = 0.015$) and drift variability ($\sigma = 0.1$ to 0.2) can be validated empirically in the port context. Regressing an exponential growth model on annual container throughput of significant existing ports in Antwerp and Rotterdam between 2010 and 2015 (Vlaamse Havencommissie, 2016) resulted in a growth rate of between 1.5% and 2% [$p < 0.05$] for this port area. The root of the squared error of the regression led to a standard deviation of 15% to 17%, justifying the 10% to 20% interval for σ. Both parameters are however varied in the analysis. In transport infrastructure studies, a discount rate in the range of 4% (Blauwens, 1988) to 8% (Centraal Planbureau, 2001) is often used. The discount rate $r = 0.06$ is selected here in the base case, as did Aguerrevere (2003). Since the choice of the discount rate is often subject to much discussion, this value is varied as well in the sensitivity analysis in Section 3.5.

One of the most difficult aspects is determining suitable values for the monetary scale factor A. Ultimately, several different values for parameter A were selected from a range which produces realistic port investment strategies and occupancy rates.[12] It should be kept in mind that the objective is to show the impact of differing customer aversions to delays on the investment decision, rather than estimating the project's exact A. The model of this chapter with its selected parameter values is summarised in Table 3.1. The assumptions behind this model are summarised in Table 3.2.

3.3 Value of the investment project

The first step of the dynamic programming methodology determines the value $V(X,K)$ of the new port project of capacity K, once it is built at the moment the demand shift parameter equals X,[13] at a cost $I(K)$. For a private port, the project value $V(X,K)$ is the sum of the discounted maximum realised profits (or losses), specified in Equation (3.14), in which the discount rate $r > \mu$ in order to guarantee convergence of the model (Dixit & Pindyck, 1994).[14] Once the investment is made and capacity K is determined and becomes fixed,

[12]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 to the value of about 40 euro per container (not per TEU) per hour (De Jong, 2007) and given that congestion will not yet pose too large a 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.

[13]Note that as a result of this definition, an X used in $V(X,K)$ is considered de facto as a threshold value (X_T).

[14]Without this convergence, discounted future cash flows would grow infinitely over time, resulting in eternal postponement of the investment. This behaviour is similar to the reaction of customers in periods of deflation.

Table 3.1: Overview of Chapter 3's model and the selected parameters.

Variables		
p	=	price
q	=	throughput
K	=	capacity
Inverse demand function: $p = X - Bq - AX\frac{q}{K^2}$		
$B(=1)$	=	slope
$A(\in[4;5])$	=	monetary scale 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 (i.e., growth)
$\sigma(\in[0.1;0.2])$	=	drift variability of Z (i.e., uncertainty)
Total cost $TC = cq + c_h K$		
$c(=1)$	=	constant marginal operational cost
$c_h(=0.5)$	=	cost to hold one unit of capacity in place
Investment cost $I = FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_3 K^3 + \gamma_4 K^4$		
$FC_I(=80)$	=	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 project size

Table 3.2: Overview of Chapter 3's model assumptions.

	Assumption(s)
Project type?	New port
Capacity constraint?	Hard constraint
Port type?	Private service port*
Port competition?	No (1 port in model)
Time to build?	Not considered
Phased investment?	Project installed at once: available after completion
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, which evolve with the market (i.c., increasing)
	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)

*: 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 TOC). Focus on lumpy investment in port infrastructure and irreversible elements of superstructure.

the instantaneous profit under different values for the demand shift parameter X can only be altered and maximised through the pricing mechanism, to yield an optimal throughput quantity q^{opt}. The optimal throughput quantity at each point in time is given by the first-order condition for maximising π in Equation (3.7) and satisfies the second-order condition. It depends on the current value of the demand shift parameter X and the installed capacity K and is given by

$$q^{opt}(X,K) = \begin{cases} 0, & 0 \leqslant X < c, \\ \dfrac{(X-c)K^2}{2(XA+BK^2)}, & c \leqslant X < \dfrac{K(2BK+c)}{K-2A}, \\ K, & X \geqslant \dfrac{K(2BK+c)}{K-2A}. \end{cases} \tag{3.15}$$

Through the boundary values for X ensuring $0 \leqslant q^{opt} \leqslant K$ in Equation (3.15), three regions can be identified for X:

$$\begin{cases} R_1 = [0, c), \\ R_2 = \left[c, \dfrac{K(2BK+c)}{K-2A}\right), \\ R_3 = \left[\dfrac{K(2BK+c)}{K-2A}, \infty\right). \end{cases} \tag{3.16}$$

In R_1, no throughput will be handled, since the operational, variable cost will always be higher than the return. In R_2, q^{opt} increases in X and in K, which means that throughput increases along with demand and installed capacity.[15] Increased throughput as a result of installing more capacity may be a consequence of the congestion cost reduction. In R_3, optimal throughput is constrained by the theoretical design capacity K. Since $X > 0$ in a GBM, it can also be seen that R_3 only exists if $K > 2A$. Otherwise, a fully occupied port is always prevented by price increases, as port users are willing to pay to avoid very high levels of congestion, resulting from fully occupied port capacity. In that case, it always holds that $q^{opt} < K$.

Each region identified has a resulting optimal instantaneous profit (or loss):

$$\pi(X,K,q^{opt}(X,K)) = \overline{\pi}(X,K) = \begin{cases} \overline{\pi}_1(X,K) = -c_h K, & X \in R_1, \\ \overline{\pi}_2(X,K) = \dfrac{(X-c)^2K^2}{4(XA+BK^2)} - c_h K, & X \in R_2, \\ \overline{\pi}_3(X,K) = (K-A)X - (BK+c+c_h)K, & X \in R_3. \end{cases} \tag{3.17}$$

Now, Equation (3.14) can be rewritten as a dynamic programming problem:

$$V(X,K) = \overline{\pi}(X,K)\mathrm{d}t + \mathrm{e}^{-r\mathrm{d}t}\,\mathbf{E}(V(X,K) + \mathrm{d}V(X,K)). \tag{3.18}$$

[15]As expected and required, $\partial q^{opt}/\partial X > 0$ in R_2. A higher X leads to a higher potential demand. Economic theory states that, if available capacity allows, optimal realised throughput q^{opt} increases when demand shifts upwards and the supply curve has a positive inclination.

Here, V is a function of the value for X at the moment of investment and the installed capacity K. Using Itô's Lemma and the Bellman equation (Dixit & Pindyck, 1994), a differential equation for the project value $V(X,K)$ as a function of the investment threshold and capacity installed is obtained, which must be solved in each region R_j:

$$\frac{\sigma^2}{2}X^2\frac{\partial^2 V}{\partial X^2}(X,K)+\mu X\frac{\partial V}{\partial X}(X,K)-rV(X,K)+\overline{\pi}(X,K)=0. \tag{3.19}$$

The solution for $j=1,2,3$ is given by

$$V(X,K)|_{X\in R_j}=V_j(X,K)=G_{j,1}(K)X^{\beta_1}+G_{j,2}(K)X^{\beta_2}+\overline{V}_j(X,K), \tag{3.20}$$

where $\overline{V}_j(X,K)$ is a particular solution of differential equation (3.19) with $\overline{\pi}=\overline{\pi}_j$. The factors $G_{j,i}$ are parameters that can be determined through the boundary conditions. The roots β_1 and β_2 satisfy the quadratic equation

$$\frac{1}{2}\sigma^2\beta(\beta-1)+\mu\beta-r=0 \tag{3.21}$$

(see Dixit & Pindyck (1994)), and are equal to

$$\beta_1=\frac{\frac{\sigma^2}{2}-\mu+\sqrt{\left(\frac{\sigma^2}{2}-\mu\right)^2+2r\sigma^2}}{\sigma^2}>1, \qquad \beta_2=\frac{\frac{\sigma^2}{2}-\mu-\sqrt{\left(\frac{\sigma^2}{2}-\mu\right)^2+2r\sigma^2}}{\sigma^2}<0. \tag{3.22}$$

All of these considerations lead to the following particular solution in each region R_j:

$$\overline{V}_j(X,K)=\begin{cases}-\dfrac{c_hK}{r}, & j=1,\\[2ex] \dfrac{K^2}{4A(r-\mu)}X-\dfrac{1}{r}\left[\dfrac{K^2}{4A}\left(2c+\dfrac{BK^2}{A}\right)+c_hK\right] & \\ \quad -\dfrac{\left(c+\frac{BK^2}{A}\right)^2}{2\sigma^2B(\beta_2-\beta_1)}\left[\dfrac{1}{\beta_1}{}_2\mathrm{F}_1\left(1,-\beta_1;1-\beta_1;-\dfrac{AX}{BK^2}\right)\right. & \\ \quad -\dfrac{1}{\beta_2}{}_2\mathrm{F}_1\left(1,-\beta_2;1-\beta_2;-\dfrac{AX}{BK^2}\right) & \\ \quad \left.-\dfrac{\Gamma(\beta_1)\Gamma(1-\beta_1)(AX)^{\beta_1}}{(BK^2)^{\beta_1}}\right], & j=2,\\[2ex] \dfrac{K-A}{r-\mu}X-\dfrac{BK^2+cK+c_hK}{r}, & j=3,\end{cases} \tag{3.23}$$

with ${}_2\mathrm{F}_1()$ hypergeometrical functions. Appendix A contains more details on the calculation of the solution to differential equation (3.19).

Six[16] boundary conditions are imposed (see Dixit & Pindyck (1994) and Dangl (1999))

[16] If R_3 does not exist, the final two conditions can be omitted, the second condition holds for $\overline{V}_2(X,K)$, and $G_{2,1}$ and $G_{3,2}$ both equal zero.

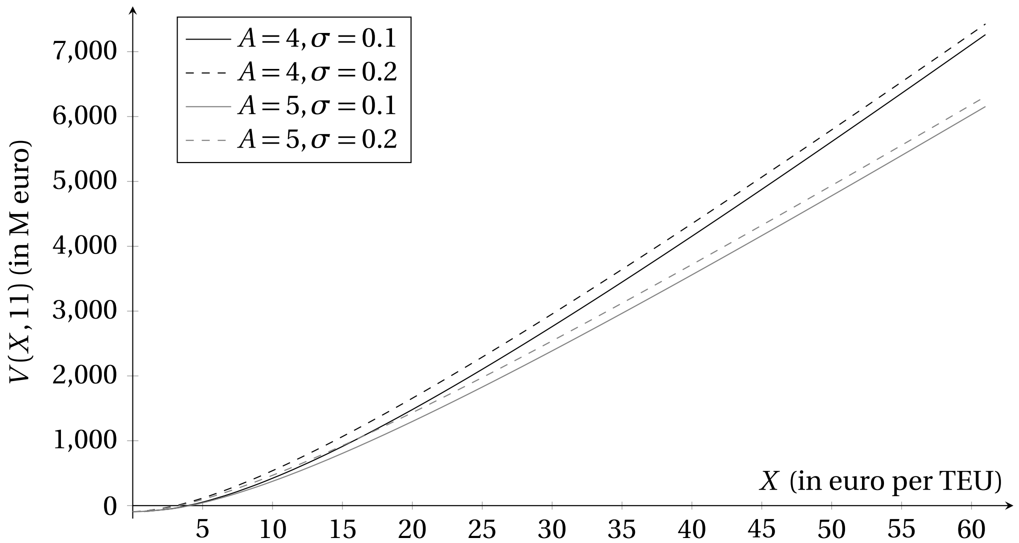
in order to calculate the factors $G_{j,i}$:

$$\begin{cases} V(0,K) = \mathbf{E}\int_0^\infty -c_h K \mathrm{e}^{-rt}\mathrm{d}t = \dfrac{-c_h K}{r}, \\ \lim\limits_{X\to+\infty}(V(X,K) - \overline{V}_3(X,K)) = 0, \\ \lim\limits_{X\overset{<}{\to}c} V(X,K) = \lim\limits_{X\overset{>}{\to}c} V(X,K), \\ \lim\limits_{X\overset{<}{\to}c} \frac{\partial V}{\partial X}(X,K) = \lim\limits_{X\overset{>}{\to}c} \frac{\partial V}{\partial X}(X,K), \\ \lim\limits_{X\overset{<}{\to}\frac{K(2BK+c)}{K-2A}} V(X,K) = \lim\limits_{X\overset{>}{\to}\frac{K(2BK+c)}{K-2A}} V(X,K), \\ \lim\limits_{X\overset{<}{\to}\frac{K(2BK+c)}{K-2A}} \frac{\partial V}{\partial X}(X,K) = \lim\limits_{X\overset{>}{\to}\frac{K(2BK+c)}{K-2A}} \frac{\partial V}{\partial X}(X,K). \end{cases} \tag{3.24}$$

The first condition implies that $G_{1,2} = 0$ and the second that $G_{3,1} = 0$. This leaves the final four (value matching and smooth pasting) conditions to define the values for $G_{1,1}$, $G_{2,1}$, $G_{2,2}$ and $G_{3,2}$ (see Hagspiel et al. (2016)). $G_{1,1}$ represents the option to start production, $G_{3,2}$ the option of flexible throughput levels below full capacity and $G_{2,1}$ and $G_{2,2}$ are two correction factors in R_2. The $G_{j,i}$ are dependent only on K, since X is evaluated in c and $\frac{K(2BK+c)}{K-2A}$.

The port investment project value for a numerical example is displayed (partly) in Figure 3.6 as a function of the chosen threshold X with a fixed capacity K. This figure shows that in a situation with higher variability σ, the project value will be slightly higher, ceteris paribus. This is because the management of the port is able to take advantage of the higher upside potential and can avoid the larger downside potential by reducing or stopping operations when port price p falls too low. When congestion poses less of a problem to the customers, as expressed by a lower value of time, reflected by a lower A, the value of the project will also be higher. This is because the available capacity can be used at higher occupancy rates, without imposing a too high generalised cost ρ on the shipping lines. Moreover, the project value will be higher when investment is made at a higher threshold for X, i.e., a higher willingness to pay, and higher revenues can be generated from the outset. The negative value of the project at $X = 0$ is caused by this point being an absorbing barrier of the GBM process of X, resulting in a port revenue being equal to zero forever, in combination with a capacity holding cost $c_h K$.

Moreover, adding extra capacity increases the project value when capacity is low. This is because at high occupancy rates, due to high demand and low capacity on the left hand side of the graph, additional capacity would sharply reduce congestion. This has a high marginal value. When there is sufficient capacity and congestion is sufficiently low, adding more capacity only reduces value. Large sums of money are invested in capacity that is not required, as current port occupancy rates and congestion are sufficiently low for the customers. Hence in such a situation, additional congestion reductions as a result of additional capacity are much more costly than beneficial, because it is costly to hold this capacity at a cost c_h. Dangl (1999) shows in this light that the value of an additional unit of capacity K



Other parameter values: $B = 1$, $c = 1$ euro per TEU, $c_h = 0.5$ euro per TEU p.a., $\mu = 0.015$, $r = 0.06$, $K = 11$ M TEU p.a.

Figure 3.6: Value of the project as a function of X at the moment of investment.

can be calculated in each region R_j as

$$\left.\frac{dV(X,K)}{dK}\right|_{X\in R_j} = \frac{dG_{j,1}(K)}{dK}X^{\beta_1} + \frac{dG_{j,2}(K)}{dK}X^{\beta_2} + \frac{\partial \overline{V}_j(X,K)}{\partial K}. \tag{3.25}$$

This can also be written as

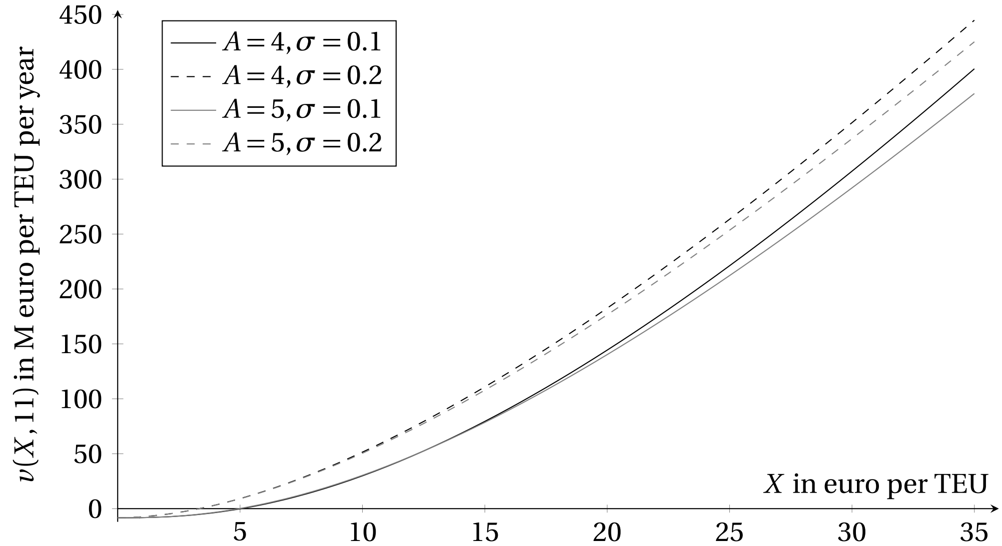
$$v(X,K)|_{X\in R_j} = v_j(X,K) = g_{j,1}(K)X^{\beta_1} + g_{j,2}(K)X^{\beta_2} + \overline{v}_j(X,K). \tag{3.26}$$

$v(X,K)$ can subsequently be determined by the conditions derived from (3.24).

$$\begin{cases} v(0,K) = \dfrac{-c_h}{r}, \\ \lim\limits_{X\to+\infty}(v(X,K) - \overline{v}_3(X,K)) = 0, \\ \lim\limits_{X\overset{<}{\to}c} v(X,K) = \lim\limits_{X\overset{>}{\to}c} v(X,K), \\ \lim\limits_{X\overset{<}{\to}c} \frac{\partial v}{\partial X}(X,K) = \lim\limits_{X\overset{>}{\to}c} \frac{\partial v}{\partial X}(X,K), \\ \lim\limits_{X\overset{<}{\to}\frac{K(2BK+c)}{K-2A}} v(X,K) = \lim\limits_{X\overset{>}{\to}\frac{K(2BK+c)}{K-2A}} v(X,K), \\ \lim\limits_{X\overset{<}{\to}\frac{K(2BK+c)}{K-2A}} \frac{\partial v}{\partial X}(X,K) = \lim\limits_{X\overset{>}{\to}\frac{K(2BK+c)}{K-2A}} \frac{\partial v}{\partial X}(X,K). \end{cases} \tag{3.27}$$

The resulting graph for $v(X,K)$ is presented in Figure 3.7, showing that the marginal value of the project with respect to capacity is higher when shipping lines have a lower value of time (as expressed by A). This difference grows with the capacity utilisation rates.[17] In

[17]When the maximum willingness to pay (X) is higher and K is fixed, capacity utilisation will be higher, as q^{opt} will increase.



Other parameter values: $B=1$, $c=1$ euro per TEU, $c_h=0.5$ euro per TEU p.a., $\mu=0.015$, $r=0.06$, $K=11$ M TEU p.a.

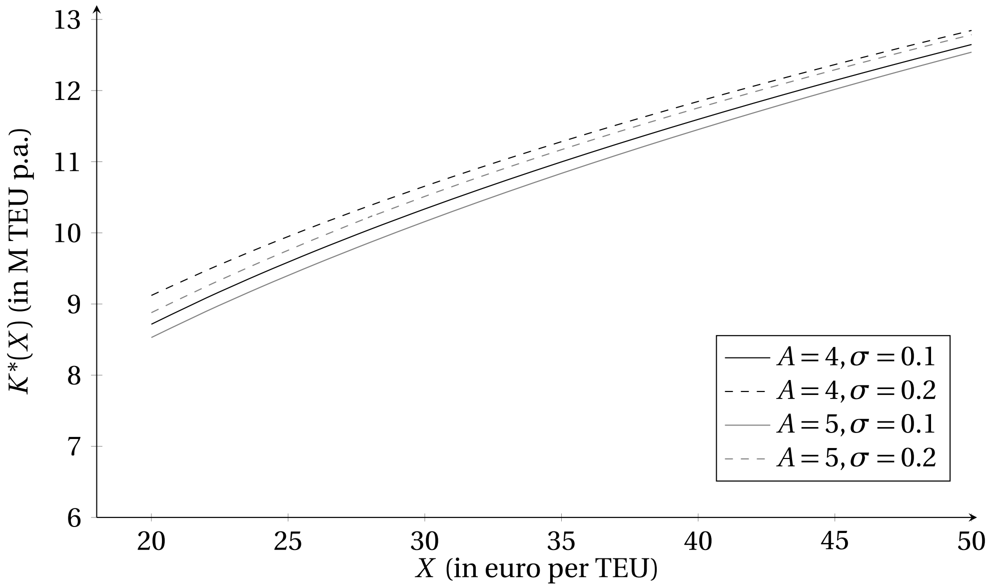
Figure 3.7: Marginal project value of capacity as a function of X.

the case of a lower value of time, the additional capacity K can relatively be more exploited and thus generates more additional revenue. Moreover, the figure shows that the marginal project value with respect to K is increasing in X, because the willingness to pay of the port customers increases with X. The marginal value is also higher when uncertainty is higher, because extra capacity is required to serve the potentially higher upward deviations in the demand (see Equation (3.2) and Figure 3.5), contributing to a higher option value under higher uncertainty.

3.4 Investment decision: optimal size and timing

In this section, the numerical values for the parameters and the calculated value of a new port project at the time of investment are used as inputs. Based on this, the optimal capacity and timing threshold are determined in order to maximise the expected discounted profit stream minus the investment cost. This allows identifying the ideal point in the trade-off between gaining additional information and foregoing income by delaying investment in the new port. When the investment is postponed, the port cannot earn a profit from handling cargo. However, when the port knows the demand is sufficiently high, there is a wedge to protect the port from negative demand fluctuations and guarantee sufficient profitability.

The option value included in the option to postpone the port capacity investment can



Other parameter values: $B = 1, c = 1, c_h = 0.5, \mu = 0.015, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12$.

Figure 3.8: Optimal capacity K^* as a function of $X \in R_2$.

be written as

$$F(X) = \max\left\{e^{-r\,dt}\,\mathbf{E}[F(X) + dF(X)], \max_K [V(X,K) - I(K)]\right\}, \tag{3.28}$$

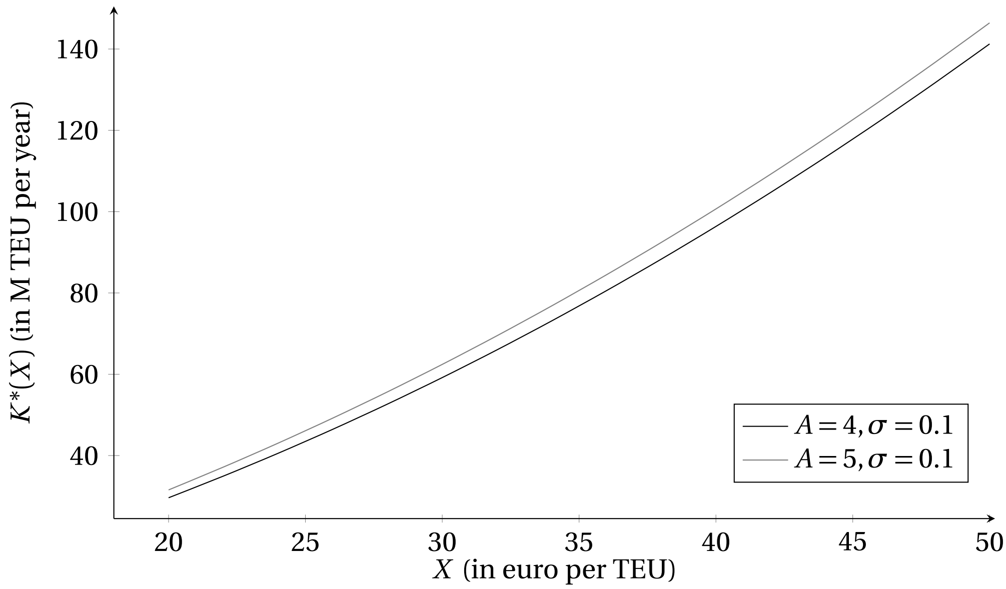
where the outer maximisation indicates whether the investment should be made or not yet (Dangl, 1999). In this way, the option $F(X)$ can be regarded as a trade-off between waiting longer to achieve a higher project value V, which however comes at the expense of higher discounting.

First, to obtain the new port's optimal capacity K^* for a given level of X at which investment takes place, a now or never (NPV-type) investment decision is examined, which is the inner maximisation of Equation (3.28). This is equivalent to obtaining the value $K = K^*(X)$ such that

$$v(X,K) - \frac{dI(K)}{dK} = 0. \tag{3.29}$$

The resulting curves $K^*(X)$ for various values of A and σ are plotted in Figure 3.8.

This analysis is relevant for ports to know their optimal design capacity K^*, should they wish to invest at an exogenously determined moment. Numerical calculations show that optimal capacity K^* is higher when the investment takes place at a higher X – in other words, later. Postponing port investment ultimately leads to a larger investment, due to the once-and-for-all nature of the investment decision. If demand is higher, a larger capacity investment is required. It is also best to invest in a larger port when uncertainty is higher, because more spare capacity should be made available for two reasons. First, more capacity allows the port to handle higher upward deviations from the expected market demand for throughput. Second, it reduces the likelihood that these extra port users will face waiting time caused by congestion (Meersman & Van de Voorde, 2014a). If the project is



Other parameter values: $B = 1, c = 1, c_h = 0.5, \mu = 0.015, r = 0.06$.

Figure 3.9: Optimal capacity K^* as a function of $X \in R_2$, with $I = I_{\text{Dangl}} = 220K^{0.6}$.

characterised by a higher average aversion to waiting, as expressed by a higher A, the port invests in less capacity. This is the result of two opposing impacts. On the one hand, with a higher A, capacity is needed more to reduce the occupancy rate and the costly congestion. On the other hand, however, the project value appears less attractive because of the reduced willingness to pay of customers and the required lower occupancy rates of the installed capacity. The latter implies an incentive for the port to invest in less capacity. The outcome of the trade-off is dependent on the specific investment cost function. Here, there is an inverse relationship between A and $K^*(X)$. Under the investment cost function I_{Dangl} of Dangl (1999) for a production plant however, the outcome of this trade-off would be the opposite, as is illustrated in Figure 3.9. Moreover, due to the sharp port investment cost increase beyond the boundary to the investment size, the increase in optimal capacity $K^*(X)$ is decreasing in X. Indeed, the characteristics of the port area with its size limit temper the positive relationship between the size of the project and the demand for port services. This is not the case with the investment cost function I_{Dangl}, where there was no boundary to the investment size considered.

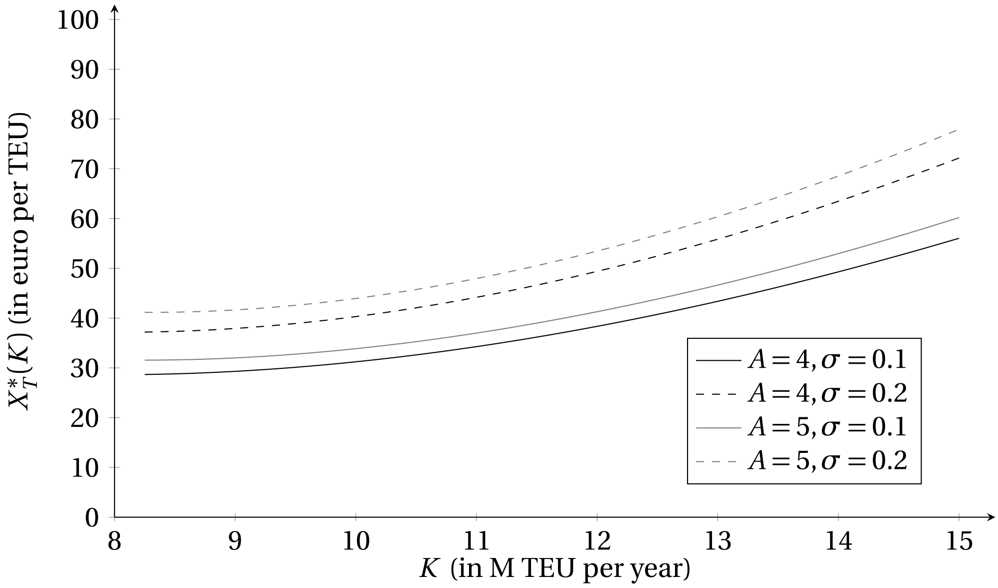
In addition to inner maximisation, outer maximisation of Equation (3.28) must also be solved. The option to delay investment with flexible throughput from Equation (3.28) satisfies a second-order differential equation (Dangl, 1999):

$$\frac{\sigma^2}{2}X^2\frac{\partial^2 F}{\partial X^2}(X,K)+\mu X\frac{\partial F}{\partial X}(X,K)-rF(X,K)=0. \tag{3.30}$$

The solution is given by

$$F(X)=H_1X^{\beta_1}+H_2X^{\beta_2}. \tag{3.31}$$

No particular solution is required here, because there is no profit from the port project before investment takes place, and the β's equal those in Equation (3.22). The conditions



Other parameter values: $B = 1, c = 1$ euro per TEU, $c_h = 0.5$ euro per TEU per year,
$\mu = 0.015, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12$.

Note: no solution exists for R_3.

Figure 3.10: Optimal threshold $X_T^* \in R_2$ as a function of K.

required to find factors H_1, H_2 and the solution for state variable X (i.e., $X_T^*(K)$) are:

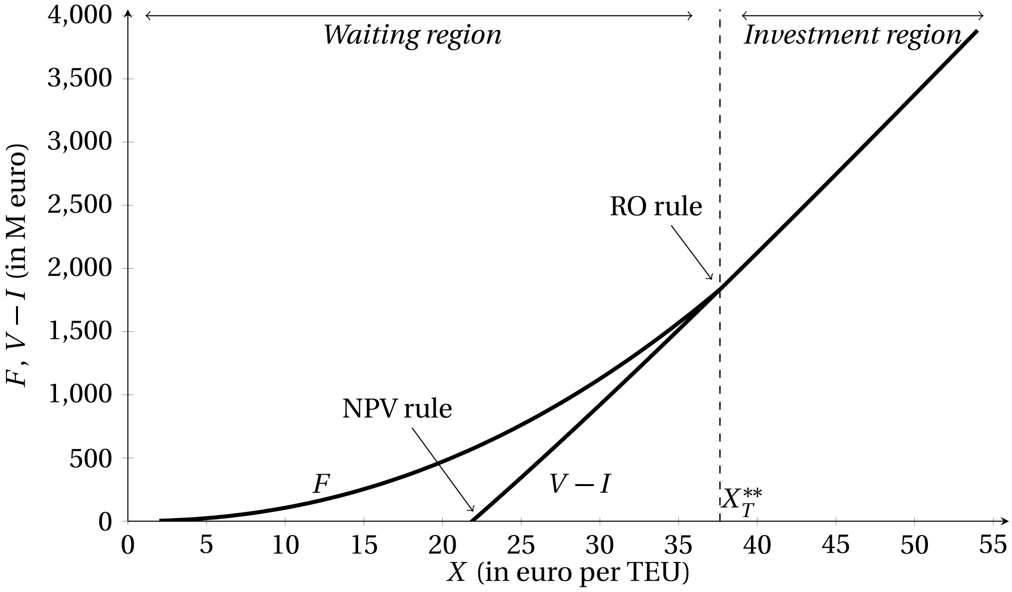
$$\begin{cases} F(0) = 0 \rightarrow H_2 = 0, \\ H_1 X_T^{*\beta_1} = V(X_T^*, K(X_T^*)) - I(K(X_T^*)), \\ \beta_1 H_1 X^{\beta_1 - 1} = \dfrac{\partial}{\partial X}(V(X, K(X)) - I(K(X)))\bigg|_{X = X_T^*}, \end{cases} \tag{3.32}$$

in which the last two conditions, known as value matching and smooth pasting, guarantee a continuous option value function (Dixit & Pindyck, 1994). The solution of this system is the optimal investment threshold X_T^* as a function of K, which can be useful for determining the optimal investment timing of a new port with a predetermined capacity.

A graph with numerical solutions is presented in Figure 3.10. The graph shows that larger investment projects are rolled out later, when demand is high enough to operate the port capacity at a sufficiently high price. It also shows that higher variability leads to later investments, as obtaining more information about the evolution of demand bears an option value. Both observations are consistent with S. Zheng & Negenborn (2017). Additionally, it can be seen that the higher the cost of delays, as expressed by A, the later the investment. This is because, in order to provide more of the costly spare capacity required in this case, more profit is needed. This is reflected by a higher threshold value for X.

In the next step, combining the optimal timing and size functions in the system

$$\begin{cases} X_T^{**} = X_T^*(K^{**}), \\ K^{**} = K^*(X_T^{**}), \end{cases} \tag{3.33}$$



The optimal investment threshold is $X_T^{**} = 37.63 \in R_2$, whereas the optimal capacity is $K^{**} = 11.17$.

Parameter values: $B = 1, c = 1, c_h = 0.5, \mu = 0.015, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12$.

Figure 3.11: Comparison between the option value $F(X)$ and the value of the project minus the investment cost $V(X, 11.17) - I(11.17)$ for $A = 5$ and $\sigma = 0.1$ in a private port.

yields the optimal flexible investment strategy (X_T^{**}, K^{**}) wherein both the timing and size of the investment are optimised. Using this solution, the option value $(F(X))$ and value of the project $V(X, K^{**}) - I(K^{**})$ can be plotted as a function of X, with K fixed at K^{**}. Figure 3.11 gives an example for $A = 5$ and $\sigma = 0.1$. In the example, an optimum can only be found in R_2, where capacity is not fully utilised. However, given the once-and-for-all nature of the investment, this will not prevent q^{opt} from eventually equalling K when X becomes large enough to reach R_3, according to Equation (3.15).

Figure 3.11 shows that in ports too, the general real options theory holds. The option to postpone investment bears a value and leads to investment postponement until $V \geqslant I + F$, as opposed to the traditional NPV rule $V > I$ (Dixit & Pindyck, 1994).[18] The new port in the example will dispose of capacity K^{**} (= 11.17 million TEU per year), which will be installed at threshold X_T^{**} (= 37.63 euro per TEU), leading to an optimal throughput at the moment of investment of 7.3 million TEU per year. The initial occupancy rate will hence be 65%, which is indeed below full occupancy. The initial price per TEU after investment, according to Equation (3.4), would be 19.31 euro, which leads to obtaining a discounted project value of 3.35 billion euro at the time of investment and compensating for the project's investment costs of 1.59 billion euro. It is interesting here to note that through the inverse demand function and given the optimal capacity, X_T^{**} can be converted into an optimal throughput quantity (in million TEU per year) that needs to be demanded at a certain price (in euro per TEU) before investment takes place. This is a more practical decision variable for port

[18]The RO rule leads to postponing the investment to $X_T = 37.63$ euro per TEU, as opposed to $X_T = 22.49$ euro per TEU under NPV.

managers.

In order to further analyse the impact of congestion costs and uncertainty on the investment decision, a number of other investment pairs (X_T^{**}, K^{**}) are calculated numerically for altered values of A and σ, as shown in Table 3.3.

A crucial question to be answered is how the port investment decision is influenced by congestion costs under uncertainty. If congestion costs were not considered ($A = 0$), the new port would be too small and it would be installed at a threshold X_T^{**} that is too low. Table 3.3 demonstrates this major result.

Result 3.1. *Under the assumptions given in Table 3.2, ports with customers that are on average more waiting-time averse, should invest in more capacity, but later.*

This observation is the result of three effects with conflicting outcomes. First, an increase in the monetary scale factor of congestion, A, leads to a lower profit. This makes the investment less attractive, resulting in a lower capacity K^*. Second, the port may also wish to wait longer before investing to increase the project's value, resulting in a higher value for threshold X_T^*. Due to the positive inclination of the $K^*(X)$-function, this results at the same time in an increase in the optimal capacity K^*. The final effect is a direct increase in capacity K^*, since congestion now poses a greater problem for port users and lower occupancy rates q/K are required. The final two effects dominate, since capacity has a higher marginal value when it is not fully occupied. Moreover, increasing the size of the project implies taking more advantage of the investment size scale economies.

Regions that want to invest in a new port, should take this result into account. If the future customers are very waiting-time averse, it is better to wait longer before building the new port. In this way, more (spare) capacity can be provided. At the same time, the investment size scale economies are exploited more by the investors. However, if the customers' value of time is lower, the investors optimise their expected present value by investing sooner in less capacity, which will however be occupied more.

The second result from the table is consistent with a well-known RO finding and is here proven to hold in a port environment as well (Dangl, 1999; Huisman & Kort, 2015):

Result 3.2. *Under the assumptions given in Table 3.2, higher demand uncertainty leads to later but more extensive investments in port capacity.*

When uncertainty is lower (or zero), the option value of waiting will be lower.[19] Consequently, the investment in less port capacity will take place at a lower threshold value.

[19] It should be noted that even in the deterministic case where $\sigma = 0$, there is an option value inherent to waiting when the project value and investment costs differ little, as shown by Dixit & Pindyck (1994, p. 138-139). In real terms, the investment cost is reduced by e^{-rt}, whereas the returns over time decrease by only a factor $e^{-(r-\mu)t}$.

Table 3.3: Optimal private port investment decision (X_T^{**}, K^{**}) under different values of A and σ.

		Uncertainty		
		$\sigma = 0.10$	$\sigma = 0.15$	$\sigma = 0.20$
Congestion	$A = 0$	(18.61, 8.15)	(22.82, 9.20)	(24.40, 10.31)
monetary	$A = 4$	(33.67, 10.83)	(44.74, 12.21)	(63.27, 13.98)
scale	$A = 4.5$	(35.96, 11.02)	(48.44, 12.55)	(70.60, 14.53)
factor	$A = 5$	(37.63, 11.17)	(52.32, 12.88)	(78.97, 15.10)

Other parameter values: $B = 1, c = 1, c_h = 0.5, \mu = 0.015, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12$.

Less capacity is required to handle smaller upward deviations from the expected market demand for throughput, leading to congestion. Hence, when demand uncertainty can be reduced, the new port installed at optimal conditions will be sooner available.

The sensitivity of the investment decision to the other parameters determining the economic and operational context of a port requires additional attention and analysis. This is the focus of the next section, which considers operational costs c, investment costs I, economic growth μ and the steepness of the demand curve as influenced by B.

3.5 Influence of the economic and operational context on the optimal investment strategy of the port: sensitivity analysis

This section discusses the sensitivity tests of the results to changes in the other parameters included in the model, which are operational costs, investment costs, economic growth and the steepness of the demand curve. It is explored how the optimal capacity (K^*) and timing (X_T^*) for the new port, displayed in Figure 3.11, alter individually following a limited increase in a single parameter and what the new optimum (X_T^{**}, K^{**}) will be.

Table 3.4 shows some important results. First of all, the direct impact of the increase on the optimal level of capacity $K^*(X)$ at a given moment is as expected for all parameters: higher operating, capital and investment costs lead to investing in a smaller port, since they reduce the project's attractiveness. One exception is the fixed investment cost parameter FC_I. Since it is a constant in the investment cost function $I(K)$, it has no influence on the optimal capacity K, which is calculated through a derivation of $I(K)$ with respect to K. A steeper demand curve caused by a higher value for B also leads to a lower investment size K, as the market is less profitable and the port can then alter its price more freely without attracting or losing many customers. If B is lower, the port stands to gain by reducing the price slightly and attracting additional customers. For this to work, however, sufficient capacity is required. Investment size is also lower for a higher discount rate, since future revenues will be of lower value, especially compared to the immediate investment cost. In

Table 3.4: Reaction of the optimal $X_T^*(K)$, $K^*(X)$ and (X_T^{**}, K^{**}) to a 10% increase in the other parameters.

Parameter change	**Timing** $X_T^*(K=11.17)$	**Size** $K^*(X=37.63)$	**Decision** (X_T^{**}, K^{**})
Base case	*37.63*	*11.17*	*(37.63, 11.17)*
c +10%	37.79 (+)	11.16 (−)	(37.87 (+), 11.19 (+))
c_h +10%	37.77 (+)	11.16 (−)	(37.85 (+), 11.19 (+))
FC_I +10%	37.75 (+)	11.17 (=)	(37.86 (+), 11.20 (+))
γ_1 +10%	40.59 (+)	11.04 (−)	(42.39 (+), 11.62 (+))
γ_2 +10%	41.11 (+)	10.88 (−)	(42.29 (+), 11.45 (+))
γ_4 +10%	40.38 (+)	10.74 (−)	(39.52 (+), 10.97 (−))
r +10%	39.74 (+)	10.74 (−)	(38.43 (+), 10.83 (−))
μ +10%	37.37 (−)	11.34 (+)	(38.50 (+), 11.45 (+))
B +10%	38.70 (+)	11.01 (−)	(38.51 (+), 11.12 (−))

Base case parameter values:
$A=5, B=1, c=1, c_h=0.5, \mu=0.015, \sigma=0.1, r=0.06, FC_I=80, \gamma_1=180, \gamma_2=19, \gamma_3=0, \gamma_4=0.12.$

contrast, a higher expected average economic growth (μ) leads to investment in a larger port. This finding explains why the growing countries such as China have been investing in mega-ports.

Moreover, a parameter change which has a positive direct impact on optimal capacity $K^*(X)$ has a negative direct impact on optimal timing threshold X_T^*, and vice versa. This is plausible, because the response to a positive economic effect might be either to increase the size of a project at a given moment (to realise more of the feasible profit, growing with the economy), or to implement a project sooner (X_T^* can be lower to obtain the same profitability). Nonetheless, there is one exception. Although an increase in FC_I has no impact on $K^*(X)$, it does have a positive impact on $X_T^*(K)$. If the fixed expenditure for making an investment increases, a port may wish to postpone investment, so that higher revenues can compensate for this increased fixed cost.

As opposed to a negative direct effect, the indirect effect of an increase in capacity (K^*) on the optimal timing is positive, because $K^*(X)$ and $X_T^*(K)$ are both increasing functions. Hence, if size and timing are both considered jointly, the net effect on the (X_T^{**}, K^{**})-equilibrium is ambiguous. One of the variables always moves in the direction of the individual direct impact. The evolution of the other variable depends on the relative sizes of the indirect and direct effects. This is determined by the relative positions and slopes of the $X_T^*(K)$ and $K^*(X)$ functions when a specific parameter is altered. This is illustrated in the example of Figure 3.12, which shows an economic change that drives $K^*(X_T)$, capacity as a function of a chosen threshold, down (direct effect on capacity). This moves the equilibrium down left along $X_T^*(K)$ (indirect effect). But also because of this change, $X_T^*(K)$ increases and the

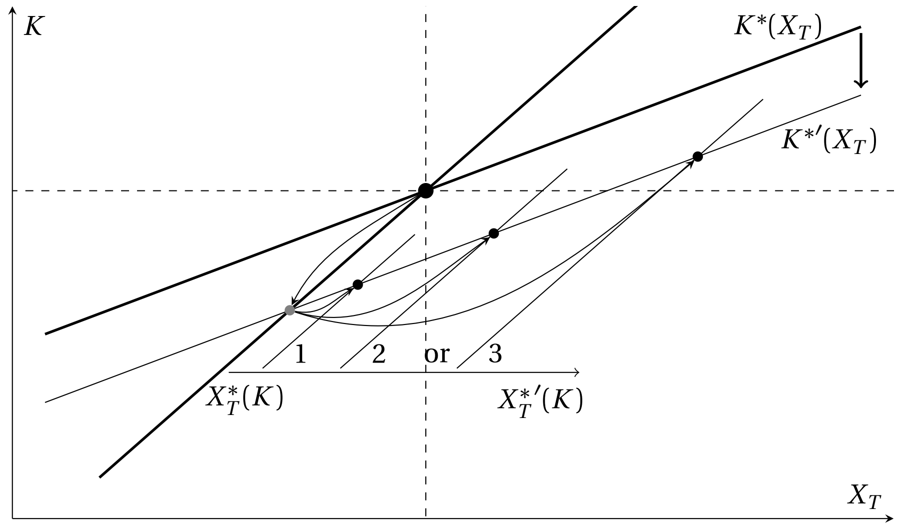


Figure 3.12: Evolution of the (X_T^{**}, K^{**})-equilibrium following a parameter change.

curve moves to the right as a result of the direct effect on the threshold value for the demand shift parameter. According to the new position of $X_T^*(K)$, the new equilibrium is in quadrant I, III or IV. Only a solution $X_T^*(K)$ in quadrant II would be impossible to reach, as this would move both X_T^* and K^* in a direction opposite to their expected direct effect.

Table 3.4 contains a number of results concerning the sensitivity of the model, based on the numerical simulations. After numerically simulating with a lot of different parameter settings, the reaction of the new optimum to a change of one parameter in Results 3.1, 3.2 and 3.3 turns out to be independent of the other parameter choices. The changes of the new optimum in the other results however do depend on the specific parameter settings.

Result 3.3. *Under the assumptions given in Table 3.2, higher port costs result in later investments in more capacity.*

Result 3.4. *If the discount rate r increases, smaller and/or later port capacity investment will be made. The impact on the new optimum depends on the specific parameter values and holds under the assumptions given in Table 3.2.*

Result 3.5. *If the growth rate increases, it is much more attractive to invest in a larger port and/or at an earlier moment. The impact on the new optimum depends on the specific parameter values and holds under the assumptions given in Table 3.2.*

Result 3.6. *A steeper demand curve leads to smaller and/or later investment in port capacity. The impact on the new optimum depends on the specific parameter values and holds under the assumptions given in Table 3.2.*

To further explore Result 3.5, the impact of a negative growth rate is examined in a scenario with $\mu = -0.005$. Here, the optimal investment decision would equal (44.30 euro per TEU, 10.32 million TEU per year). The port would be much smaller than in the case of positive growth, since the project would be less attractive due to expected decreasing profits

Table 3.5: Optimal investment decision (X_T^{**}, K^{**}) using a different discount rate.

Discount rate	**Decision** (X_T^{**}, K^{**})
$r = 0.03$	(87.81, 21.88)
$r = 0.04$	(43.96, 14.27)
$r = 0.06$	(37.63, 11.17)
$r = 0.08$	(41.24, 10.36)

Other parameter values:
$A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12.$

over time. In such a situation, less capacity would be needed too, as throughput levels will fall. Additionally, in order to compensate for future decreases in demand, the project would only be implemented at a much higher threshold, which is less likely to be reached. This explains why port investments are unlikely to take place in a decreasing market.

As the discount rate is subject to a lot of discussion in the literature, it is varied in Table 3.5 between the usual 4% and 8%. Recently, however, interest rates have been falling. Therefore, also the investment decision at 3% is calculated.

A higher discount rate r leads to a decreased net present value of future profits, hence reducing the value of the project and making the investment less attractive. It can be seen from the results that increased discount rates lead to smaller investment sizes. If the discount rate is small, an increase in the discount rate leads to lower a threshold X_T^{**}. For higher discount rates, the threshold will rise with an increased discount rate (see from $r = 0.06$ to $r = 0.08$).

If the discount rate is very low, it becomes very profitable to invest in more capacity, even to the extent that more capacity is installed than space allows. This is only feasible for the port if additional land and property is purchased. Hence, costly expropriation to extend the port area will take place to install the large amount of capacity. Since a high net growth rate is a consequence of the low discount rate, it is a good strategy to make the investment only at a large threshold for X so that the option value in the project can be exploited fully. Yet this observation should be interpreted with caution, for two reasons. First, at low discount and growth rates, the investment decision is also very sensitive to the growth rate. A growth rate of 1% in combination with a discount rate of 3% results in an investment in a capacity of 13.64 million TEU per year at threshold $X_T^{**} = 34.26$ euro per TEU, which is much more similar to the base case decision. Second, at historically low interest and hence discount rates, these rates can be expected to rise again in the future. Such volatility has a significant negative impact on investment size (Cassimon et al., 2002) and moderates the increase in investment triggered by low discount rates. Such discount rate volatility was however not included in this chapter's real options model.

Table 3.6: Optimal private port investment decision (X_T^{**}, K^{**}) under different values of r and σ.

		Uncertainty		
		$\boldsymbol{\sigma = 0.09}$	$\boldsymbol{\sigma = 0.10}$	$\boldsymbol{\sigma = 0.11}$
Dis-	$\boldsymbol{r = 0.05}$	(35.13, 11.73)	(37.72, 12.10)	(40.75, 12.51)
count	$\boldsymbol{r = 0.06}$	(35.67, 10.90)	(37.63, 11.17)	(39.87, 11.46)
rate	$\boldsymbol{r = 0.07}$	(37.46, 10.45)	(39.14, 10.67)	(41.01, 10.90)

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

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 3.6. 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 a considerable increase in the project size. Although increased uncertainty leads to investment postponement, the impact of the discount rate on timing was already shown to be ambiguous and dependent on the size of the discount rate. Therefore, the net impact of the combined effects on timing depends on the size of the interest rate as well.

3.6 Conclusion of this chapter

In order to account for the uncertainty, irreversibility and lumpiness of port capacity investments, a real options model has been built in this chapter to derive a first decision rule to find the optimal investment size and timing of the investment in a new port, fully operated by one private actor. As an addition to the available literature, the presented model includes the variable aversion to waiting time of the port's users in the investment analysis. Moreover, a continuum of potential investment decisions is considered to determine the optimal decision. To this end, a variable monetary scale factor allows differentiating the impact of waiting between different goods categories and port users involved. Moreover, the impact of uncertainty and other project and economic variables on the optimal investment decision has been analysed.

The main conclusion of this chapter is that considering the congestion cost in the analysis under uncertainty alters the investment decision considerably. If the congestion cost were not considered ($A = 0$), a new port that would be too small would be installed too early. As the examples here show too, the port will invest in more capacity at a later time through a higher threshold if the port customers are more waiting-time averse. When the uncertainty or port costs are higher, the port authority is advised to postpone investment and invest in more capacity as well, as this allows awaiting sufficient market information to become available to justify the investment. Moreover, waiting longer for a larger market provides the required wedge to protect against the downside of this uncertainty. Finally, increased net economic growth leads to a larger, later investment, as the investment project will be much more attractive.

The presented first real options model of this thesis serves as the base case for the next chapters. However, some of the assumptions of this chapter need relaxing in the following chapters, in order to deal with different situations. These outcomes can then be compared with the findings of this chapter and related to the impact of the different assumptions. For example the complicating impact of the port's ownership structure on the investment decision requires attention. When governments are involved, local benefits and consumer surplus as part of social welfare are frequently considered in the investment decision (Xiao et al., 2012). For governments, investment postponement not only involves foregoing profit, but also other economic effects are foregone and economic growth may be hampered. The specific distribution of the different revenues and costs between the port authority and terminal operating companies might alter the final investment decision as well. These impacts of public ownership and of the different actors involved in the capacity investment decision are studied in the next chapter.

Chapter 4

Port capacity investments with two actors and public money involved

In the previous chapter, the port capacity investment decision has been studied for a privately owned port, entirely operated by one single actor. In such a service port, the port operator owns the infrastructure and superstructure and is responsible for providing cargo handling services (Trujillo & Nombela, 2000; Slack & Frémont, 2005). In the majority of ports worldwide, the port product is realised by a combination of actors under the landlord model (Suykens & Van de Voorde, 1998). From Chapter 1 it was concluded that the capacity investment decision in such ports is influenced by different actors. This complicates the investment decision in two ways. First, the infrastructure and land are owned by the port authority (PA), while the terminal operating company (TOC) owns the superstructure and handles the cargo under a concession agreement with the PA. A second aspect typical for large and costly infrastructure projects such as port infrastructure is the involvement of public money, because ports create value beyond the border of a port (Brooks & Cullinane, 2007). In this light, Xiao et al. (2012) studied the influence of multiple port owners on capacity investment, showing that private ports tend to invest less in capacity than publicly owned ports. A port with public involvement exhibits a faster expansion path, since profit maximisation is not its only objective (Asteris et al., 2012). They also want to maximise social welfare, value added, and/or employment, which is often linked to the amount of throughput. This offers an explanation for a large number of ports trying to maximise their throughput (Tsamboulas & Ballis, 2014; Jiang et al., 2017). A similar study of Zhang & Zhang (2003) for airports unveiled that publicly owned airports invest sooner in capacity than private airports as well.

The previously discussed papers allowing for different types of ownership do not consider uncertainty. As Chen & Liu (2016), Xiao et al. (2012) and the previous chapter already demonstrated in a port operated by a single actor, uncertainty as well as congestion alter the investment decision a lot and need to be considered in the port capacity investment analysis. Therefore, the objective of this chapter is to analyse how a new port's optimal capacity investment decision under congestion and uncertainty is influenced by the interaction between the PA and the TOC and the involvement of public money. This allows analysing investment cases such as the port of Luanda and the port of Gioia Tauro in its development phase. To this end, the previous chapter's real options model is extended, which allows answering the following research sub-questions in this chapter: (RQ 4.1) How are the investment decisions of the PA and the TOC in new port capacity influenced by each other's decisions under uncertainty without competition? and (RQ 4.2) How are the investment decisions influenced by public PA ownership under uncertainty without competition? The results of this chapter are compared with the optima resulting from the previous chapter's set-up.

The structure of this chapter is as follows. The next section introduces the adaptations to the economic model to incorporate the distinction between the PA and the TOC in a landlord port and the involvement of public money in the ownership of a PA. Section 4.2 explains how the values for the additional model parameters are selected. Section 4.3 shows how the RO model and calculations are influenced by introducing a cooperative game between the PA and the TOC. Section 4.4 discusses the results, followed by a sensitivity analysis in Section 4.5. The conclusion of this chapter is given in Section 4.6.

4.1 Economic setting and methodology

In the type of ports considered here, the PA and the TOC invest in complementary elements of port capacity to realise their individual activities and earn in return different revenues. The sources of these revenues and the investment outlays of both actors are displayed in Figure 4.1. Other TOC income sources than the terminal tariff (e.g., storage) are ignored here, as they do not apply for every unit of throughput handled or they are negligible. Moreover, other activities such as tugging and piloting are assumed to be provided by other actors and left beyond the scope of this analysis. Demand originates from a receiver buying goods from the shipper, who ships them through a shipping line (Coppens et al., 2007). Containers, the pricing base of the TOC that handles them, are carried by shipping lines on their ships, the pricing base of the PA. As the focus is on the supply side with the PA and the TOC, the complexity of the demand side needs simplification. The number of ships can therefore be expressed in terms of the amount of throughput, or vice versa, through a conversion factor. As throughput generates welfare (Xiao et al., 2012), the number of ships is converted to the number of containers in Section 4.2. In this way, demand depends on one single variable, which reduces mathematical complexity.

The objectives of the PA and the TOC often diverge, because of their different activities and type of ownership (Heaver et al., 2000; Meersman et al., 2015; Xiao et al., 2012). As a result, this chapter's model presents two extensions compared with the previous chapter and

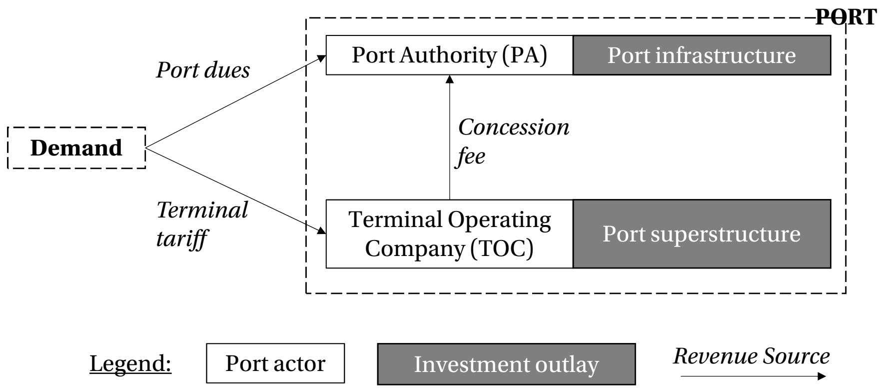


Figure 4.1: Revenue sources and investment outlays of the PA and the TOC.

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

4.1.1 Economic assumptions

Like the previous chapter, this chapter deals with the development of a new container port. The dock and terminal are in this chapter assumed to be installed at once and without time to build, by two actors, respectively one PA and one TOC. Since again the port is assumed to be situated in a location where little or no competition is present, the investment decision in only one port is studied. Moreover, the PA and the TOC have the option to make a once-and-for-all investment decision, of which the size and timing are flexible.

Next to these assumptions related to the economic environment and the investment decision, some behavioural assumptions are made in relation to landlord ports studied in this chapter. The assumption is made that the PA has full information about the TOC's price and cost decisions. In reality, the PA often only has full information about the realised throughput of the TOC. The PA could however make decent predictions of prices and costs of an efficient TOC, based on the limited available information about terminal operators already active in other ports and the expected demand. These predictions allow the PA to ex-ante calculate its expected part of the income from terminal operations. This income is realised by the PA through a concession fee, charged to the TOC. This income constitutes a considerable part of the port authority's profit and its correct inclusion in the calculations is required to accurately decide on the optimal size and timing of the infrastructure investment. The specific assumptions regarding the concession agreement and the mathematical model are included in the next subsections.

4.1.2 Differentiating between TOC and PA

This subsection describes how the distinction between the PA and the TOC is made in the economic model. The division of revenues and costs is described first. Next, the modelling of the concession fee and the related assumption of a renewal of the concession agreement are discussed. Finally, it is explained why the omission of time to build leads to assuming the PA and the TOC to install infrastructure and superstructure of the same capacity and at the same time.

The distribution of revenues and costs between both actors

The port customer faces the same demand function as in Equation (3.4) from the previous chapter. Since the price p is the sum of the terminal tariff

$$p_{\mathrm{TOC}} = \alpha_1 \cdot p, \tag{4.1}$$

paid by the shipping company to the TOC, and port dues

$$p_{\mathrm{PA}} = (1-\alpha_1) \cdot p, \tag{4.2}$$

paid by the shipping company to the PA; it holds that

$$p = p_{\mathrm{TOC}} + p_{\mathrm{PA}}. \tag{4.3}$$

In this chapter, the TOC and the PA independently set their respective prices for servicing ships and handling cargo, before the capacity is operated. The chosen relative prices determine α_1, the average share of the terminal tariff in the total price. The calculation of α_1 in practice, using real data and average port occupancy, is illustrated in Section 4.2. This share then remains fixed over time, as both the port dues and terminal tariff are assumed to subsequently follow the evolution of the demand shift parameter X, which determines the evolution of the market.[1] A growth of X leads to a higher total price p. This market growth, with its uncertainty as expressed by a GBM, is distributed accordingly over the TOC and the PA by the shares α_1 and $1-\alpha_1$. As a result, the customers' reduced willingness to pay due to congestion is also distributed by the same shares α_1 and $1-\alpha_1$ respectively.

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

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

cost $c_h K$ are divided between the TOC and the PA. The investment cost is the same fourth-order function of capacity as in Equation (3.9), which involves fixed investment costs (FC_I), economies of scale in investment size (negative second-order term) and a boundary to the maximum investment size (positive fourth-order term). For the division of the investment cost, the shares α_3 and $1-\alpha_3$ are used, whereas for the capacity holding cost, they are α_4 and $1-\alpha_4$ respectively. These express the cost structure differences between superstructure and infrastructure investments.[2]

Modelling the concession fee

An additional element that needs to be modelled to account for the different actors involved, is the concession fee. The PA grants a TOC the right to exploit a certain area of the port to handle the cargo, in exchange for a fee. The concession agreement stipulates for how long the TOC is allowed to exploit this area, the size of the concession fee, what specific activities will be performed, the minimum amount of activity required (often expressed in terms of throughput, the port's output) and the penalty linked to not meeting these requirements, e.g., the immediate end of the agreement or a penalty fee (Aronietis et al., 2010; Pallis et al., 2008; G. W. Y. Wang & Pallis, 2014).

According to Aronietis et al. (2010) and Meersman et al. (2009), the concession policy of a PA is the most important, or even unique, instrument to keep control over the terminal operators, which have become more powerful, and related shipping companies. Hence, the time length and contractual requirements of the concession agreement should be carefully considered and decided upon by the PA. In this way, the PA both retains sufficient control over the TOC and at the same time allows the TOC to have realised a profit at the end of the concession's life span. Concessions of 30 years including targets that match the common interests of both the PA and the TOC well, are a commonly observed practice. Longer concessions would imply the PA losing a significant part of its (already limited) power over the TOC, whereas shorter concessions would hamper the TOC to fully recover the investment cost during the project lifespan.

In this chapter, one TOC handles all the containers in the port. In return, the PA receives a concession fee from the TOC. Many different concession fee schemes exist, such as a lump sum, an annual fee, a quantity-dependent fee, a percentage of the revenue or a combination of these elements (Saeed & Larsen, 2010). The impact of the different forms of concession agreements is beyond the scope of this chapter. Hence and in order to avoid setting an arbitrary value for the concession fee, it is modelled as the TOC paying a share α_5 of its annual operational profit to the PA.[3] In this way, the modelled concession fee values are

[2]Note that α_1, α_2, α_3 and α_4 do not need to be equal, as they encompass different elements of the project cash flows (i.e., revenues and costs). The meaning of these α's is summarised in Table 4.1.

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

endogenous and more realistic. This would not be the case if the concession fee had been based on revenue, since the PA creaming off a too high percentage of the TOC's revenue would leave the TOC with losses and being discouraged to invest.

Setting an arbitrary percentage of the revenue can only be avoided by ex-ante calculating the concession fee as a share of the TOC's operational profit, taking in this way both revenues and costs into account. If operating is profitable for the TOC, it will remain so after paying the concession fee, since only a share of this profit is to be paid. In case the TOC cannot be profitable from operations, it could decide to suspend operations, especially if losses are persistent in the long term. Hence, operational profit will always remain greater than or equal to zero after deducting the concession fee. This is a prerequisite for a meaningful calculation of the concession fee.[4]

In reality, different ways to grant a concession and close the contract exist. According to Farrell (2012), who studied 781 international terminals, different procedures are used in different countries. Examples of recent awarding schemes include open tenders often involving auctions or one- or multiple-round negotiations, direct talks with terminal operators and joint ventures (Farrell, 2012; Meersman, 2005; Notteboom et al., 2012; G. W. Y. Wang & Pallis, 2014). Additionally, new concession contract types are constantly being developed (Tsamboulas & Ballis, 2014; Cruz & Marques, 2012). An important aspect of the concession agreement is that the port passes some of its demand risk, i.e., potential losses caused by the difference between forecasts and the actual realisation of the uncertain demand level, on to the concessionaire. For this, models have been developed to assess concessions under uncertainty (Niu & Zhang, 2013). To obtain a concession, the TOC has to present a business plan, including the expected NPV of the project. This serves as a good basis for the PA to determine the required minimum activity, a correct concession fee and a possible penalty for not meeting the predetermined objectives (G. W. Y. Wang & Pallis, 2014).

In this chapter, it is assumed that the PA has full information about the TOC and that negotiations about the final concession agreement between the PA and the TOC take place before the PA's investment decision.[5] As a result, the PA can *a priori* estimate the discounted profit of the TOC over time. With this information, the PA can decide on the concession fee, modelled by parameter α_5, the percentage of the TOC's operational profit to be creamed off, resulting in a discounted income stream. This can subsequently be converted into one of the in reality commonly applied concession fee systems with an equal net present value,

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

[5]In practice, concession agreements are negotiated at a later point. Although this implicit assumption is needed for modelling purposes, the impact on the outcomes is limited when the PA has a good ex-ante insight into the TOC's demand for concessions.

e.g., a lump sum, annual, throughput or revenue based fee (Pallis et al., 2008). This conversion is required to be able to implement the outcome of the ex-ante calculations and outcomes from the model in reality.

Since the concession fee has an impact on the returns of both the TOC and the PA and is set by the PA, the latter can influence its own profit and optimal investment decision as well as those of the TOC. This makes the concession fee an important decision variable for the PA to obtain desired behaviour of the TOC, without resorting to penalties that are in reality difficult to enforce.[6] In fact, such penalties involve negative consequences for both parties. When the concession agreement terminates prematurely, the port foregoes future throughput and income from this site. Due to the limited number of TOCs available following horizontal and vertical concentration in the market, it is complicated to replace a TOC. For the TOC, suspending the concession agreement involves the loss of the residual value (future profits) from the investment in the irreversible elements of the superstructure, such as paving, warehouses or specific equipment (e.g., cranes) that is very costly to transport. Moreover, not meeting the concession requirements might sometimes be caused by an adverse economic period, which is beyond the control of the TOC's management. A penalty might then induce even higher losses for the TOC than already incurred. As a consequence of assuming the TOC fulfilling the negotiated concession agreement conditions to the extent that the economic situation and demand allow it, future renewals of the agreement are assumed (G. W. Y. Wang & Pallis, 2014). This and the capacity holding expenses to maintain the capacity ($c_h K$ from the previous chapter) lead to assuming an infinite project lifetime in the calculations.

Possible investment and concession strategies for the PA

In the described port, the optimal timing (expressed as threshold X_T) and size (K) of the investment decision of the PA and the TOC may differ, because they have different operational objective functions to optimise. In the framework of Xiao et al. (2015) studying port infrastructure investments preventing disasters, different investments of the PA and the TOC are possible. In this chapter however, the chosen investment size and timing of both actors need to be the same, as they are considered the outcome of a cooperative game. Also Xiao et al. (2015) take the contract of cooperation between the PA and the TOC into account. Since a public party considers aggregated social welfare rather than individual profits, cooperation can be justified. An additional advantage of this approach is that it allows elaborating on how the optimum from the previous chapter can be reached in a landlord port. However, results are compared with a non-cooperative outcome as well, where the PA as a Stackelberg leader has all the power to set the concession fee. Although a PA prefers higher

[6]See for example the case where PSA only had to pay a fraction of the total penalty for handling less cargo between 2009 and 2012 than agreed upon in the concession agreement with the Port of Antwerp. In this case, the reason was a significant exogenous fall in demand due to the financial crisis of 2008.

concession fees, it should set the concession fee in a way that the incentive for the TOC is such that it would not invest too little nor too late.

In a landlord port, the PA and the TOC need each other's efforts to maximise their objectives through throughput generation. The PA's infrastructure investment facilitates the TOC servicing the ships and handling the goods. In the described cooperative game considering a lumpy once-and-for-all investment without time to build or phased investment, it would be disadvantageous for both parties or even impossible to invest at a different moment or in a different size. Infrastructure needs to be installed before superstructure can be installed and the capacity of the infrastructure poses a limit to the capacity of the superstructure. In this way, the decision of the PA can limit the TOC's investment options. If phased investment is not an option and construction lead times are omitted from the analysis, it does not make sense for a PA to invest in more capacity than the TOC's capacity investment under the concession agreement, as it would only cause a loss of money because of unused capacity. The same holds for the PA investing before the TOC, which would result in a period without profits, as the infrastructure would not yet be operated. As a result, the PA would not invest in the infrastructure before the moment the TOC is willing to install the superstructure. Hence, if optimal timing and size differ for both individual actors, their optima constitute an interval from which the unique final investment decision needs to be determined. (Meersman & Van de Voorde, 2014a)

Two possible investment strategies are discerned in this setting, depending on the negotiation power the PA possesses during the concession negotiations. Both are numerically illustrated in Section 4.4. A first investment strategy involves both the TOC and the PA giving in from their individual optima to invest at the aggregate optimum of a service port, which is often comprised in the decision interval. If the PA invests in a size at a threshold deviating from its optimum, it can urge the TOC to deviate as well through the concession negotiation or auction following the concession tender. If the TOC is not willing to deviate, it could be denied the concession. In that case, the PA of course needs to search for a new concessionaire. Under the described cooperative strategy, the concession fee can be interpreted as a redistribution of the project value after the deduction of investment costs ($V-I$) from one party to another. The concession fee should always be below a critical value that ascertains that the TOC's $V-I$ is sufficient to be willing to invest. It should be positive and exceed the opportunity cost of investing in a different port with a higher $V-I$. In this way, the concession fee size is market- and competition-dependent. These conditions set, a port wondering what the best concession fee is, could pursue different objectives when determining its concession fee:

- reaching an equal distribution of the entire project's $V-I$ over both actors;
- reaching a distribution of $V-I$ according to each actor's share in the operational cost, investment cost or a weighted sum of both;
- reaching a distribution according to other objectives based on the port's strategy, e.g.,

the relative effort made for marketing and attracting port customers;

- equalling the amount of discounted $V-I$ given up by each actor to deviate from the individual optimum to the agreed decision.

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

A second investment strategy for the PA to deal with deviating optima in the described scenario could be to urge the TOC to decide at the same time to invest in the same amount of capacity through economic incentives.[7] If the PA invests later or in a smaller amount than the TOC's optimum, the TOC is urged to adapt its strategy by taking this limiting investment decision variable as given for its own investment decision. The remaining decision variable can then be optimised conditionally on the already fixed variable. With a carefully selected concession fee, the TOC's conditional optimal value for this remaining decision variable will equal the PA's optimum. This competitive strategy hence also leads to the TOC and the PA investing in the same amount of capacity at the same market threshold. The downside of this strategy however is that less profit is realised at port level, aggregated over TOC and PA, as it differs from the global optimum in a service port.

4.1.3 Allowing for both public and private ownership of the PA

The analysis in Chapter 3 considered a private port. In reality however, very few ports are privately owned. Very often, public money is involved in a landlord port with a (partly) publicly owned PA (Suykens & Van de Voorde, 1998). If a government is involved, the PA will not maximise profit, but social welfare (SW), as infrastructure involves a benefit for society as a whole (Jenné, 2017). Social welfare is the sum of profit, spillover benefits for the local economy generated by the throughput handled in the port as discussed in Chapter 1, and consumer surplus (CS). Spillover benefits are included in the operational objective function as λq, with λ the spillover benefits per unit q. According to Xiao et al. (2012), consumer surplus is in this case calculated as

$$CS = \int_0^q \rho(Q)\mathrm{d}Q - \rho(q)q = Bq^2/2, \tag{4.4}$$

with ρ the gross willingness to pay. Some governments however only tend to consider the CS relevant for the region they govern. The Belgian government might for example only consider the CS of Belgian customers, and might disregard the CS of other shipping companies. To account for this in the operational objective function, s_{CS} is the share of total

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

consumer surplus considered by the government. This adaptation of the framework of Xiao et al. (2012) better models the European port doctrine.

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

$$SW(X,K,q) = \pi_{\text{PA}}(X,K,q) + \lambda q + s_{CS} \cdot Bq^2/2, \tag{4.5}$$

with $\pi_{\text{PA}}(X,K,q)$ the instantaneous annual profit of the PA, given the instantaneous value for the demand shift parameter X, the theoretical design capacity of the port K and the instantaneous annual throughput q. As discussed in Section 2.1.1, it might also be the case that the port is owned by a combination of public and private entities. The aggregated operational objective function (Π) of the PA is assumed to become the weighted sum of the individual owners' operational objective functions. The shares of ownership are used as the weights:

$$\begin{aligned} \Pi_{\text{PA}}(X,K,q) &= (1-s_G)\cdot \pi_{\text{PA}}(X,K,q) + s_G \cdot SW(X,K,q) \\ &= \pi_{\text{PA}}(X,K,q) + s_G \cdot \lambda q + s_G s_{CS} \cdot Bq^2/2, \end{aligned} \tag{4.6}$$

with s_G the relative number of PA shares owned by the government. As the sum of the shares needs to equal 1, the private parties together own a share of $1-s_G$ of the PA.[8]

4.1.4 Summary of the model adaptations and assumptions

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

$$\pi_{\text{TOC}}(X,K,q) = (1-\alpha_5)\cdot\left\{\alpha_1\cdot\left[p(q)q - AX\left(\frac{q}{K}\right)^2\right] - \alpha_2\cdot cq\right\} - \alpha_4\cdot c_h K, \tag{4.7}$$

$$I_{\text{TOC}}(K) = \alpha_3\cdot\left(FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_4 K^4\right), \tag{4.8}$$

whereas for the PA, it results in:

$$\begin{aligned} \pi_{\text{PA}}(X,K,q) &= [(1-\alpha_1)+(\alpha_1\alpha_5)]\cdot\left[p(q)q - AX\left(\frac{q}{K}\right)^2\right] \\ &\quad -[(1-\alpha_2)+(\alpha_2\alpha_5)]\cdot cq - (1-\alpha_4)\cdot c_h K, \end{aligned} \tag{4.9}$$

$$I_{\text{PA}}(K) = (1-\alpha_3)\cdot\left(FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_4 K^4\right). \tag{4.10}$$

The profits and costs of both actors are determined by the same drivers. However, these drivers are distributed differently over the TOC and the PA. It is hereby interesting to note that the sum of the profit functions on the one hand and the investment functions on the other hand both result in the profit and investment function of a private service port with

[8] As noted in Chapter 2, in some cases with majority ownership, a winner-take-all approach is better suited to model the PA's operational objective function. This comes down to setting s_G to 1 if the public owner has the majority share, and to 0 if the private owner has the majority share.

one single actor. In this way, the presented model can be used to calculate the private service port optimum as well. Since a (partly) publicly owned PA also considers social welfare, the operational objective function of the PA has been extended in Equation (4.6) with spillover benefits and consumer surplus, weighted by the share of public ownership.

Table 4.1 provides an overview of the entire economic model. It contains a short explanation of all the variables, equations and parameters, together with the values for the numerical examples as determined in the previous chapter and the next section. The assumptions of this chapter are summarised in Table 4.2.

4.2 Calibration of the parameters related to public ownership and the distribution of income and costs

In Section 3.2 in the previous chapter, a hypothetical example of a new container terminal of about 8 to 14 million TEU was used to illustrate the theoretical analysis. The parameters that were already calibrated are retained in Table 4.1. Since the model in this chapter accounts for public ownership and for a distinction between the PA and the TOC, additional parameters are introduced. In this section, the reasoning behind the chosen numerical values is explained.

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

As a result of differentiating between the TOC and the PA, five alphas are introduced. $\alpha_5 (\in [0;1])$ is a variable that can be set by the PA to determine the size of the concession fee. It represents the share of the TOC's operational profit that is paid to the PA. The share of the superstructure cost in the total investment cost is expressed by α_3. Based on Vanelslander (2005), Jacob (2013) and Jenné (2017), it is set to 0.35.[9] The share of superstructure holding cost in the total capacity holding cost $c_h K$, i.e., α_4, varies a lot depending on the specific

[9]For example, for a project with a capacity of 10 million TEU, the infrastructure would cost about 1 billion euro and the superstructure about 550 million euro, including cranes, straddle carriers, warehouses and gates. Note that this is an average of large and small terminals. For the investment analysis of a specific project, it is crucial to recalculate the share of the superstructure cost in this specific project's total cost.

Table 4.1: Overview of Chapter 4's model and the selected parameters.

Variables		
p	$=$	price
q	$=$	throughput
K	$=$	capacity
α_5	$=$	concession fee parameter: share of TOC's annual operational profit paid to PA
Aggregated inverse demand function: $p = X - Bq - AX\frac{q}{K^2}$		
$B(=1)$	$=$	slope
$A(=5)$	$=$	monetary scale 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 (i.e., growth)
$\sigma(=0.1)$	$=$	drift variability of Z (i.e., uncertainty)
Aggregated total cost $TC = cq + c_h K$		
$c(=1)$	$=$	constant marginal operational cost
$c_h(=0.5)$	$=$	cost to hold one unit of capacity in place
TOC investment cost $I_{\text{TOC}} = \alpha_3 \cdot \left(FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_3 K^3 + \gamma_4 K^4\right)$		
PA investment cost $I_{\text{PA}} = (1-\alpha_3) \cdot \left(FC_I + \gamma_1 K - \gamma_2 K^2 + \gamma_3 K^3 + \gamma_4 K^4\right)$		
$\alpha_3(=0.35)$	$=$	share of total investment cost I incurred by TOC
$FC_I(=80)$	$=$	fixed investment cost
$\gamma_1(=180)$	$=$	first-order coefficient
$\gamma_2(=19)$	$=$	coefficient reflecting investment economies of scale
$\gamma_3(=0)$	$=$	omitted third-order coefficient
$\gamma_4(=0.12)$	$=$	coefficient posing boundary to maximum project size
TOC profit = operational objective function π_{TOC}		
	$=$	$(1-\alpha_5) \cdot \left\{\alpha_1 \cdot \left[p(q)q\right] - \alpha_2 \cdot cq\right\} - \alpha_4 \cdot c_h K$
PA profit $\pi_{\text{PA}} = [(1-\alpha_1) + (\alpha_1\alpha_5)] \cdot \left[p(q)q\right] - [(1-\alpha_2) + (\alpha_2\alpha_5)] \cdot cq - (1-\alpha_4) \cdot c_h K$		
$\alpha_1(=0.9)$	$=$	share of terminal tariff in total price p
$\alpha_2(=0.95)$	$=$	share of c incurred by TOC
$\alpha_4(=0.5)$	$=$	share of capacity holding cost incurred by TOC
PA operational objective function $\Pi_{\text{PA}} = \pi_{\text{PA}} + s_G \cdot \lambda q + s_G s_{CS} \cdot CS$		
$\lambda(=0.4)$	$=$	spillover benefits per unit q
CS	$=$	consumer surplus, i.e., $Bq^2/2$
$s_G(\in[0;1])$	$=$	share of PA owned by the government
$s_{CS}(\in[0;1])$	$=$	share of total CS taken into account by the government

Table 4.2: Overview of Chapter 4's model assumptions.

	Assumption(s)
Project type?	New port
Capacity constraint?	Hard constraint
Port type?	Public and/or private, service* or landlord port**
Port competition?	No (1 port in model)
Time to build?	Not considered
Phased investment?	Project installed at once: available after completion
Specific assumptions	PA can derive full information about TOC prices and costs
	Distribution of port income and costs between PA and TOC are fixed over time
	PA invests in infrastructure, TOC invests in irreversible superstructure elements
	Investment timing and size of PA and TOC need to be equal: negotiated before construction, or forced by PA
	Concession fee is *modelled* as a percentage of the TOC's operational profit and is paid by the TOC to the PA
	Concession agreements are renewed over time → infinite project lifetime
	TOC handles the goods → TOC sets the throughput level (q^{opt})
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, which evolve with the market (i.c., increasing)
	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)

*: Owned and operated by one single actor.

**: Owned by the PA, operated by one TOC (actor differs from the PA).

***: 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 TOC).
Focus on lumpy investment in port infrastructure and irreversible elements of superstructure.

project considered and the related dredging contract. As an average, it is set here to 0.5, but it is varied in the sensitivity analysis (T. Zheng, 2015; Jan De Nul, 2012; Keskinen et al., 2017; Luck, 2017). Next, α_2 expresses the relative share of the TOC's operational cost in the total operational cost of the cargo handling services. To load and unload ships, the TOC encounters the cost of labour and electricity, which is the major part. The PA's marginal operational cost is negligible and mainly incurred by administration, since other services such as piloting and tugging are left beyond the scope of this analysis. By consequence, α_2 is set to 0.95.

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

In 2016, 4500 container ships called the Port of Antwerp (2017b), with an average GT of 55 000. Moreover, about 10 million TEU was handled in the same year, which results in an average of 2222 TEU per container ship. The prices of Port of Antwerp (2017a) show that the port dues per GT are 0.2 euro, if the ship is operated by a container line, without reductions included. The container supplement is 0.2 euro per ton and the Port of Antwerp (2017b) assumes 12 ton per TEU on average, so that the additional port dues for handling one TEU are 2.4 euro. As a result, the average total port dues equal 7.35 euro per TEU. The terminal tariff is 69 euro per TEU, as handling a container, involving two moves, costs about 110 euro and the average container is 1.59 TEU (Port of Antwerp, 2017b; Saeed & Larsen, 2010; Wiegmans & Behdani, 2018). Based on these numbers, the relative share of terminal tariffs in the total port income is calculated as:

$$\alpha_1 = \frac{69 \cdot 10 \times 10^6}{(69 \cdot 10 \times 10^6) + (0.2 \cdot 4500 \cdot 55000 + 0.2 \cdot 12 \cdot 10 \times 10^6)} = 0.90. \tag{4.11}$$

Altering the terminal tariff, port dues and average weight of one TEU within reasonable boundaries, indicates that for many ports, α_1 could be in a range of 0.8 to 0.95.

To study the impact of the determined values and changes in these values, they will be altered in the sensitivity analysis in Section 4.5.

4.3 Solving for the optimal investment strategy in a landlord port

With the operational objective functions of the port actors deciding on capacity and the numerical values for the parameters at hand, the optimal investment decision in a landlord port can be calculated. In reality, the PA first decides at which moment it would invest in infrastructure and how much capacity it would provide. Once this investment is made, it poses two boundaries to the superstructure investment of the TOC that obtained a concession agreement through negotiations or an auction following a tender. Since the TOC is responsible for the operation of the terminal, it sets the optimal throughput maximising its own profit: q_{TOC}^{opt}. This needs to be below K, because in this setting throughput cannot exceed the total design capacity K. Moreover, the assumption of full ex-ante information for the PA and the interactions with the TOC preceding a concession agreement lead to the consequence that the PA and the TOC select the same size and timing of the investment. The decision will often be somewhere between the extrema of both actors' optima, which constitute the decision interval as described in Section 4.1.2. If the TOC deviates from the PA's decision, the PA will not grant the concession and the TOC cannot invest in and operate the terminal.

In this chapter, the same dynamic programming methodology of the previous chapter is used to backwards solve the real options problem including congestion and multiple actors (a: TOC and PA) in a port. The way congestion is modelled gives again rise to hypergeometric functions (${}_2F_1$) in the expressions of the project value functions (after investment at time T_{a}) of the TOC:

$$V_{\text{TOC}} = \mathbf{E} \int_0^\infty \max_{q_{\text{TOC}}} \{\pi_{\text{TOC}}(T_{\text{TOC}} + \tau)\}\, \mathrm{e}^{-r\tau}\, \mathrm{d}\tau \tag{4.12}$$

and the PA:

$$V_{\text{PA}} = \mathbf{E} \int_0^\infty \Pi_{\text{PA}}\big(q_{\text{TOC}}, T_{\text{PA}} + \tau\big)\, \mathrm{e}^{-r\tau}\, \mathrm{d}\tau. \tag{4.13}$$

These equations highlight the important difference compared with a service port. The optimisation is to be executed for the two actors separately, but only one actor handles the goods. In order to find the optimal investment decision of each actor, each actor maximises the expected future discounted profit stream minus the investment outlay of its project, with respect to timing T_{a} and capacity K_{a} (Huisman & Kort, 2015). If $X(t = 0) < X_{T,\text{a}}$ so that it is not optimal to invest from the beginning, this gives rise to each actor's investment problem objective function:

$$\max_{T_{\text{a}} \geqslant 0, K_{\text{a}} \geqslant 0} \mathbf{E}\big\{\big[V_{\text{a}}(X_{T,\text{a}}, K_{\text{a}}) - I_{\text{a}}(K_{\text{a}})\big]\mathrm{e}^{-rT_{\text{a}}} | X(t=0) = X\big\}, \tag{4.14}$$

which is the same maximisation as for a service port, but now defined for each actor a.[10]

[10]Although this unrestricted optimisation problem for each actor can be solved independently, the final in-

Since each actor has the option to postpone the investment, each investment decision contains an option value $F_{\mathrm{a}}(X)$, based on the economic equations in Section 4.1. These option values are similar to the one derived in Section 3.1. Analogously, the optimisation with respect to timing again comes down to finding the critical threshold value $X_{T,\mathrm{a}}$ for which it is better to invest rather than to wait.

In order to solve this RO problem and optimise the investment decisions of both actors, similar calculations as in the previous chapter are required. However, some extensions and differences are present too. Here, the first step of the methodology determines the TOC's optimal throughput $q^{opt}_{\mathrm{TOC}}(X,K)$ through the first and second-order conditions for the $\pi_{\mathrm{TOC}}(q,X,K)$ of Equation (4.7). This results in

$$q^{opt}_{\mathrm{TOC}}(X,K)=\begin{cases}0, & X<\dfrac{\alpha_2}{\alpha_1}c,\\ \dfrac{(\alpha_1X-\alpha_2c)K^2}{2\alpha_1(AX+BK^2)}, & \dfrac{\alpha_2}{\alpha_1}c\leqslant X<\dfrac{(2\alpha_1BK+\alpha_2c)K}{\alpha_1(K-2A)},\\ K, & X\geqslant\dfrac{(2\alpha_1BK+\alpha_2c)K}{\alpha_1(K-2A)},\end{cases} \tag{4.15}$$

given the size of the port K and the instantaneous value for X. As it should hold that $0\leqslant q^{opt}_{\mathrm{TOC}}\leqslant K$, q^{opt}_{TOC} is again divided into three mathematical regions, defined by boundaries for X, as was also done in Chapter 3. Plugging q^{opt}_{TOC} into $\pi_{\mathrm{TOC}}(q,X,K)$ leads to $\overline{\pi}_{\mathrm{TOC}}(X,K)$, defined in the same three regions.

Second, through differential equation

$$\frac{\sigma^2}{2}X^2\frac{\partial^2V_{\mathrm{TOC}}}{\partial X^2}(X,K)+\mu X\frac{\partial V_{\mathrm{TOC}}}{\partial X}(X,K)-rV_{\mathrm{TOC}}(X,K)+\overline{\pi}_{\mathrm{TOC}}(X,K)=0, \tag{4.16}$$

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

$$F_{\mathrm{TOC}}(X)=\max\left\{\mathrm{e}^{-r\mathrm{d}t}\,\mathbf{E}(F_{\mathrm{TOC}}(X)+\mathrm{d}F_{\mathrm{TOC}}(X)),\max_{K_{\mathrm{TOC}}}[V_{\mathrm{TOC}}(X,K_{\mathrm{TOC}})-I_{\mathrm{TOC}}(K_{\mathrm{TOC}})]\right\} \tag{4.17}$$

gives the option value of investment postponement, which is maximised in order to find the optimal investment timing threshold and size of the TOC's investment $(X^{**}_{T,\mathrm{TOC}},K^{**}_{\mathrm{TOC}})$. Fourth, the resulting operational objective function of the PA, $\overline{\Pi}_{\mathrm{PA}}(X,K)$, is determined by plugging q^{opt}_{TOC} into $\Pi_{\mathrm{PA}}(q,X,K)$ from Equation (4.6), as it is the TOC that sets the throughput quantity. Using q^{opt}_{TOC} results in the same three regions for the PA's operational objective function as found for the TOC's profit. Fifth, the differential equation

$$\frac{\sigma^2}{2}X^2\frac{\partial^2V_{\mathrm{PA}}}{\partial X^2}(X,K)+\mu X\frac{\partial V_{\mathrm{PA}}}{\partial X}(X,K)-rV_{\mathrm{PA}}(X,K)+\overline{\Pi}_{\mathrm{PA}}(X,K)=0 \tag{4.18}$$

vestment decision made in a landlord port is the result of multiple interactions between the interdependent actors. The modelling of these interactions has been discussed in Section 4.1.2 and relates to the final step in Figure 4.2.

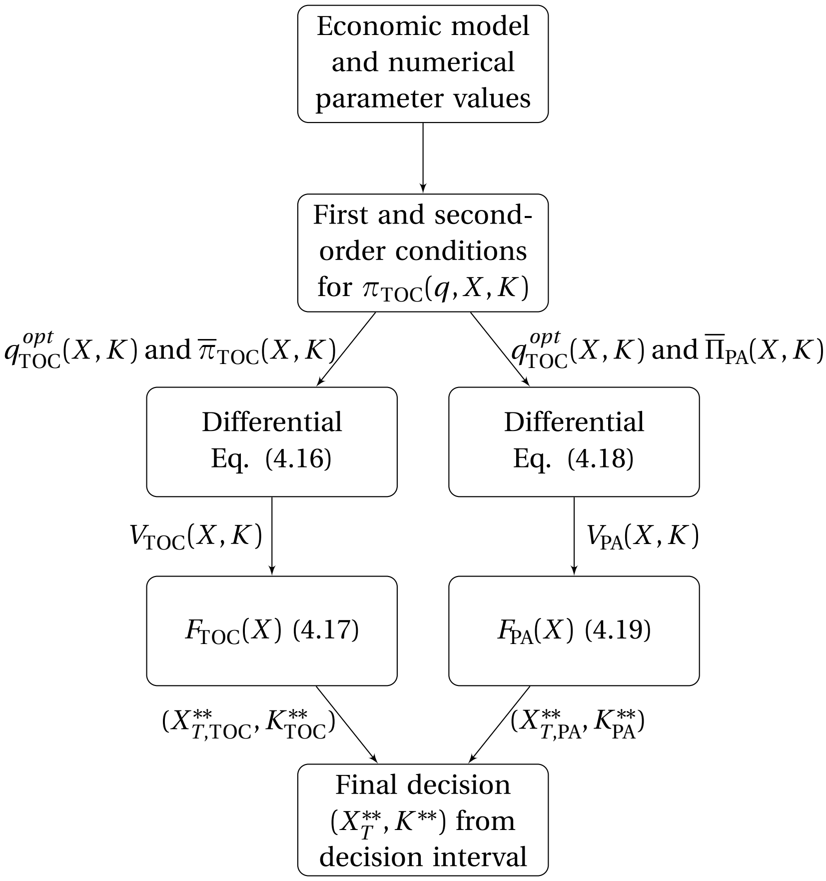


Figure 4.2: Summary of the cooperative RO game methodology.

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

$$F_{PA}(X) = \max\left\{ e^{-r\,dt}\,\mathbf{E}(F_{PA}(X) + dF_{PA}(X)), \max_{K_{PA}}[V_{PA}(X, K_{PA}) - I_{PA}(K_{PA})] \right\} \tag{4.19}$$

allows calculating the optimal investment timing threshold and size for the PA $(X_{T,PA}^{**}, K_{PA}^{**})$. Both $(X_{T,TOC}^{**}, K_{TOC}^{**})$ and $(X_{T,PA}^{**}, K_{PA}^{**})$ together constitute the decision interval from which the final investment decision is to be selected. The flowchart in Figure 4.2 summarises the steps of the cooperative RO game methodology of this chapter.

4.4 Results and discussion

In this section, numerical solutions for different port types are calculated using the previously described methodology. The investment decisions are compared with the optimal decision for a private service port with the same values for the common parameters. This optimum has been calculated as X_T^{**} = 37.63 euro per TEU and K^{**} = 11.17 million TEU

Table 4.3: Optimal $X^*_{T,\mathrm{a}}(K)$, $K^*_{\mathrm{a}}(X)$ and $(X^{**}_{T,\mathrm{a}}, K^{**}_{\mathrm{a}})$ under different α_5 in a private landlord port.

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

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

per year in Chapter 3. In this section, the impact on the investment decision of the division between the PA and the TOC and the size of the concession fee in a private landlord port is first studied separately from the impact of government involvement as a PA shareholder in a service port, partly or fully owned by the government. Afterwards, both are combined in a landlord port setting with public money involvement.

4.4.1 Division between PA and TOC

If the distinction between the PA and the TOC in a private landlord port (no government involvement, or s_G set to zero) is made according to the model in Table 4.1, an individual optimal investment threshold can be calculated for both the PA and the TOC. Indeed, given their individual revenues and costs, both the PA and the TOC might have a different individual investment optimum. Numerical simulations show that an α_5 leading to the same optimal investment size (α_5^K) and an α_5 leading to the same optimal timing for both actors (α_5^X) exist for different divisions of the revenues and costs between the PA and the TOC (see e.g., Table 4.10). Moreover, this optimal value common for both actors is almost equal to the optimum of the private service port where the port is directed and operated by one single actor. The other decision variable determining the optimal investment strategy then differs per actor, giving rise to a decision interval. This interval often also comprises the optimum value from the private service port.

The previous reasoning is illustrated with the numerical example in Table 4.3. If the TOC needs to pay 59.48% of its operational profit as a concession fee to the PA, the optimal investment threshold $X^{**}_{T,\mathrm{TOC}} = X^{**}_{T,\mathrm{PA}} = 37.63$ euro per TEU will be the same for both actors, which is nearly the same investment threshold as found in a private service port.[11] In that case, the optimal capacity for the PA will equal 11.12 million TEU per year, whereas for the TOC it will be optimal to invest in 11.26 million TEU per year. Indeed, the optimal capacity from a similar private service port (11.17 M TEU p.a.) is comprised in this decision interval. With a lower concession fee (α_5 set to 0.469) however, the optimal size of the investment is equal for both the PA and the TOC, almost equalling the optimal capacity $K^{**} = 11.17$ M TEU p.a. from a private service port. The optimal thresholds are then $X^{**}_{T,\mathrm{PA}} = 43.18$ euro per TEU and $X^{**}_{T,\mathrm{TOC}} = 31.30$ euro per TEU. Through mutual concessions, the same optimal threshold from a private service port, $X^{**}_T = 37.63$ euro per TEU, is attainable. It is also possible for other concession fees to select the global optimum from the decision interval.

Table 4.3 moreover illustrates the influence of the concession fee on the optimal investment decisions of both the PA and the TOC. If the TOC is required to pay a higher share of its operational profit, the TOC will invest later, or in less capacity ceteris paribus, because the project will be less attractive. This is opposed to the investment becoming more attractive for the PA, leading to an earlier investment or a larger investment size. In the previous chapter, it was observed that every parameter change increasing X^*_T, reduces K^* and vice versa. When observing the final optimal investment decision combining timing and size however, X^{**}_T will always be close to X^*_T, which does not hold for K^{**} and K^*. A later optimal timing X^{**}_T coincides with a higher optimal design capacity K^{**}, because the effect of the increasing $K^*(X)$ and $X^*_T(K)$-functions dominate the opposite shifts of these functions following a change in α_5. More specifically, due to the specific shape of the investment function with its economies and diseconomies of scale, the net impact of changes in the economic environment on the timing is larger than the net impact on the size of the investment.

Additional numerical calculations further illustrate the strategy of selecting the private service port optimum, which has a total project value minus investment costs $V - I$ of 1.76 billion euro. If the PA and the TOC in a private landlord port invest both at this optimum, their aggregated $V - I$ also equals 1.76 billion euro, independent of the size of the concession fee. Hence, this concession fee only has an impact on the distribution of the revenues and costs among both actors. The different concession fee strategies from Section 4.1.2 are illustrated in Table 4.4. The table shows that in this numerical example, $\alpha_5 = 0.5204$ leads to an equal $V - I$ for both actors. Setting α_5 to 0.6058 equals the share each actor has in both $V - I$ and I, which is 65% for the PA and 35% for the TOC.

The case involving a TOC paying 59.475% of its operational profit to the PA as a concession fee allows easily calculating each actor's impact of diversion from its own optimum. Since it is optimal with this concession fee for both actors to invest at the same time, $V - I$ of both can be compared at the moment of investment. No additional discounting is required. This scenario is quantified in Table 4.5 for different investment strategies included

[11] Only the rounded numbers are slightly different. As $X_T >> c$ and the chosen α_1 and α_2 do not differ by much in this numerical example, their impact on q^{opt}_{TOC} in Equation (4.15) and the optimal investment strategy is limited.

Table 4.4: $V - I$ of the PA and TOC under different concession fees, if both actors invest at the optimum of a private service port.

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

Parameter values: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.1, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, \alpha_1 = 0.9, \alpha_2 = 0.95, \alpha_3 = 0.35, \alpha_4 = 0.5, X_T = 37.63, K = 11.17$.

Table 4.5: $V - I$ of the PA and TOC with $\alpha_5 = 0.59475$ under possible investment strategies, equally followed by both actors.

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

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

in Table 4.3.

The results show that the PA investing in the service port optimum, which entails more capacity than its own optimum, leads to a decrease in $V - I$ for itself of 0.2 million euro. This however allows the TOC to make a larger investment, which is already closer to its own optimum. As the TOC can now invest in $K = 11.17$ M TEU p.a. instead of 11.12, the TOC's $V - I$ increases with 0.3 million euro. This leads to an aggregated gain of 0.1 million euro. In reality, such a situation would hardly be observed if the PA were privately owned, since only the own welfare would be maximised. Therefore, a public PA owner, caring about aggregated social welfare, is introduced in the next subsections. Deviating from the aggregate optimum would lead to a destruction of welfare, compared with situation b). Both actors investing at the TOC's optimum would make the TOC win an additional 0.2 million euro, but the PA would lose 0.8 million euro, destroying 0.6 million euro of aggregated profit. As argued before, the additional aggregated profit in situation b) can be distributed among the PA and the TOC through the adaptation of the concession fee. The size of the concession fee set by the PA is part of its strategy as discussed in Section 4.1.2 and is an important element in concession negotiations. Additionally, it is noteworthy that the deviations in project $V - I$ are limited in absolute terms for both actors. This favours the negotiations between the actors.

Table 4.6: Illustration of the PA's concession fee strategy forcing the TOC to take the same investment decision.

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

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

The results in Table 4.3 also bear worthy information for a PA searching for a good concession fee. For any value of α_5 between 46.9% and 59.475%, the PA poses a limit to both the size and timing of the TOC's optimal investment decision. In this range for the concession fee, the optimal timing of the TOC is earlier than the timing of the PA and the optimal capacity of the TOC would exceed that of the PA. In such a case, the PA knows that as soon as it invests in the negotiated capacity, the TOC will be willing to invest too in the same amount of capacity, as long as this still is a profitable strategy. This is important from a game-theoretic point of view, as the TOC's incentives to deviate from the contract should be minimised. In this light, the PA needs to have sufficient power to enforce the concession contract (G. W. Y. Wang & Pallis, 2014).

However, if α_5 is too low (i.c., below 0.469), the TOC may be willing to invest in less capacity than what has been decided on, whereas a too high α_5 (i.c., above 0.59475) could lead to the TOC investing later than the moment agreed upon. Although these latter two cases bear an incentive for the TOC to deviate from the PA's optimum, the PA still has some negotiation power that could turn out to be sufficient. In the first case, the PA could install the project at its own optimal threshold, which is higher than what is optimal for the TOC. As was explained before, this is a limiting factor and the TOC will internalise this higher threshold. Subsequently the TOC's optimal size is determined as $K^{*}_{\text{TOC}}(X^{**}_{T,\text{PA}})$, which might come closer to or even equal or exceed the optimal size of the PA. In this way, the PA retains a strong position. In the second case, a smaller project than what is optimal for the TOC could be installed. The TOC then takes the size as given and determines its remaining investment decision degree of freedom, its optimal threshold, conditionally on the size of the PA. This $X^{*}_{T,\text{TOC}}(K^{**}_{\text{PA}})$ might come closer to or even equal or be below the optimal threshold of the PA. An illustration is given in Table 4.6 for the unique α_5, given the other parameters, allowing the PA to force the TOC to invest exactly at the PA's optimum.

If $\alpha_5 = 0.60035$, the optimal decision for the TOC is to invest later and in more capacity than the PA. Hence, the TOC knows that it has to reduce its investment size accordingly, to the 11.11 million TEU per year of the PA. Taking this into account, the TOC calculates its conditional optimal threshold $X^{*}_{T,\text{TOC}}(11.11) = 37.43$ euro per TEU, which is equal to the threshold of the PA. The impact on the individual and aggregated discounted $V - I$ is shown in Table 4.7. It contains the discounted $V - I$ for both the PA and the TOC under different possible strategies at the moment where $X(t) = 35$ euro per TEU. These strategies are equally followed by both actors.[12] It is shown that the PA forcing the TOC to invest at its own optimum does in this case only cause small deviations in individual and aggregated discounted $V - I$ from the private service port optimum, or even from the optimal TOC's investment strategy.

Table 4.7: Discounted $V - I$ under under possible investment strategies equally followed by both actors in a private service port where the PA can force the TOC to invest in the PA optimum at the moment $t : X(t) = 35$ euro per TEU.

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

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

For any other α_5 than 0.60035, $X^*_{T,\text{TOC}}(K^{**}_{\text{PA}})$ will be either higher than the $X^{**}_{T,\text{PA}}$, meaning that the TOC is even more forced to deviate from its conditional optimum, or below $X^{**}_{T,\text{PA}}$, still implying an incentive for the TOC to invest below the PA's optimal capacity. For the given parameter values, in the other situation where the optimal timing of the PA is later than the optimal timing of the TOC, the resulting optimal size of the TOC will still exceed the PA's size. So there the TOC has to deviate even more from its optimum. There is no concession fee leading to $X^{**}_{T,\text{PA}} > X^{**}_{T,\text{TOC}}$, coinciding at the same time with $K^*_{\text{TOC}}(X^{**}_{T,\text{PA}}) = K^{**}_{\text{PA}}$.

The discussion of the numerical results of this subsection is summarised in the following result:

Result 4.1. *Under the assumptions given in Table 4.2, there are two ways to decide on the PA and TOC's common final investment decision. First, a well-thought-out concession fee and subsequent negotiations may allow choosing the aggregated investment optimum, which at the same time avoids incentives to deviate from this decision. Alternatively, the PA may set a concession fee and invest in its individual optimum which forces the TOC to invest at the same time in exactly the same amount of capacity. This strategy is the TOC's conditionally optimal strategy.*

This result shows that in the port that is to be built, the selection of the concession fee is

[12]This discounted $V - I$ is calculated as $(X/X_T)^{\beta_1} \cdot (V - I)$, with $(X/X_T)^{\beta_1}$ the stochastic discount factor at time t where $X(t) = X$ and with $\beta_1 = \dfrac{\frac{\sigma^2}{2} - \mu + \sqrt{\left(\frac{\sigma^2}{2} - \mu\right)^2 + 2r\sigma^2}}{\sigma^2}$ (Huisman & Kort, 2015).

Table 4.8: Optimal $X_T^*(K)$, $K^*(X)$ and (X_T^{**}, K^{**}) under different s_G and s_{CS} in a service port, partly or fully publicly owned.

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

Parameter values:

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

important, and has implications for the investment decision, given the negotiation power of both actors. If it turns out difficult for the PA to negotiate with the TOC about the investment strategy and the concession fee, which will be strongly dependent on the specific port situation, the PA can still pursue the second strategy. Using a well-chosen concession fee, the PA can force the TOC to also invest in this optimum of the PA.

4.4.2 Government involvement

Next to a private owner maximising profit, also a social welfare-maximising government can be a PA shareholder. As was explained, the government in the model owns a share s_G of the considered service port. The private partner then owns the remaining share $1 - s_G$. The share of total consumer surplus taken into account by the government is given by s_{CS}. Some possible scenarios are presented in Table 4.8.

The first line in Table 4.8 reflects the situation from Chapter 3 with a privately owned single port actor in a private service port. If the government's share of ownership or the considered share of consumer surplus is higher, the considered project benefits will be larger as well, as the spillover benefits and consumer surplus are taken more into account in the PA's operational objective function $\overline{\Pi}_{\text{PA}}(X, K)$. This is translated into a lower threshold for $X_T^*(K)$, which goes again hand in hand with a higher investment size $K^*(X)$. The analysis confirms the finding that public entities tend to invest sooner or in more capacity than private entities (Asteris et al., 2012). The optimal investment strategy (X_T^{**}, K^{**}) changes accordingly. If the government's share of ownership or the considered share of *CS* increases, the project is valued a lot higher because social welfare is taken more into account. As a result, the individual effects of earlier and larger investment dominate the positive relationship between size and timing, to lead to the following result:

Result 4.2. *Under the assumptions given in Table 4.2, increased government ownership or this government taking social welfare more into account leads to installing the new port ear-*

lier. This new port will moreover have a larger design capacity.

This finding is remarkable, because it is opposite to the common real options finding, where more capacity leads to a later investment or vice versa due to the dominating effect of the increasing $K^*(X)$ and $X_T^*(K)$-functions. When welfare effects are considered more, it proves beneficial to dispose of the new port capacity soon enough, and make it sufficiently large so that sufficient welfare effects are realised. Indeed, waiting implies foregoing consumer surplus and spillover benefits, as economic growth of the region is hampered by the current lacking of a port. Moreover, sufficient throughput to generate these effects is desired as well.

The optimal port capacity investment decision of the government is derived under the assumption that sufficient public budget is available and allocated to port investments. However, if the optimal investment size exceeded the available budget, the size of the actual investment would be limited by the available budget, and only the investment timing could be optimised, taking this maximum size as given: $X_T^*(K_{\max})$. Moreover, this result is reconsidered for a port expansion decision in Chapter 6.

4.4.3 Landlord port with public ownership

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

The results are similar to the outcomes in Table 4.3 for a private landlord port. Hence, Result 4.1 still holds in this context. The table shows that the inclusion of mixed ownership with governments involved does not have an impact on the TOC's decision, as this remains a private party with the same profits, costs and operational objective function as before. For the same concession fee, their optimal decision remains unchanged. Public involvement in the model only has an impact on the PA's optimal decision, which will be earlier and larger. As a result, the α_5's matching both actors' investment timing or size will alter. This result is summarised as follows:

Result 4.3. *Under the assumptions given in Table 4.2, public ownership in a landlord port has no impact on the optimal investment decision of a private TOC. It however alters the optimum of the PA, and hence the final decision made.*

From both Table 4.3 and Table 4.9, it can be verified that, independent of the amount of public money involved, the project will become less attractive for the TOC with a higher

Table 4.9: Optimal $X^*_{T,\mathrm{a}}(K)$, $K^*_\mathrm{a}(X)$ and $(X^{**}_{T,\mathrm{a}}, K^{**}_\mathrm{a})$ under different α_5 in a landlord port with public ownership.

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

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

concession fee. The reason is that they retain a lower share of their profit. Unexpectedly however, it is optimal for the TOC individually to invest in more capacity. This counter-intuitive result is explained by the fact that the TOC reacts by postponing the investment to a moment when the market has grown more, requiring more capacity. At the same time, the investment becomes more attractive for the PA. As a result, the PA wants to invest earlier, although its optimal capacity will then be lower.

The combination of mixed ownership of the PA and a landlord port model leads to two different results compared with the private landlord port setting. First, as was also apparent from Table 4.8, an increased share of public involvement leads to the PA investing earlier and in more capacity, because welfare effects other than profit are considered in the analysis too. Second, the optimum with the same $s_G = s_{CS} = 1/2$ as for the equivalent service port in Table 4.8 lies in some cases further outside the decision interval than in the case of a private port. At $\alpha_5^X(=0.5693)$ for example, $X^{**}_{T,\mathrm{PA}}$ equals $X^{**}_{T,\mathrm{TOC}} = 36.08$ euro per TEU, which is higher than the threshold $X^{**}_T(=35.98)$ in Table 4.8. This is caused by the fact that the PA's optimum is influenced by its public ownership, whereas the TOC's optimal investment decision and optimal throughput level are not altered, as the private TOC does not take social welfare into account. As a private party, it only considers profit in its operational objective function.[13]

In the present scenario, the two described concession strategies remain possible. First, the PA could aggregate the operational objective functions of itself and the TOC and invest

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

at the optimum of a service port. Through the concession agreement, the PA could then urge the TOC to handle at least a certain minimal throughput. Negotiating a favourable (i.e., lower) concession fee could be an adequate incentive for this. Especially for publicly owned PAs, the approach of applying a concession fee that allows for the aggregate investment optimum is relevant. Second, if $\alpha_5 = 0.57252$, the optimal investment decision for the PA would be (35.96, 11.16), and the TOC would be forced to reduce its optimal investment of (36.27, 11.24) to a size of $K_{\text{TOC}} = 11.16$ M TEU p.a. The corresponding $X^*_{T,\text{TOC}}(11.16)$ would then be 35.96 euro per TEU, which equals $X^{**}_{T,\text{PA}}$.

4.5 Investment decision sensitivity to an altered economic situation

In this section, the sensitivity of the results to changes in other parameters is discussed. Table 4.10 shows how the investment decisions of the different actors alter with each parameter change. To this end, the decisions at respectively α_5^X and α_5^K are given for each altered situation, as this information allows understanding the direction of change of the optimal investment decision caused by different concession fees.

With the monetary scale factor of congestion $A = 4$ instead of 5, the equalled investment threshold and installed capacity for the PA and the TOC are lower, confirming Result 3.1. Also, α_5^K and α_5^X are lower than in the base case. With a lower A, congestion poses less of a problem to the port users, so that relatively more throughput is acceptable at the same infrastructure and that less capacity is required. If uncertainty (σ) is higher, the investment is made at a later moment, but the installed capacity will also be higher. Since these conclusions were also drawn in a private service port setting in the previous chapter, the robustness of this chapter's model is guaranteed. Additionally, the increase in uncertainty (σ) leads to another interesting observation. In this case, $\alpha_5^X (= 0.5624)$ is below $\alpha_5^K (= 0.829)$. This inversion of α_5's has an important consequence for the negotiation power of the PA. Below $\alpha_5 = 0.5624$, the port still has negotiation power through timing the project at a higher threshold than what is optimal for the TOC. Above $\alpha_5 = 0.829$, the power of the PA also still lies in providing less capacity than what would be optimal for the TOC. However, between α_5^X and α_5^K, the TOC has a larger incentive to deviate from the PA's optimum. This is because it is optimal to later install less capacity than what has already been provided by the PA. This contains a reasonable incentive for the TOC to deviate by handling less cargo than agreed under the concession agreement. To avoid such a deviation, the PA could select the second investment strategy of urging the TOC to follow the PA's optimal strategy by reducing the TOC's investment decision degrees of freedom.

The sensitivity of the results to changes in the parameters discerning a public landlord port from a private service port are also included in Table 4.10. If the average local benefits

Table 4.10: Changes of the PA and TOC's optimal investment decisions ($X^{**}_{T,\mathrm{a}}$, K^{**}_{a}) at the respective α_5^K's and α_5^X's as a result of different parameter changes in a landlord port with public ownership.

Parameter change	$\boldsymbol{\alpha_5}$	***Actor a***	**Decision ($X^{**}_{T,\mathrm{a}}$, K^{**}_{a})**
Base case	*0.504*	*PA*	(38.54, **11.20**)
		TOC	(32.77, **11.20**)
	0.5693	*PA*	(**36.08**, 11.16)
		TOC	(**36.08**, 11.24)
A= 4	*0.472*	*PA*	(35.09, **10.85**)
		TOC	(28.40, **10.85**)
	0.5643	*PA*	(**32.12**, 10.81)
		TOC	(**32.12**, 10.89)
σ= *0.15*	*0.5624*	*PA*	(**49.88**, 12.74)
		TOC	(**49.88**, 13.02)
	0.829	*PA*	(41.04, **12.81**)
		TOC	(91.83, **12.81**)
λ= *0.5*	*0.491*	*PA*	(38.89, **11.19**)
		TOC	(32.19, **11.19**)
	0.5673	*PA*	(**35.96**, 11.15)
		TOC	(**35.96**, 11.24)
α_1= *0.95*	*0.546*	*PA*	(37.94, **11.19**)
		TOC	(33.41, **11.19**)
	0.594	*PA*	(**36.07**, 11.17)
		TOC	(**36.07**, 11.23)
α_2= *0.9*	*0.521*	*PA*	(37.92, **11.19**)
		TOC	(33.43, **11.19**)
	0.5714	*PA*	(**36.07**, 11.17)
		TOC	(**36.07**, 11.23)
α_3= *0.3*	*0.5124*	*PA*	(40.20, **11.20**)
		TOC	(30.29, **11.20**)
	0.6235	*PA*	(**36.08**, 11.15)
		TOC	(**36.08**, 11.28)
α_4= *0.45*	*0.5448*	*PA*	(37.13, **11.19**)
		TOC	(34.45, **11.19**)
	0.57434	*PA*	(**36.08**, 11.18)
		TOC	(**36.08**, 11.21)

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

per TEU were higher ($\lambda = 0.5$), the social welfare generated by the project would be higher too, making the project itself more attractive for the PA. As a result, the investment would be made slightly earlier, but it would also be smaller. Moreover, lower α_5's are required for the port to equal the size or timing of both actors' investment decision. As was already explained, local benefits and consumer surplus are not included in the private TOC's operational objective function (π_{TOC}) and hence do not influence the TOC's optimal investment decision. This is opposed to the PA, whose project's attractiveness is now higher. Hence, the PA requires less income from the concession since already more welfare has been generated. The last four blocks of Table 4.10 show the impact of the PA receiving less of the total port revenue or incurring a higher share of the port costs (represented respectively by an increase in α_1 and a decrease in α_2, α_3 or α_4). Qualitatively, the decision intervals remain similar. Additionally, almost identical optima as in the base case can be achieved, although through a higher value for α_5. In each of the altered cases, the PA has a lower share of total port profit. Hence, the PA requires a higher concession fee, expressed as a share of the TOC's profit, to obtain the same level of welfare as in the base case.

4.6 Conclusion of this chapter

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

The results show that the PA and TOC's different objectives in a landlord port lead to a decision interval constituted by the different optimal investment strategies for both actors. From this interval, a common investment decision is to be made. Through the concession agreement, the PA could persuade the TOC to follow the strategy that is optimal for a service port in order to maximise the aggregate project value minus investment costs $V - I$. The concession fee can then be used as a redistribution mechanism of this $V - I$. Another possible strategy for the PA is to urge the TOC to invest in the PA's optimal strategy. This can be achieved by setting a concession fee that limits one of the two investment decision degrees of freedom of the TOC. The remaining investment decision variable is then conditionally optimised and could equal the optimal value of the PA. This discussion shows that although the PA would like to maximise and the TOC would like to minimise the concession fee to maximise their respective income, the optimal fee should also be considered from an investment analysis perspective. In this process, the negotiation power of the two actors has an impact on the optimal fee as well. In future research, it would be interesting to further elaborate the non-cooperative game approach with the PA acting as a Stackelberg leader, who moreover has all the power to set the concession fee.

The results also bear worthy capacity investment policy lessons to be learnt. Since the benefits of port capacity are not only for current and future port users, but also for the economy of an entire region, the involvement of public money has a positive impact. First of all, more PA shares held by the government leads to larger and earlier investments in port capacity. More benefits and positive externalities are generated for the entire economy. This finding is opposite to the common RO finding, where more capacity leads to a later investment or vice versa. Another advantage of involving a public owner in the PA is that the concession fee can be set to trigger investment at the aggregated optimum. In such a case, the concession fee instrument will not be used to maximise PA profits, but can rather enable an equitable distribution of income and costs in the port. Of course, the PA should at the same time avoid incentives for the TOC to deviate from the concession agreement. Interesting to observe in light of reaching the aggregate optimum is that the optimum of a service port is not always reachable by a landlord port when the PA is (partly) publicly owned and the TOC privately. The TOC sets the optimal throughput without taking social welfare into account. This leads to a higher deviation from the aggregate optimal throughput and hence the investment strategy in a service port made by a single port actor, partly or fully owned publicly. As a result, the concession agreement is an important instrument to align the objectives of the TOC, the PA and the government. Finally, the model allows confirming two conclusions from the previous chapter. Both an increase in congestion costs and uncertainty lead to a new port investing in more capacity, but at a later moment in time.

The analyses made in this chapter and the previous chapter consider the port as a monopolist. In reality however, many ports do not operate as monopolists. They experience competition from nearby ports. The port that is part of the chain with the lowest generalised cost has the highest probability to attract and handle the cargo. In the Hamburg - Le Havre range for example, Antwerp and Rotterdam are fierce competitors in their attempts to attract important loops of global shipping lines. In such cases, the capacity investment decision of a neighbouring port influences the own decision. Both ports try to invest before the other, to offer free capacity that reduces waiting time in the own port. This is crucial to attract the shipping lines and their cargo for the overlapping hinterland, as these shipping lines are averse to waiting. As this competition was left out of the scope of this chapter, it forms the starting point of the next chapter. In that chapter, the capacity investment decisions of two competing service ports are considered, instead of the decision of one monopoly port. As was shown in this chapter, the PA and TOC can decide to invest in the aggregate optimum. By readopting the service port model in the next chapter, the focus will be on the impact of competition on the aggregate optimal port investment decision. Also the isolated functions of the PA could be used to focus on the PA's individual optimum, which could subsequently be imposed on the TOC. Moreover, both port authorities will be assumed to have the same ownership structure, which can be private, public or a combination of both, in line with those of this chapter.

Chapter 5

The capacity investment decisions of two competing ports

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

In order to avoid congestion, ports can charge a higher price, leading to a demand reduction (Xiao et al., 2013), or accommodate the demand by investing in more throughput capacity (Meersman & Van de Voorde, 2014a; Xiao et al., 2012). Y.-T. Chang et al. (2012) used an economic approach to balance all elements of capacity in a port, given the objectives of the port owners, explicitly taking waiting time costs into account. An important consideration is that a congestion-reducing capacity investment in one congested port increases its own demand, and that it reduces the demand in the other congested port, if the level of congestion in the investing port will become relatively lower than the level of congestion in the other port (Wan et al., 2013). When there is more competition, excess (free) capacity is required more. In this light, the port's investment decision also depends on the decision of the competitor which serves (a part of) the same hinterland. In this way, competition has an impact on the capacity investment decision of ports and vice versa (Huisman & Kort, 2015; Xiao et al., 2012; Haralambides, 2002). Therefore, the port needs to endogenise the other port's investment decision to avoid investing in capacity that is not used due to the other port's capacity serving part of the demand (Huberts et al., 2015).

The capacity decision is even more complicated by the fact that the demand faced by the port is very uncertain (Vilko & Hallikas, 2012; Huisman & Kort, 2015). Many different sources of this uncertainty have been identified in Chapter 2, including not only the impact of the financial crisis on global trade and the uncertain decisions of many actors in the logistics chain, but also technological, environmental and regulatory changes. To correctly account for the value of different sorts of managerial flexibility in capacity investment decisions under uncertainty in a competitive environment, real options models have been identified (Dixit & Pindyck, 1994; Bar-Ilan & Strange, 1996; Dangl, 1999; Aguerrevere, 2003; Hagspiel et al., 2016), in combination with game-theoretic modelling (Azevedo & Paxson, 2014). The options considered in this chapter are a one-shot investment in a new port with flexible size and timing and a flexible throughput level. The present chapter extends the previous models and the real options literature in general by determining the investment timing and capacity choice in a continuous-time framework that simultaneously deals with competition and volume flexibility.

The objective of this chapter is to analyse how the capacity investment in two new ports is influenced by inter-port competition under congestion and demand uncertainty. To this end, the following research sub-question is put forward: (RQ 5.1) What impact does inter-port competition have on the investment decision of both the leader's and the follower's new port under uncertainty? In order to accurately analyse the capacity investment decisions of the competing ports, a game-theoretic RO model including congestion and uncertainty is developed in this chapter. This model extends the state-of-the-art in the field of industrial organisation with a port-specific application, wherein congestion plays an important role (De Borger & Van Dender, 2006; De Borger et al., 2008).

As opposed to the majority of the port competition literature, the timing decision is included, which allows for heterogeneous ports in a game where the ports do not necessarily invest at the same time. In this way, the model accounts for entry deterrence and preemption as additional strategies to the often solely considered accommodation strategy. Luo et al. (2012) modelled the preemptive prices by the dominant port, but did not consider uncertainty and congestion.[1] In order to study a port context, the real options model of Huisman & Kort (2015) is extended in three ways, to account for the cost of port congestion, differentiated services offered by different ports (Bichou & Gray, 2005) and mixed ownership by both private and public actors (Xiao et al., 2012).

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

As a result of this chapter's methodological additions, it is possible to account for the frequently observed phenomenon that port investments in two competing ports do not necessarily take place at the same time, notwithstanding that simultaneous investment is also possible. However, some simplification with respect to the previous chapter's model is needed too, in order to guarantee the mathematical tractability of this model and without losing general applicability. The previous chapter indicated that the concession fee is a viable port authority (PA) instrument to steer the capacity investment of the terminal operating company (TOC) to the desired direction. The PA could force its own optimum, or the optimum from an aggregated viewpoint could be obtained through mutual compromises. Hence, to study the impact of competition between neighbouring ports on the capacity investment decision of both ports, it could be possible to resort to the individual PA's objective functions or the aggregated objective functions. Since the previous chapter showed that the differences in discounted cash flows and investment decisions are negligible between the individual PA's optimum or the aggregate optimum, it is assumed in this chapter that the aggregate optimal strategy is followed. Hence, the considered ports are modelled as public service ports. This argument especially holds in the case of a publicly owned port or if there is only one actor operating the port. Hence, the model from Chapter 3 forms the starting point here. The extension with public and private ownership from Chapter 4 is however retained.

This chapter is structured as follows. The next section describes the basic model for the two-port setting and each port's investment decision making objectives. Subsequently in Section 5.2, this chapter's specific methodology and analysis are described. Since no closed-form solutions can be derived here either, the numerical results with respect to the impact of competition combined with different government ownership structures are discussed in Section 5.3. Sensitivity analysis in Section 5.4 identifies the impact of other factors on the investment decision in a competitive setting. The final section presents this chapter's conclusion.

5.1 Economic setting and methodology

In this chapter, two private or public service ports that compete to handle a flexible amount of throughput, but offer differentiated services, are considered. The next subsection deals with the individual situation in, and the relevant information for each port. This is followed by a discussion of the type of competition between both ports and the related game-theoretic modelling.

5.1.1 Individual port situations

The fact that ports offer differentiated services is mainly the result of the different geographic locations of the ports, implying different distances to the hinterland. Moreover, each port being organised differently adds to this service differentiation. Also their service levels as expressed by their occupancy rates, with an impact on their prices, may differ (De Borger & Van Dender, 2006). The product market's heterogeneity is expressed through the differentiation parameter δ in the inverse demand function of the previous chapters, giving rise to the gross willingness to pay, ρ_i, for port i at time t (Vives, 1999; Xiao et al., 2012):

$$\rho_i(t) = X(t) - Bq_i(t) - \delta Bq_j(t), \tag{5.1}$$

with X being the demand shift parameter, q_i the throughput of port i and q_j the throughput of port j $(j \neq i)$. A similar function holds for port j, with subscripts i and j interchanged.[2]

Depending on the location and services of both ports, parameter δ can vary between zero and one. In the case of a port not experiencing competition from another port, e.g., with two distinct hinterlands, δ would equal 0 and the model would simplify to a monopoly model. For two identical, hypothetical ports at the same location and offering exactly the same services, δ would equal 1. In this way, δ also reflects the difference in hinterland and port access (tugging and piloting) costs. Initially, δ is set to 0.6 to take the different characteristics of two competing ports in a close range into account (e.g., Antwerp and Rotterdam in the Hamburg - Le Havre range). This value is altered in the sensitivity analysis to 0.9, to account for ports situated back to back but offering slightly different services, (e.g., Los Angeles (LA) and Long Beach in California, Seattle and Tacoma in Washington, Vancouver and Prince Rupert in British Columbia, or Gdynia and Gdansk in Poland), and to 0.3 to account for two ports that are situated further from each other, possibly at different coast lines and with only partly overlapping hinterlands (e.g., LA/Long Beach and New York/New Jersey in America, or Hamburg - Le Havre and Trieste/Koper in Europe (De Langen, 2007)).

In order to model the uncertain demand evolution, the intercept of the inverse demand function, X, again follows a GBM with an independent parameter for the drift (economic growth, μ) and the variability (uncertainty, σ): see Equation (2.4). Additionally, the slope of the demand function (B) is again normalised and set to 1. For the sake of readability, denoting the functional dependence on time will be omitted in the remainder of this chapter. Since the gross willingness to pay involves not only the price paid in port i, p_i, but also a cost incurred because of congestion and resulting waiting times at high occupancy rates (Zhang & Zhang, 2006; Xiao et al., 2012), according to the discussion in Chapter 3, price p_i can be written as

$$p_i = X - Bq_i - \delta Bq_j - AX\frac{q_i}{K_i^2}, \tag{5.2}$$

[2]As a result of port services being differentiated products leading to different prices in different ports, a single market demand function cannot be used.

with the latter term the congestion unit cost term and K_i the theoretical design capacity of port i. Total congestion cost for port i then equals $AX(q_i/K_i)^2$.

An important difference from the economic models of Chapters 3 and 4 is that in this chapter, the design capacity K_i is not a hard constraint for the maximum throughput. This adaptation is necessary to avoid unnecessary mathematical complexity.[3] Realism is not to be lost if A, the monetary scale factor in the congestion cost, is sufficiently high. In that case, the price would become too low to profitably operate if $q_i > K_i$. This will be avoided as much as possible, but in some emergency cases, the port has no other choice than to handle the additional cargo. If one of the main customers wants the port to handle more than its capacity, the port needs to find solutions such as temporarily stocking containers on the quay. These organisational complexities imply high extra costs, but losing the customer is even a lot worse. To have a realistic setting, $A = 5$ is retained from the previous chapters. This results in a congestion cost size that discourages full occupancy in most situations, but that does not prevent it de facto and that allows in some exceptional cases for exceeding design capacity, at a high cost. Since in most cases, ports like to avoid these high costs and because a nearby port with free capacity offers an alternative, such high levels of occupancy are hardly encountered in reality as well as in the numerical simulations of the described ports in this chapter.

Since not only situations with two private ports are considered, but also with two public ports, it is not sufficient to only consider annual profit maximisation,[4] which is the objective of a private port. Governments also consider positive externalities or local spillover benefits per unit of throughput handled (e.g., employment and local industry growth), and consumer surplus in their social welfare (SW_i) maximisation (Xiao et al., 2012; Jiang et al., 2017). In this chapter, social welfare generated by port i is calculated as the sum of the profit of port i, the spillover benefits $\lambda \cdot q_i$ and a share s_{CS} of consumer surplus generated by port i (CS_i), since some governments only consider the part that is relevant for the region they govern.[5] To account for the fact that the two ports are owned by a different, independent

[3]The impact of this change on the results in a monopoly setting is negligible, as is proven in Chapter 6. The disadvantage of the constraint $q_i \leqslant K_i$ in a two-port setting is that more regions for q_i^{opt} arise (e.g., one of the two ports at full capacity, both at full capacity, etc.) and that the relative order of these regions is endogenous and capacity dependent. It could be added to the model, but only complexity would increase and tractability would be reduced.

[4]$\pi_i = (p_i - c) \cdot q_i - c_h K_i$, with c the marginal operational cost and c_h the capacity holding cost

[5]The Antwerp city council, shareholder of the Port of Antwerp's port authority, might only be interested in local spillover benefits next to port profit, which in turn differs from the objectives of Rotterdam's council. Similarly, the Canadian government, shareholder of the Port of Vancouver, might or might not consider the CS of Chinese shipping lines, having an influence on parameter s_{CS}. To compare with a full social planner in each country, state or city, instances with s_{CS} set to 1 are included as well. In Section 5.4, the case where one government owns shares of both ports, giving rise to a different CS_i calculation, is considered as well.

government, consumer surplus in port i is calculated as follows (Xiao et al., 2012):

$$\begin{aligned} CS_i(q_i, q_j) = CS_i(q_i) &= \int_0^{q_i} \rho_i(y, q_j)\mathrm{d}y - \rho_i(q_i, q_j)q_i \\ &= \int_0^{q_i} (X - By - \delta B q_j)\mathrm{d}y - (X - Bq_i - \delta B q_j)q_i \\ &= \frac{Bq_i^2}{2}. \end{aligned} \tag{5.3}$$

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

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

$$\Pi_i(X, K_i, q_i, q_j) = \pi_i(X, K_i, q_i, q_j) + s_G \cdot \lambda q_i + s_G s_{CS} \cdot Bq_i^2/2. \tag{5.4}$$

In this chapter, s_G is varied between 0 and 1 in the numerical simulations. Hence, the same range of ownership structures as in Chapter 4 is considered, but in every case the two governments own the same share of their respective ports, and attach the same weight to consumer surplus. Nonetheless, as higher s_G and s_{CS} lead to social welfare being taken more into account by the ports, two public ports fully considering consumer surplus will generate the highest social welfare.

In this chapter, the analysis is not restricted just to ports that are homogeneous in costs, as is often done in game-theoretic approaches. Here, the ports may differ in costs. The investment cost of the project, I_i, and more specifically the fixed investment cost $FC_{I,i}$ is chosen to reflect the cost difference of a similar project. This is illustrated by the example of Antwerp and Rotterdam. In Antwerp, the Deurganckdok has been dug, whereas the Maasvlakte 2 in Rotterdam has been constructed in open water through rainbowing sand, resulting in an $FC_{I,2}$ that is 20 million euro higher for this second project (Rotterdam) than the $FC_{I,1}$ of the project in Antwerp. The existence of the cost difference is assumed to be known, as both ports can ex-ante observe the type of construction technology used. This situation gives rise to a Stackelberg leader-follower game, with the possibility of simultaneous investment under entry accommodation (Huisman & Kort, 2015). According to Musso et al. (2006), the Stackelberg oligopoly structure with leaders and followers is a good framework to analyse port investments in a competitive environment. It is however impossible for the port with a cost disadvantage to become the leader. It will be the follower, unless it chooses to invest simultaneously (Pawlina & Kort, 2006).[6] Hence in this chapter, the in-

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

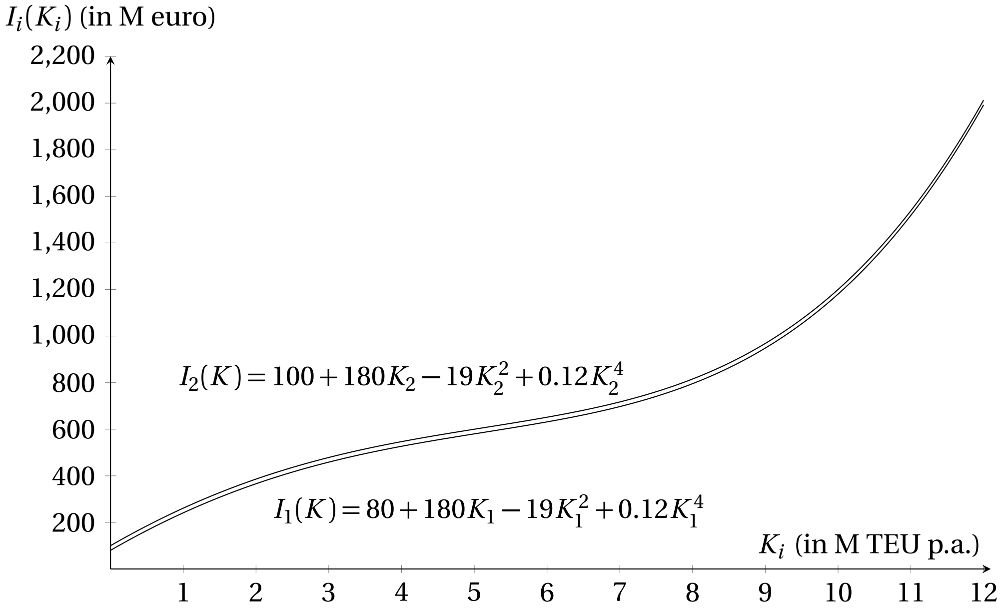


Figure 5.1: Total investment cost functions for the two projects.

vestment timings of both ports are endogenous, allowing for simultaneous investment as well.

The investment cost functions of one single capacity project of respectively the port with a cost advantage (project 1) and with a cost disadvantage (project 2) are graphed in Figure 5.1. These functions are similar fourth-order polynomials as in Chapter 3, with the same parameters except for the two different intercepts $FC_{I,i}$ to express cost differences between the two ports. In Table 5.1, the full economic model is summarised. The parameters derived in Chapters 3-4 are retained here. The assumptions of this RO competitive game model are recapitulated in Table 5.2.

5.1.2 Game-theoretic modelling of competition

As opposed to the majority of the literature, the analysis in this chapter is not limited to both ports investing simultaneously. When the leader invests in sufficient capacity at the moment the market is not large enough to accommodate two ports, the leader is deterring the entry of the follower to a later moment. In this way, a four-stage game is discerned in the case of entry deterrence (Huberts et al., 2015). In the first stage, the leader installs capacity K^{L} as soon as its relevant investment threshold X_T^{L} is reached for the first time from below at time T^{L}; see Figure 5.2.[7] In the second stage, immediately after the first stage, the

[7]In line with the terminology of Huberts et al. (2015), the first port to enter the market, i.e., the leader, becomes the incumbent after investment. If this initial investment is sufficiently large, it will be entry deterring, to delay the follower's investment. If the leader's initial investment is relatively small, it will be entry accommodating to allow simultaneous follower investment. This is described later in a three-stage game.

Table 5.1: Overview of Chapter 5's model and the selected parameters.

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

Table 5.2: Overview of Chapter 5's model assumptions.

	Assumption(s)
Project type?	Two new ports
Capacity constraint?	Soft constraint
Port type?	Public and/or private service ports*
Port competition?	Duopoly: Stackelberg (investment) and Cournot quantity (operations) competition
Time to build?	Not considered
Phased investment?	Project installed at once: available after completion
Specific assumptions	Each port is owned by a different, independent government
	Each government has the same objectives and ownership structures of both ports are equal
	Ports differ in location and service quality, as well as in fixed investment costs
	Fixed investment cost difference between ports due to different construction technology: known by both ports
	Cost-advantaged port will be the investment leader. Follower invests simultaneously or later
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 ports: delays start at about 50% and increase sharply beyond 75-80% occupancy
	User congestion costs depend on dock users' average value of time, which evolve with the market (i.e., increasing)
	Investment costs: fourth-order polynomial with economies of scale and size boundary
	Deterministic, linear operational and capacity holding costs
	Flexibility of investment timings and sizes → Options to postpone the investment
	Once-and-for-all investment decisions with flexible throughput levels
	Infinite project life times (maintenance executed)

*: 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 TOC).
Focus on lumpy investment in port infrastructure and irreversible elements of superstructure.

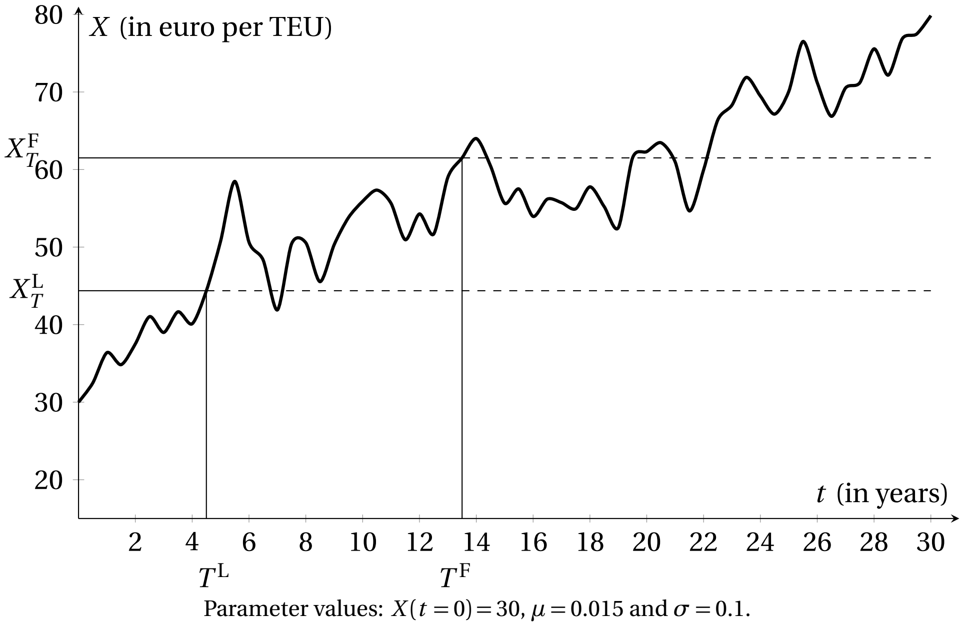


Figure 5.2: Sample evolution of demand shift parameter X, following a GBM over time, showing the relationship between the optimal investment timing (T^L and T^F) and the threshold for X (X_T^L and X_T^F) of the leader and the follower port.

incumbent starts to operate under a temporary monopoly at its optimal throughput level, $q(X, K^L, 0)$. This throughput level is flexible, and depends on the instantaneous value of X. In the third stage, when the market has grown sufficiently until X_T^F is reached at time T^F, the follower will invest in K^F. This size is not only dependent on the timing of the follower's investment, but also conditional on the investment size of the leader. Once the follower invests, the incumbent loses its monopoly. Both ports will now operate at their optimal throughput level, given the level of the other port, their capacity investment size and the current value for the demand shift parameter X. In this light, both ports compete in quantities, leading to a Cournot equilibrium.

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

> "The general idea which emerges from the theoretical analysis is that when transport capacities are high, or can be enlarged through the transfer of capacity from other locations, and the services provided are not differentiated, then

> competition is likely to be of a Bertrand type, based on price. [...] If, on the other hand, capacity is difficult to increase, then competition is likely to be of a Cournot type, based on quantities. This is the case found, for example, in rail, maritime or inland waterway transport."

The main reason why port capacity is difficult to change (relative to the ease and speed with which prices can be adjusted) is that port capacity investment is lumpy, time-consuming and irreversible, which is consistent with the set-up described above. Moreover, it involves high investment costs, including high fixed costs of designing, scheduling and implementing investments.[8] Indeed, with capacity constraints, Van Reeven (2010) assumes quantity competition between TOCs, based on Kreps & Scheinkman's (1983) argument of capacity-constrained price competition yielding quantity competition. Furthermore, the market “conduct parameters" with respect to port charges of the three largest, competing Australian seaports were empirically estimated by Menezes et al. (2007). The calculation based on their results indicates that at the 10% level of statistical significance, the hypothesis of price competition among the ports is rejected.[9] As a result of Cournot competition, Wan & Zhang (2013) find that investment increases the own port's profit, which is not necessarily true under Bertrand competition (De Borger et al., 2008). Additionally, the use of quantity as a decision variable has been observed for firms in the production of goods as well as for firms in the production of services (e.g., competition among airlines or airports; see Zhang & Czerny (2012) for a recent survey of the literature). A final advantage of using quantity competition is that it is found to increase competition between ports, whereas price competition leads to collusion (Musso et al., 2006). The latter would be a less realistic framework to describe the competing ports.

As a final remark to the described game, note that it is slightly, but not substantially, different in case the leader invests when the market is large enough to accommodate two ports. This would lead to a three-stage game, as stage 2 is omitted. In this situation, leader investment (stage 1) is immediately followed by the follower's investment (stage 3). Right after this investment, both ports again set their optimal throughput levels under Cournot competition in stage 4. The structure of the game is summarised in Figure 5.3.

5.2 Optimal investment strategies

With two heterogeneous competing ports making a decision to invest in new capacity, of which the size and the timing are not ex-ante defined, the optimisation problem is solved

[8]Here, abstraction is made of the fact that ports can increase capacity to a limited extent in the short term, e.g., by increasing productivity or extending working hours. Such an approach is plausible when studying the investment of market entrants.

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

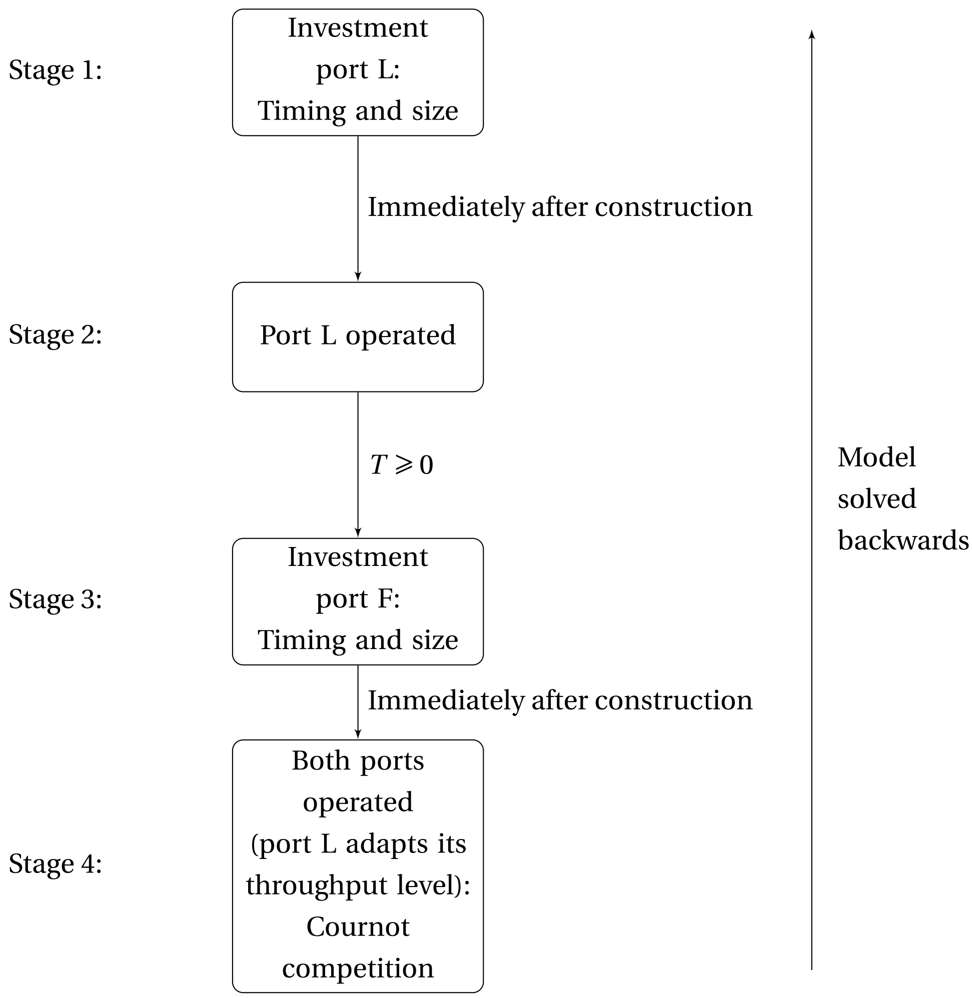


Figure 5.3: Summary of the competitive RO Stackelberg investment game methodology.

backwards using dynamic programming. First, the decision of the follower is optimised, taking the decision of the leader as given. Subsequently, the optimal entry-deterring or entry-accommodating decision of the leader is explicated, taking the information about the resulting follower's optimal decision into account as expressed by its reaction function.

5.2.1 A port's throughput decision

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

$$q_i^{opt}(X, K_i, q_j) = \max\left\{0, \frac{X + s_G\lambda - c - \delta B q_j}{2\frac{AX}{K_i^2} + (2 - s_G s_{CS})B}\right\}. \tag{5.5}$$

By substituting the expression for $q_j^{opt}(X, K_j, q_i)$ into $q_i^{opt}(X, K_i, q_j)$, q_i^{opt} can be expressed in terms of X, K_i and K_j. The advantage of such an expression is that this value is dependent only on X once both investments are made, as opposed to also being dependent on the continuously changing q_j. This leads to

$$q_i^{opt}(X, K_i, K_j) = \begin{cases} 0, & X < c - s_G\lambda, \\ \dfrac{(X + s_G\lambda - c)\left(2\frac{AX}{K_j^2} + (2 - s_G s_{CS} - \delta)B\right)}{\left(2\frac{AX}{K_i^2} + (2 - s_G s_{CS})B\right)\left(2\frac{AX}{K_j^2} + (2 - s_G s_{CS})B\right) - \delta^2 B^2}, & X \geqslant c - s_G\lambda. \end{cases} \tag{5.6}$$

Through the boundary value ensuring $q_i^{opt} \geqslant 0$ in Equation (5.6), two regions for X are identified for both ports: $R_1 = [0, c - s_G\lambda)$ where throughput is zero and $R_2 = [c - s_G\lambda, \infty)$ where throughput equals the optimal throughput. In this R_2, throughput could exceed capacity, but only at a substantial congestion cost. Hence, as opposed to Yang & Zhang (2012), not just the interior solutions are considered; rather also corner solutions are considered.

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

5.2.2 The follower's investment decision

To determine the follower's optimal investment decision, the approach of Chapter 3 can be followed, thereby taking the capacity installed by the leader additionally into account.

$\overline{\Pi}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)$ at the time port i invests after port j's investment in K^{L}_j, forms the input to calculate the value of the investment project for port i, $V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)$, for which it pays $I_i(K^{\mathrm{F}}_i)$ when it invests at threshold $X^{\mathrm{F}}_{T,i}$ at time T^{F} in capacity K^{F}_i,[10] given that the other port has invested in K^{L}_j. The differential equation for $V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)$ in a two-port setting is found by applying Itô's Lemma and Bellman Equation to

$$V^{\mathrm{F}}_i = \mathbf{E}\int_0^\infty \max_{q_i}\{\Pi_i(T^{\mathrm{F}}+\tau)\}\mathrm{e}^{-r\tau}\mathrm{d}\tau = \mathbf{E}\int_0^\infty \overline{\Pi}_i(T^{\mathrm{F}}+\tau)\mathrm{e}^{-r\tau}\mathrm{d}\tau. \tag{5.7}$$

This results in

$$\begin{aligned}\frac{\sigma^2}{2}(X^{\mathrm{F}}_{T,i})^2\frac{\partial^2 V^{\mathrm{F}}_i}{\partial (X^{\mathrm{F}}_{T,i})^2}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) + \mu X^{\mathrm{F}}_{T,i}\frac{\partial V^{\mathrm{F}}_i}{\partial X^{\mathrm{F}}_{T,i}}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)&\\ -rV^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) + \overline{\Pi}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) = 0,&\end{aligned} \tag{5.8}$$

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

The solution for each region R_k is given by

$$\begin{aligned} V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)|_{X^{\mathrm{F}}_{T,i}\in R_k} &= V^{\mathrm{F}}_{i,k}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)\\ &= G^{\mathrm{F}}_{i,(k,1)}(K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)\cdot(X^{\mathrm{F}}_{T,i})^{\beta_1} + G^{\mathrm{F}}_{i,(k,2)}(K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)\cdot(X^{\mathrm{F}}_{T,i})^{\beta_2}\\ &\quad + \overline{V}^{\mathrm{F}}_{i,k}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j), \end{aligned} \tag{5.9}$$

with $\overline{V}^{\mathrm{F}}_{i,k}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)$ the particular solution of differential equation (5.8) and $\overline{\Pi}_i = \overline{\Pi}_{i,k}$ in each region R_k. The roots β_1 and β_2 are given by Equation (3.22), whereas the boundary conditions are given by

$$\begin{cases} V^{\mathrm{F}}_i(0, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) = \mathbf{E}\int_0^\infty -c_h K^{\mathrm{F}}_i \mathrm{e}^{-rt}\mathrm{d}t = \dfrac{-c_h K^{\mathrm{F}}_i}{r}\\ \lim\limits_{X^{\mathrm{F}}_{T,i}\to+\infty}\left(V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) - \overline{V}^{\mathrm{F}}_{i,2}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)\right) = 0\\ \lim\limits_{X^{\mathrm{F}}_{T,i}\overset{<}{\to} c-s_G\lambda} V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) = \lim\limits_{X^{\mathrm{F}}_{T,i}\overset{>}{\to} c-s_G\lambda} V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j)\\ \lim\limits_{X^{\mathrm{F}}_{T,i}\overset{<}{\to} c-s_G\lambda} \frac{\partial V^{\mathrm{F}}_i}{\partial X^{\mathrm{F}}_{T,i}}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) = \lim\limits_{X^{\mathrm{F}}_{T,i}\overset{>}{\to} c-s_G\lambda} \frac{\partial V^{\mathrm{F}}_i}{\partial X^{\mathrm{F}}_{T,i}}(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j). \end{cases} \tag{5.10}$$

The follower's investment problem objective function

$$\max_{T^{\mathrm{F}}_i\geqslant 0, K^{\mathrm{F}}_i\geqslant 0}\mathbf{E}\left\{\left[V^{\mathrm{F}}_i(X^{\mathrm{F}}_{T,i}, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) - I_i(K^{\mathrm{F}}_i)\right]\mathrm{e}^{-rT^{\mathrm{F}}_i}|X(t=0)=X\right\}, \tag{5.11}$$

gives rise to the following option value

$$F^{\mathrm{F}}_i(X, K^{\mathrm{L}}_j) = \max\left\{\mathrm{e}^{-r\mathrm{d}t}\,\mathbf{E}(F^{\mathrm{F}}_i(X)) + \mathrm{d}F^{\mathrm{F}}_i(X)), \max_{K^{\mathrm{F}}_i}\left[V^{\mathrm{F}}_i(X, K^{\mathrm{F}}_i, K^{\mathrm{L}}_j) - I_i(K^{\mathrm{F}}_i)\right]\right\}, \tag{5.12}$$

[10]Note that in contrast to the other chapters, the threshold notation is used here to clearly diversify between the different thresholds considered in this chapter.

which is to be maximised. This allows determining the optimal timing and size of the follower port's capacity investment decision, given the size of the leader's investment. This analysis is relevant for deciding on new port projects near existing ports. If the Italian government for instance wants to install a new port close to the French border and the port of Marseille, e.g., near Ventimiglia, this approach can be used. The inner maximisation of Equation (5.12) considers the project's net present value, $V_i^{\mathrm{F}}(X_{T,i}^{\mathrm{F}}, K_i^{\mathrm{F}}, K_j^{\mathrm{L}})$ minus $I_i(K_i^{\mathrm{F}})$, in order to determine the optimal capacity of the follower ($K_i^{*,\mathrm{F}}$) in terms of its timing threshold ($X_{T,i}^{\mathrm{F}}$) and the capacity already installed by the other port (K_j^{L}). This optimal capacity needs to satisfy

$$\frac{\partial V_i^{\mathrm{F}}}{\partial K_i^{\mathrm{F}}}(X_{T,i}^{\mathrm{F}}, K_i^{*,\mathrm{F}}, K_j^{\mathrm{L}}) = \frac{\partial I_i}{\partial K_i^{\mathrm{F}}}(K_i^{*,\mathrm{F}}), \tag{5.13}$$

stating that capacity is added up to the point where the marginal added value of extra capacity equals the marginal cost of extra capacity. Using the relevant boundary conditions from Section 3.4, including the smooth pasting and value matching conditions, on the outer maximisation of Equation (5.12), the follower's optimal timing threshold ($X_{T,i}^{*,\mathrm{F}}$) can be determined in terms of its own installed capacity (K_i^{F}) and the capacity already installed by the other port (K_j^{L}) (Dangl, 1999; Huisman & Kort, 2015; Hagspiel et al., 2016).

Solving the system

$$\begin{cases} X_{T,i}^{**,\mathrm{F}}(K_j^{\mathrm{L}}) = X_{T,i}^{*,\mathrm{F}}(K_i^{**,\mathrm{F}}(K_j^{\mathrm{L}}), K_j^{\mathrm{L}}), \\ K_i^{**,\mathrm{F}}(K_j^{\mathrm{L}}) = K_i^{*,\mathrm{F}}(X_{T,i}^{**,\mathrm{F}}(K_j^{\mathrm{L}}), K_j^{\mathrm{L}}), \end{cases} \tag{5.14}$$

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

5.2.3 The leader's investment decision

The leader port with the cost advantage needs to decide on its own optimal timing and capacity, taking the calculated reaction function of the follower into account. There are three investment alternatives for the leader. First, if the market is initially large enough, the leader could invest in an entry-accommodating capacity, which is low enough so that the follower can profitably invest at the same time and serve a part of the market as well (Huisman & Kort, 2015). If the market is initially smaller and the leader has a large cost advantage, it is also possible to invest in a capacity that is higher, so that the entire market is served at the moment of investment, the unrestricted entry deterrence threshold. In this case, entry of the follower is deterred to a later moment, when the market will have grown and it will have become also for this port profitable to invest. If the cost differences are rather small however, both ports could strive to be the first to invest. The leader's investment then occurs at the preemption point of the port with the cost disadvantage, where the latter's follower value, $V_2^{\mathrm{F}} - I_2$, equals its leader value $V_2^{\mathrm{L}} - I_2$. This is called the preemption equilibrium. All of these strategies are calculated and discussed in greater detail in the following subsections.

Entry deterrence

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

$$V_{i,2}^{\mathrm{L_{det}}}(X_{T,i}^{\mathrm{L}}, K_i^{\mathrm{L}}) = V_{i,2}^{\mathrm{M}}(X_{T,i}^{\mathrm{L}}, K_i^{\mathrm{L}}) - \left(\frac{X_{T,i}^{\mathrm{L}}}{X_{T,j}^{**,\mathrm{F}}(K_i^{\mathrm{L}})}\right)^{\beta_1} \times \left(V_{i,2}^{\mathrm{M}}(X_{T,j}^{**,\mathrm{F}}(K_i^{\mathrm{L}}), K_i^{\mathrm{L}}) - V_{i,2}^{\mathrm{F}}(X_{T,j}^{**,\mathrm{F}}(K_i^{\mathrm{L}}), K_i^{\mathrm{L}}, K_j^{**,\mathrm{F}}(K_i^{\mathrm{L}}))\right), \quad (5.15)$$

for $X_{T,i}^{\mathrm{L}} \in R_2$. As demonstrated by Huisman & Kort (2015), the monopoly value $V^{\mathrm{M}}(X_{T,i}^{\mathrm{L}}, K_i^{\mathrm{L}})$ is corrected for the reduced profit stream once the follower invests. This follower investment will always take place in region R_2 as well, since this is the only region wherein it is optimal for the follower to invest. Equation (5.15) indicates that the leader has an incentive to increase its investment size, as it further delays the follower's moment of entry. In that way, the leader can take advantage, because it earns the higher monopoly profit for a longer time. The monopoly value $V_{i,2}^{\mathrm{M}}(X_{T,i}^{\mathrm{L}}, K_i^{\mathrm{L}})$ in region R_2 can be calculated like in Chapter 3, with the exception that here only two regions are retained and that the boundary conditions need to be adopted accordingly, such that $G_{2,1}$ is set to zero.

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

$$\left(\frac{X_{T,i}^{\mathrm{L}}}{X_{T,j}^{**,\mathrm{F}}(K_i^{\mathrm{L}})}\right)^{\beta_1} \quad (5.16)$$

is used here. This factor accounts for the time until the follower port's investment threshold is expected to be reached from the current market state. However, the discounted future

[11] Alternatively, the correction term could be written as $+\left(\frac{X_{T,i}^{\mathrm{L}}}{X_{T,j}^{**,\mathrm{F}}(K_i^{\mathrm{L}})}\right)^{\beta_1} \times \left(V_{i,2}^{\mathrm{F}}(X_{T,j}^{**,\mathrm{F}}(K_i^{\mathrm{L}}), K_i^{\mathrm{L}}, K_j^{**,\mathrm{F}}(K_i^{\mathrm{L}})) - V_{i,2}^{\mathrm{M}}(X_{T,j}^{**,\mathrm{F}}(K_i^{\mathrm{L}}), K_i^{\mathrm{L}})\right)$, as $V_{i,2}^{\mathrm{F}}$ replaces $V_{i,2}^{\mathrm{M}}$ for the leader after the follower's investment.

reductions of the profit flows are more complicated to explicate than in the case of Huisman & Kort (2015), because of output flexibility and the two resulting regions for $\overline{\Pi}_i$. In that light, the correction can be considered as a reduction of the residual value of the project after the follower's investment. As a result, it is calculated as the difference in value V for the leader between being the sole active port and the duopoly situation at the moment the follower invests. The value at the moment that both ports have invested is calculated using Equation (5.9) with port i being the leader and port j the follower. The solution takes into account that the follower invests in its own optimal size based on the capacity installed by the leader.[12]

It should be noted that each V in Equation (5.15) contains a term of the form $G^{\mathrm{S}}_{i,(k,l)}X^{\beta_l}$, with S the role (L or F) of port i, k the region and $l \in \{1,2\}$ to account for the possibility of X crossing the boundary between R_1 and R_2. The value matching and smooth pasting conditions automatically hold for $V_i^{\mathrm{L_{det}}}$. This is because these conditions need to be imposed for $V^{\mathrm{M}}_{i,1}(X^{\mathrm{L}}_{T,i}, K^{\mathrm{L}}_i)$ and $V^{\mathrm{M}}_{i,2}(X^{\mathrm{L}}_{T,i}, K^{\mathrm{L}}_i)$ (see Hagspiel et al. (2016)) and because the correction terms remain the same for each region of $V_i^{\mathrm{L_{det}}}$. The latter is because the follower will always invest only in the profitable region R_2, giving rise to a sequential problem.[13]

Analogously to the previous section, $V_i^{\mathrm{L_{det}}}(X^{\mathrm{L}}_{T,i}, K^{\mathrm{L}}_i)$ and $I_i(K^{\mathrm{L}}_i)$ together allow calculating the optimal capacity $K_i^{*,\mathrm{L_{det}}}$ for a given timing ($X^{\mathrm{L}}_{T,i}$), whereas the relevant value matching and smooth pasting conditions for $F_i^{\mathrm{L_{det}}}(X)$ lead to the optimal unrestricted timing $X^{*,\mathrm{L_{det}}}_{T,i}$ as a function of installed capacity (K^{L}_i). Combining both leads to $(X^{**,\mathrm{L_{det}}}_{T,i}, K_i^{**,\mathrm{L_{det}}})$, the investment decision jointly optimal in both timing and size for the leader playing the entry deterrence strategy. According to Huisman & Kort (2015) however, the leader can only play the deterrence strategy when $X \in [X^{\mathrm{det}_1}_{T,i}, X^{\mathrm{det}_2}_{T,i}]$. This is the case when demand is small enough so that one port suffices to handle the cargo. $X^{\mathrm{det}_1}_{T,i}$ on the one hand is calculated as the lowest X for which an optimal $K_i^{*,\mathrm{L_{det}}}$ exists, so that an entry-deterring investment becomes possible. Since infinitesimal investment is never profitable due to the fixed investment cost, a slightly different calculation is needed than the one of Huisman & Kort (2015). Here, the following condition is solved:

$$V^{\mathrm{L_{det}}}_{i,2}(X^{\mathrm{det}_1}_{T,i}, K_i^{*,\mathrm{L_{det}}}(X^{\mathrm{det}_1}_{T,i})) - I_i(K_i^{*,\mathrm{L_{det}}}(X^{\mathrm{det}_1}_{T,i})) = 0. \tag{5.17}$$

Any investment in another capacity level at this threshold would not be profitable, nor can a profitable investment be made at a lower threshold. On the other hand, $X^{\mathrm{det}_2}_{T,i}$ is implicitly defined as

$$X^{*,\mathrm{F}}_{T,j}(K_i^{*,\mathrm{L_{det}}}(X^{\mathrm{det}_2}_{T,i})) = X^{\mathrm{det}_2}_{T,i} \tag{5.18}$$

(Huisman & Kort, 2015).

In this light, it should always be verified that $X^{**,\mathrm{L_{det}}}_{T,i} \in [X^{\mathrm{det}_1}_{T,i}, X^{\mathrm{det}_2}_{T,i}]$ to make sure that this

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

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

optimal entry deterrence strategy is feasible and indeed deters the follower. In the case of sufficiently large cost differences, the leader will wait to invest until the optimal deterrence threshold is reached if $X(t = 0) < X_{T,i}^{**,\mathrm{L}_{\mathrm{det}}}$, whereas the port will invest right away if the market is large enough from the outset, so that $X(t=0) > X_{T,i}^{**,\mathrm{L}_{\mathrm{det}}}$.

Entry accommodation

It may occur that entry deterrence is not the optimal strategy for the port to follow. This is the case when the market is initially large enough to accommodate two operating ports right away from the start. Then the leader does not have the incentive to overinvest in order to delay the follower's investment, since it would be too costly to do so. This is because installing a very large port could involve diseconomies of scale, or the required space could be lacking in the port area. Consequently, it is better for the leader port to invest in less capacity than what would be optimal under entry deterrence, so that the other port can be installed simultaneously to handle the large demand together with the first port.

Under entry accommodation, the value function of the leader is different than under entry deterrence, because the follower invests right away and there is no V^{M}-term. It is however similar to Equation (5.9), as the two ports invest at the same time (Huisman & Kort, 2015). The difference is that the capacity of the other port, i.e., the follower, is now endogenous, since it depends on the capacity of the leader and the given threshold, which is by definition equal to the timing of the leader. The value of the leader now becomes:

$$V_i^{\mathrm{L}_{\mathrm{acc}}}(X_{T,i}^{\mathrm{L}}, K_i^{\mathrm{L}}) = V_i^{\mathrm{F}}(X_{T,i}^{\mathrm{L}}, K_i^{\mathrm{L}}, K_j^{*,\mathrm{F}}(X_{T,i}^{\mathrm{L}}, K_i^{\mathrm{L}})). \tag{5.19}$$

The entry accommodation strategy can only be played when the market is large enough such that $X \in [X_{T,i}^{\mathrm{acc}_1}, \infty)$, with $X_{T,i}^{\mathrm{acc}_1} \leqslant X_{T,i}^{\mathrm{det}_2}$ and $X_{T,i}^{\mathrm{acc}_1}$ implicitly defined as

$$X_{T,j}^{*,\mathrm{F}}(K_i^{*,\mathrm{L}_{\mathrm{acc}}}(X_{T,i}^{\mathrm{acc}_1})) = X_{T,i}^{\mathrm{acc}_1} \tag{5.20}$$

(Huisman & Kort, 2015). In a similar way as under entry deterrence, the optimal entry accommodation investment strategy $(X_{T,i}^{**,\mathrm{L}_{\mathrm{acc}}}, K_i^{**,\mathrm{L}_{\mathrm{acc}}})$ can be calculated. Again however, this optimum is only feasible if $X_{T,i}^{**,\mathrm{L}_{\mathrm{acc}}} > X_{T,i}^{\mathrm{acc}_1}$.

It is moreover possible to determine whether it is optimal to play the entry deterrence or entry accommodation strategy if $X \in [X_{T,i}^{\mathrm{acc}_1}, X_{T,i}^{\mathrm{det}_2}]$. If $X_{T,i}^{\mathrm{acc}_1} < X_{T,i}^{\mathrm{det}_2}$, there exists an $\hat{X}_{T,i} \in [X_{T,i}^{\mathrm{acc}_1}, X_{T,i}^{\mathrm{det}_2}]$ for which it holds that for $X < \hat{X}_{T,i}$, it is optimal for the leader to play the entry deterrence strategy, while for $X > \hat{X}_{T,i}$ the entry accommodation strategy is optimal.[14] $\hat{X}_{T,i}$ satisfies

$$V_i^{\mathrm{L}_{\mathrm{det}}}(\hat{X}_{T,i}, K_i^{*,\mathrm{L}_{\mathrm{det}}}(\hat{X}_{T,i})) - I(K_i^{*,\mathrm{L}_{\mathrm{det}}}(\hat{X}_{T,i})) = V_i^{\mathrm{L}_{\mathrm{acc}}}(\hat{X}_{T,i}, K_i^{*,\mathrm{L}_{\mathrm{acc}}}(\hat{X}_{T,i})) - I(K_i^{*,\mathrm{L}_{\mathrm{acc}}}(\hat{X}_{T,i})), \tag{5.21}$$

meaning that at this market state, the value of both strategies is equal for the leader port.

[14] If $X_{T,i}^{\mathrm{acc}_1} = X_{T,i}^{\mathrm{det}_2}$, $\hat{X}_{T,i} = X_{T,i}^{\mathrm{acc}_1} = X_{T,i}^{\mathrm{det}_2}$.

Preemption

In the case of a small cost asymmetry between the ports, both ports have an incentive to be the first investor (Corchón & Marini, 2018). At the optimal investment threshold $X_{T,1}^{**,\mathrm{L_{det}}}$ of the first port with the cost advantage, the project value $V_1^{\mathrm{L}} - I_1$ of being the leader for this port is higher than the discounted value of being the follower $V_1^{\mathrm{F}} - I_1$. If the same holds for the second port, this follower would then prefer to become the leader, as this port would achieve higher value if it invested first. The second port could achieve this by investing at an X that is infinitesimally smaller than $X_{T,1}^{**,\mathrm{L_{det}}}$:

$$X_{T,1}^{**,\mathrm{L_{det}}} - \varepsilon, \tag{5.22}$$

with ε an infinitesimal small positive number. The first port would then invest at $X_{T,1}^{**,\mathrm{L_{det}}} - 2\varepsilon$ to remain the leader. This process of epsilon preemption as described by Huisman & Kort (2015) would continue until the preemption threshold X_T^{P} for which it holds that

$$\begin{aligned} V_2^{\mathrm{L}}(X_T^{\mathrm{P}}, K_2^{*,\mathrm{L}}(X_T^{\mathrm{P}})) - I_2(K_2^{*,\mathrm{L}}(X_T^{\mathrm{P}})) = \left(\frac{X_T^{\mathrm{P}}}{X_{T,2}^{**,\mathrm{F}}(K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}}))} \right)^{\beta_1} \times \\ \left[V_2^{\mathrm{F}}(X_{T,2}^{**,\mathrm{F}}(K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}})), K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}})), K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}})) - I_2(K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}}))) \right]. \end{aligned} \tag{5.23}$$

At this point, the port with the cost disadvantage is indifferent between leader and the follower role. The cost advantage for the other port leads to its leader value, $V_1^{\mathrm{M}} - I_1$, at this point still being higher than its discounted follower, $V_1^{\mathrm{F}} - I_1$. Hence, at this point no further preemption will take place, and port 1 will act as the leader and invest at X_T^{P} in $K_1^{*,\mathrm{L}}(X_T^{\mathrm{P}})$ to preempt port 2, whose investment will be deterred. However, if the market is currently small enough and the cost difference between the two ports is so large that the optimal investment timing is earlier than the preemption point so that $X < X_{T,1}^{**,\mathrm{L_{det}}} < X_T^{\mathrm{P}}$, the port with the cost advantage will invest at its deterrence optimum and the preemption point will be insignificant.

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

As the previous subsections illustrated, the leader port can choose from three different investment strategies. The choice it will make, depends on the initial state of the market as expressed by X. In this subsection, these possible strategies are discussed using a number line for X in Figure 5.4.

If X is initially very small, i.e., below $X_{T,i}^{\det_1}$, no profitable investment is possible for any port at the beginning. As soon as $X \geqslant X_{T,i}^{\det_1}$, the leader (i.e., port i) can profitably invest in an entry-deterring quantity. However, it will not decide to do so, since waiting is an even more valuable strategy. As soon as $X = X_T^{\mathrm{P}}$ and assuming that $X_T^{\mathrm{P}} < X_{T,i}^{**,\mathrm{L_{det}}}$ due to relatively small cost differences between the ports, the port with the cost advantage will decide to invest in the optimal entry-deterring quantity $K_1^{*,\mathrm{L_{det}}}(X_T^{\mathrm{P}})$. If it does not do so, the other port will invest first to preempt the port with the cost advantage. The latter will then become the follower. This would imply a lower value for the cost-advantaged port than if it were the leader. However, if the preemption point were higher than the optimal investment threshold of the leader due to a larger cost advantage, the leader could wait longer until X reaches $X_{T,i}^{**,\mathrm{L_{det}}} \in [X_{T,i}^{\mathrm{det_1}}, X_{T,i}^{\mathrm{det_2}}]$. At that point, the port with the cost advantage could invest at its unrestricted leader threshold, involving entry deterrence with $K_i^{**,\mathrm{L_{det}}}$ being the amount of capacity.

If X initially exceeds $\min\{X_T^{\mathrm{P}}, X_{T,i}^{**,\mathrm{L_{det}}}\}$, the leader will invest right away. The investment strategy and related capacity are dependent on the actual value of X. As long as $X < X_{T,i}^{\mathrm{acc_1}} \leqslant X_{T,i}^{\mathrm{det_2}}$, the optimal instantaneous investment strategy for the leader is the deterrence strategy, which is at the same time the only feasible strategy. If $X > X_{T,i}^{\mathrm{det_2}} \geqslant X_{T,i}^{\mathrm{acc_1}}$, it is optimal for the leader to invest right away in an entry-accommodating strategy, which is in this situation, again, the only feasible strategy. If $X \in [X_{T,i}^{\mathrm{acc_1}}, X_{T,i}^{\mathrm{det_2}}]$, both the deterrence and accommodation strategies are feasible. If $X < \hat{X}_{T,i}$, the deterrence strategy is more profitable, while if $X > \hat{X}_{T,i}$, accommodation is the more profitable strategy to play. As a result, a higher $\hat{X}_{T,i}$ decreases the probability that the leader will invest in an entry-accommodating capacity level.

The decision of the follower (i.c., port j) is easier to determine. If the leader invests in an entry-deterring capacity, the follower will wait with investment until X reaches its optimal threshold, which is $X_{T,j}^{**,\mathrm{F}}$. At that point, the follower will invest in the corresponding optimal capacity $K_j^{**,\mathrm{F}}$. Both depend on the capacity of the leader, as described in Section 5.2.2. If the leader invests in an entry-accommodating quantity, the follower will invest at the same time in its corresponding optimal capacity $K_j^{*,\mathrm{F}}(X_{T,i}^{\mathrm{L_{acc}}})$ as calculated before.

5.3 The impact of competition and port ownership on the investment decisions

In this section, the previously described methodology is applied to a two-port setting, specified by the parameters derived in Chapter 3 and summarised in Table 5.1. The specific $X_{T,i}$ and K_i from Figure 5.4 are calculated in order to describe the full domain of possible decisions for both the leader and the follower port. In order to examine the impact of competition intensity, the product differentiation parameter δ is varied from 0.6 to 0.9 for intensified competition and to 0.3 for less competition with more diversified port services. For each δ, the analysis is carried out under three different ownership structures: a private port (such as the English ports, e.g., the port of Felixstowe), a public port taking full consumer surplus into account (such as Spanish ports, e.g., the port of Valencia) and a port that

Figure 5.4: Number line with the leader's critical investment thresholds.

Table 5.3: Investment strategies of the leader (port 1: $X_{T,1}^{\mathrm{L}}, K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X_{T,1}^{\mathrm{L}})$) and follower (port 2: $(X_{T,2}^{**,\mathrm{F}}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X_{T,1}^{\mathrm{L}})), K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X_{T,1}^{\mathrm{L}}))))$ for each characteristic X_T in Figure 5.4.

s_G	s_{CS}	***Port role***	$X_{T,i}^{\mathrm{det}_1}$	X_T^{P}	$X_{T,i}^{**,\mathrm{L}_{\mathrm{det}}}$	$X_{T,i}^{\mathrm{acc}_1}$	$\hat{X}_{T,i}$ **(acc)**	$\hat{X}_{T,i}$ **(det)**	$X_{T,i}^{\mathrm{det}_2}$
0	*0*	*Leader (1)*	19.84, 8.39	32.75, 10.35	(36.24, 10.79)	48.72, 12.02	48.84, 12.04	48.84, 12.19	48.91, 12.20
		⟶ *Follower (2)*	(44.67, 11.76)	(46.89, 11.91)	(47.38, 11.94)	(48.72, 12.02)	48.84, 12.04	(48.90, 12.03)	(48.91, 12.03)
1/2	*1/2*	*Leader (1)*	19.09, 8.45	30.97, 10.34	(34.68, 10.83)	47.89, 12.15	48.06, 12.17	48.06, 12.36	48.16, 12.38
		⟶ *Follower (2)*	(43.35, 11.84)	(45.67, 12.00)	(46.28, 12.05)	(47.89, 12.15)	48.06, 12.17	(48.15, 12.17)	(48.16, 12.17)
1	*1*	*Leader (1)*	17.01, 8.73	25.93, 10.39	(30.49, 11.10)	47.75, 12.90	48.48, 12.99	48.48, 13.46	48.96, 13.52
		⟶ *Follower (2)*	(40.25, 12.29)	(43.06, 12.53)	(44.34, 12.64)	(47.75, 12.90)	48.48, 12.99	(48.85, 12.99)	(48.96, 13.00)

Parameter values: $A=5, B=1, \delta=0.6, c=1, c_h=0.5, \mu=0.015, \sigma=0.1, r=0.06, FC_{I,1}=80, FC_{I,2}=100, \gamma_1=180, \gamma_2=19, \gamma_3=0, \gamma_4=0.12, \lambda=0.4$.

Table 5.4: Investment strategies of the leader (port 1: $X^{\mathrm{L}}_{T,1}, K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X^{\mathrm{L}}_{T,1})$) and follower (port 2: $(X^{**,\mathrm{F}}_{T,2}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X^{\mathrm{L}}_{T,1})), K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X^{\mathrm{L}}_{T,1}))))$ for each characteristic X_T in Figure 5.4 under higher product diversification.

s_G	s_{CS}	*Port role*	$X^{\mathrm{det}_1}_{T,i}$	X^{P}_{T}	$X^{**,\mathrm{L}_{\mathrm{det}}}_{T,i}$	$X^{\mathrm{acc}_1}_{T,i}$	$\hat{X}_{T,i}$ (acc)	$\hat{X}_{T,i}$ (det)	$X^{\mathrm{det}_2}_{T,i}$
0	*0*	*Leader (1)*	19.50, 8.36	35.12, 10.71	(36.57, 10.89)	43.19, 11.61	43.20, 11.61	43.20, 11.65	43.20, 11.65
		⟶ *Follower (2)*	(41.52, 11.51)	(42.75, 11.59)	(42.84, 11.59)	(43.19, 11.61)	43.20, 11.61	(43.20, 11.61)	(43.20, 11.61)
1/2	*1/2*	*Leader (1)*	18.75, 8.42	33.31, 10.69	(34.93, 10.90)	41.88, 11.68	41.89, 11.69	41.89, 11.73	41.90, 11.74
		⟶ *Follower (2)*	(40.04, 11.56)	(41.34, 11.65)	(41.46, 11.66)	(41.88, 11.68)	41.89, 11.69	(41.90, 11.69)	(41.90, 11.69)
1	*1*	*Leader (1)*	16.67, 8.68	28.12, 10.74	(30.45, 11.08)	39.04, 12.13	39.11, 12.13	39.11, 12.25	39.15, 12.26
		⟶ *Follower (2)*	(36.27, 11.90)	(37.91, 12.04)	(38.20, 12.06)	(39.04, 12.13)	39.11, 12.13	(39.15, 12.13)	(39.15, 12.13)

Parameter values: $A=5, B=1, \delta=0.3, c=1, c_h=0.5, \mu=0.015, \sigma=0.1, r=0.06, FC_{I,1}=80, FC_{I,2}=100, \gamma_1=180, \gamma_2=19, \gamma_3=0, \gamma_4=0.12, \lambda=0.4$.

Table 5.5: Investment strategies of the leader (port 1: $X^{\mathrm{L}}_{T,1}, K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X^{\mathrm{L}}_{T,1})$) and follower (port 2: $(X^{**,\mathrm{F}}_{T,2}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X^{\mathrm{L}}_{T,1})), K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X^{\mathrm{L}}_{T,1}))))$ for each characteristic X_T in Figure 5.4 under lower product diversification.

s_G	s_{CS}	*Port role*	$X^{\mathrm{det}_1}_{T,i}$	X^{P}_{T}	$X^{**,\mathrm{L}_{\mathrm{det}}}_{T,i}$	$X^{\mathrm{acc}_1}_{T,i}$	$\hat{X}_{T,i}$ (acc)	$\hat{X}_{T,i}$ (det)	$X^{\mathrm{det}_2}_{T,i}$
0	*0*	*Leader (1)*	20.10, 8.43	31.15, 10.14	(36.28, 10.80)	55.27, 12.52	55.76, 12.57	55.76, 12.93	56.08, 12.96
		⟶ *Follower (2)*	(47.76, 12.02)	(50.87, 12.23)	(52.09, 12.32)	(55.27, 12.52)	55.76, 12.57	(56.02, 12.56)	(56.08, 12.57)
1/2	*1/2*	*Leader (1)*	19.35, 8.50	29.43, 10.13	(34.79, 10.86)	55.20, 12.73	55.94, 12.80	55.94, 13.26	56.43, 13.31
		⟶ *Follower (2)*	(46.60, 12.12)	(49.81, 12.36)	(51.29, 12.46)	(55.20, 12.73)	55.94, 12.80	(56.33, 12.80)	(56.43, 12.80)
1	*1*	*Leader (1)*	17.24, 8.79	24.64, 10.22	(30.90, 11.23)	60.33, 14.02	64.82, 14.46	64.82, 15.64	68.30, 16.03
		⟶ *Follower (2)*	(44.06, 12.69)	(47.88, 13.02)	(50.89, 13.27)	(60.33, 14.02)	64.82, 14.46	(66.66, 14.49)	(68.30, 14.61)

Parameter values: $A=5, B=1, \delta=0.9, c=1, c_h=0.5, \mu=0.015, \sigma=0.1, r=0.06, FC_{I,1}=80, FC_{I,2}=100, \gamma_1=180, \gamma_2=19, \gamma_3=0, \gamma_4=0.12, \lambda=0.4$.

is 50% owned publicly by a government taking 50% of port i's generated consumer surplus into account (such as the port of Tauranga in New Zealand).[15] This allows discerning the impact of different government ownership structures on the investment decision. The resulting investment decisions for port 1 (the leader) and port 2 (the follower) are shown in Tables 5.3 - 5.5.

$X_{T,i}^{\text{det}_1}$ is the first critical threshold that requires analysis. If the share of the public owner is larger, investment will be considered beneficial sooner already, when the market might still be smaller. This threshold decreases with the involvement of public money in the port. In this case, the project becomes more attractive, since more welfare effects are taken into account. Because of this, the threshold for the inverse demand function intercept from which investment for the leader becomes profitable, decreases. Moreover, the leader's installed capacity will be larger. The follower's decision is impacted in the same way. The increase in project attractiveness leads to an earlier and larger investment. In the case of a lower δ, product diversification is higher, for which competition between the two ports is lower. As a result, the ports experience a lower impact from each other's operations on the own price. Hence, the price will be higher, ceteris paribus, and the project will be more attractive, so that the leader will be willing to invest earlier, whereas the size will be slightly smaller. Nevertheless, the follower will invest earlier too, since its project will also be more attractive because the competition from the leader is lower. This leads to the leader having a monopoly position for a shorter time, but this is largely made up for by the higher price because of less competition, even after the monopoly period has ended.

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

[15]The port of Tauranga is 55% state owned and the rest is listed on the New Zealand Stock Exchange (Cairns, 2013).

the amount of competition. As a result of increased competition, the leader would invest in more capacity than what would be optimal under a monopoly setting in order to delay follower entry for a longer time, leading to a prolonged monopoly position (Huberts et al., 2019). This explains why follower investment is later and hence larger when there is more competition, notwithstanding the leader's earlier investment timing under the preemption strategy. Hence, if for example the Italian government wanted to install a new port closer to Marseille, it would be advised to wait until the market is large enough for two ports to handle the cargo. The findings are summarised in the following results, which are derived numerically, since closed-form analytical results could not be obtained.

Result 5.1. *Under the assumptions given in Table 5.2, intensified competition and resulting preemption not only lead to earlier investment of the leader, but also to less capacity installed. The follower however invests later and in more capacity.*

If there are large cost differences, the leader is able to invest at the unrestricted threshold $X_{T,i}^{**,\mathrm{L}_{\mathrm{det}}}$. The impact of competition on this optimal timing threshold is ambiguous and limited. The impact of an increase in public money involvement however is less ambiguous and the result from the previous chapter can be confirmed:

Result 5.2. *Under the assumptions given in Table 5.2, an increase in public money involvement leads to an earlier unrestricted investment in more capacity by both the leader and the follower.*

Result 5.2 confirms the finding of the previous chapter and is in line with Asteris et al. (2012), namely that public companies invest sooner and in more capacity than private companies.

If the initial X is high enough (above $\hat{X}_{T,i}$), the market is so profitable that the cost-disadvantaged port will also invest immediately. This implies that entry accommodation becomes the most profitable strategy for the leader. The leader will invest in less capacity than under entry deterrence, because then there is no incentive to prolong the monopoly period. The thresholds indicating the beginning of the accommodation region and the end of the deterrence region increase with a higher δ. As previously noted, if the competitive impact of the other port increases, the leader has a larger incentive to deter the follower from entry. This can be done through investing in more capacity to delay the follower's investment. The impact of public involvement on the two boundaries is ambiguous. Additionally, (increased) public money involvement and product diversification both widen the interval wherein both strategies (entry deterrence and accommodation) are possible. This is caused by a combination of effects. Due to public money involvement, investment becomes more beneficial for both ports. Since it is more profitable for the leader, deterrence is feasible over a longer time span, but because investment is also more profitable for the follower, at the same time it is more difficult to deter entry.

The follower's decision does not depend on the initial value of X and the different leader thresholds. It only depends on the capacity choice of the leader. Given the size of this capacity, the follower can decide to invest right away, or delay the investment until the market is large enough for two ports to be operating. In the latter case, the follower will calculate its optimal size and timing of the investment. If the leader follows an entry-accommodating strategy, the follower will de facto find it optimal to invest at the same timing, and it calculates its optimal size accordingly. If the leader has invested in more capacity, the follower will invest later, independent of the timing of the leader. The reason is that the leader has been able to capture a larger share of the market. Hence the follower needs to await more market growth in order to be able to invest profitably. Given the positive relationship between timing and size, the follower will not only invest later, but also invest in more capacity.

If relatively more public money is involved, the follower will ceteris paribus invest earlier in more capacity. This observation is analogous to the impact on the leader's decision. If the port services are more homogeneous due to being situated closer to one another, in turn leading to increased competition, the negative impact of the leader's activity on the follower's price is higher. As a result, the follower needs to wait longer in order to be able to invest profitably and the installed capacity will be larger. The reason is that under more intense competition, investment by the leader has more effect on the follower's profitability. By consequence, it requires less effort of the leader port to reduce profitability of the follower, thus making entry deterrence a relatively easier strategy to follow. This effect can however be offset by public government involvement, since social welfare being considered more, can facilitate the construction of a new port closer to an existing port.

5.4 The impact of other parameters on the investment decision: sensitivity analysis

In order to analyse the impact of the size of congestion costs (A), uncertainty (σ), growth (μ) and the investment cost difference between the two ports (as expressed by $FC_{I,i}$) on the investment decision, the respective parameter is each time altered and compared with the base case (where $\delta = 0.6$ and $s_G = s_{CS} = 0.5$). In this light, the outcomes in Table 5.6 allow verifying the sensitivity of the results with respect to the altered parameters and the robustness of some of the previous chapters' findings with respect to adding a second port to the model.

If the port customers are more averse to waiting, the willingness to pay is lower for the same utilisation rate. As a reaction, both the leader and the follower port will invest in more capacity, but at a later moment. This result confirms the finding of Chapter 3 in a monopoly port.

Table 5.6: Investment strategies of the leader (port 1: $X^{\mathrm{L}}_{T,1}, K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X^{\mathrm{L}}_{T,1})$) and follower (port 2: $(X^{**,\mathrm{F}}_{T,2}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X^{\mathrm{L}}_{T,1})), K_2^{**,\mathrm{F}}(K_1^{*,\mathrm{L}_{\mathrm{det/acc}}}(X^{\mathrm{L}}_{T,1}))))$ for each characteristic X_T in Figure 5.4 under different parameter changes.

Parameter change	***Port role***	$X_{T,i}^{\mathrm{det}_1}$	X_T^{P}	$X_{T,i}^{**,\mathrm{L}_{\mathrm{det}}}$	$X_{T,i}^{\mathrm{acc}_1}$	$\hat{X}_{T,i}$ **(acc)**	$\hat{X}_{T,i}$ **(det)**	$X_{T,i}^{\mathrm{det}_2}$
Base case	*Leader (1)*	19.09, 8.45	30.97, 10.34	(34.68, 10.83)	47.89, 12.15	48.06, 12.17	48.06, 12.36	48.16, 12.38
	⟶ *Follower (2)*	(43.35, 11.84)	(45.67, 12.00)	(46.28, 12.05)	(47.89, 12.15)	48.06, 12.17	(48.15, 12.17)	(48.16, 12.17)
A= 4	*Leader (1)*	17.23, 8.25	27.56, 10.07	(31.29, 10.61)	44.57, 12.05	44.75, 12.07	44.75, 12.30	44.86, 12.31
	⟶ *Follower (2)*	(40.04, 11.72)	(42.25, 11.89)	(42.90, 11.94)	(44.57, 12.05)	444.75, 12.07	(44.85, 12.07)	(44.86, 12.07)
σ= 0.15	*Leader (1)*	18.63, 8.51	41.32, 11.86	(49.36, 12.78)	N/A	N/A	N/A	N/A
	⟶ *Follower (2)*	(69.38, 14.79)	(80.77, 15.67)	(84.30, 15.93)	N/A	N/A	N/A	N/A
σ= 0.14	*Leader (1)*	18.75, 8.50	38.62, 11.48	(44.84, 12.21)	78.10, 15.18	78.70, 15.23	78.70, 15.51	79.12, 15.55
	⟶ *Follower (2)*	(60.79, 13.90)	(68.11, 14.47)	(70.02, 14.61)	(78.10, 15.18)	78.70, 15.23	(79.02, 15.25)	(79.12, 15.25)
μ= 0.02	*Leader (1)*	16.82, 8.47	33.08, 11.23	(38.09, 11.90)	62.51, 14.42	62.89, 14.45	62.89, 14.70	63.15, 14.73
	⟶ *Follower (2)*	(50.83, 13.45)	(56.10, 13.91)	(57.44, 14.02)	(62.51, 14.42)	62.89, 14.45	(63.10, 14.46)	(63.15, 14.46)
μ=−0.01	*Leader (1)*	29.51, 8.44	33.29, 8.89	(36.07, 9.20)	43.35, 9.60	43.54, 9.61	43.54, 9.93	43.69, 9.95
	⟶ *Follower (2)*	(44.24, 9.56)	(42.67, 9.57)	(42.97, 9.58)	(43.35, 9.60)	43.54, 9.61	(43.68, 9.61)	(43.69, 9.61)
$FC_{I,2}$= 196.3	*Leader (1)*	19.02, 8.44	(34.74, 10.84)	(34.74, 10.84)	51.33, 12.51	51.51, 12.53	51.51, 12.74	51.63, 12.75
	⟶ *Follower (2)*	(46.12, 12.17)	(49.20, 12.38)	(49.20, 12.38)	(51.33, 12.51)	51.51, 12.53	(51.61, 12.53)	(51.63, 12.53)
Single	*Leader (1)*	19.02, 8.44	31.46, 10.41	(34.70, 10.83)	46.29, 12.03	46.40, 12.04	46.40, 12.19	46.46, 12.19
government	⟶ *Follower (2)*	(42.53, 11.77)	(44.61, 11.92)	(45.06, 11.95)	(46.29, 12.03)	46.40, 12.04	(46.46, 12.04)	(46.46, 12.04)

Base case parameter values: $A=5, B=1, \delta=0.6, c=1, c_h=0.5, \mu=0.015, \sigma=0.1, r=0.06, FC_{I,1}=80, FC_{I,2}=100, \gamma_1=180, \gamma_2=19, \gamma_3=0, \gamma_4=0.12, s_G=0.5, s_{CS}=0.5, \lambda=0.4.$

If the economic environment is more uncertain, both ports benefit from waiting longer to invest, in order to gain more information. Increased uncertainty not only leads to waiting longer before investment due to a higher option value of waiting, but also to more capacity installed. This confirms the frequent real options observation, also found in the previous chapters. However, this effect is lower under competition, since competition has a negative impact on the option value of waiting. Next to the common real options result, uncertainty also has another effect. It might even be that due to high uncertainty, entry accommodation is no longer a feasible strategy. If uncertainty increases, the value of waiting for the follower rises. As a result, for sufficiently high values of uncertainty, the follower always waits whenever the leader invests. This implies the absence of an investment accommodation region. Since higher uncertainty implies that the follower invests later, the leader is a monopolist for a longer time in the deterrence region. This makes deterrence more attractive for the leader, implying that $X_{T,i}^{\det_1}$ can be lower.

If average growth is higher, both ports need to install substantially more capacity, in order to be able to accommodate the future demand for throughput without too much congestion. However, a larger investment requires a larger market, implying later investment. This result was also found in Chapter 3. Additionally, the $X_{T,i}^{\det_1}$ threshold will be lower as well, since the project is more attractive, and the port will be willing to install the project earlier. However, also the impact of negative economic growth needs some attention in this setting. If growth is negative, the port will need to wait for a higher threshold to be reached, in order to be able to profitably install the project. Due to the negative growth rate, reaching this threshold is much less probable. Moreover, the project will be much smaller, since future demand is expected to decrease. This finding is also in line with the results found in Chapter 3. Since the leader's project will be much smaller, the follower speeds up investing. Hence, the follower's investment size will be smaller too, due to the declining market and the earlier investment.

The impact of a cost advantage increase for the leader, such that $FC_{I,2}$ increases, is that the leader can wait longer to invest in order to still deter or preempt the follower. The reason is that the follower needs to wait longer in order to be able to profitably invest in capacity, due to its higher investment cost. This leads to both ports not only investing later, but also in more capacity. As a consequence, when the cost advantage becomes large enough, preemption no longer takes place. In such a case, the role of each port is ex-ante determined. The first port (leader) can invest at its unrestricted leader threshold, while at this point the follower value of the second port is at least as high as its leader value. Additionally, it is observed that $X_{T,i}^{\det_1}$ slightly decreases. The leader knows that it will benefit for a longer time of its monopoly position due to the FC-cost increase for the other port. As a result, investing in capacity becomes profitable earlier. This result is summarised as follows:

Result 5.3. *Under the assumptions given in Table 5.2, a larger fixed investment cost difference decreases the competing port's impact on the cost-advantaged port's optimal investment decision.*

Throughout this chapter, the analyses were made under the assumption that the public owner involved in port i differs from the public owner involved in port j. However, it is worthwhile to check the robustness of the analysis with respect to the same government owning a share of both ports i and j. This could be the case if those two ports are located in the same country or province. In such a case, the government would consider the consumer surplus of both ports, CS_{i+j}, which under product differentiation equals

$$CS_{i+j}(q_i, q_j) = B/2 \cdot (q_i^2 + 2\delta q_i q_j + q_j^2), \tag{5.24}$$

due to the calculation through a line integral (Singh & Vives, 1984). As a result, CS_i in Equation (5.3) would no longer be valid, as it needs to be replaced by

$$CS_i = B/2 \cdot (q_i^2 + \delta q_i q_j). \tag{5.25}$$

The consumer surplus of the other port would equal

$$CS_j = B/2 \cdot (q_j^2 + \delta q_i q_j), \tag{5.26}$$

so that the sum of both equals $CS_{i+j}(q_i, q_j)$. Implementing this in the model yields the investment strategies in the last two lines of Table 5.6, indicated by 'single government'. The effect on the calculated investment decisions is limited and is qualitatively similar to the effect of a decreased impact of the other port's throughput quantity q_j on the own port's price p_i, mathematically expressed as a decrease in δ.

5.5 Conclusion of this chapter

Many examples of competing ports, operating in an uncertain environment, exist. Depending on the geographical situation and services offered, the amount of competition may however differ. This chapter has explored the impact of inter-port competition and other typical port characteristics under uncertainty on port capacity investment decisions. Simultaneous investment when the leader invests in an entry-accommodating capacity was allowed for, next to the possibility for the leader to deter entry in a leader-follower timing game.

When competition is more intense, the option value of waiting is reduced, because each port has a larger incentive to invest before the other port. As a result of this earlier investment, the leader's investment will be smaller as well. The follower will however invest later and in more capacity. The same effect on the timing is observed when government involvement increases. The consideration of social welfare in the operational objective function of publicly owned ports leads to a more attractive project. As a result, the ports will invest earlier, but in more capacity. If growth expectations are higher in this competitive market, it is beneficial to wait longer and benefit from the larger market and higher price. As a result, more capacity will be installed at this later moment too. The same holds for higher uncertainty, since the option value of waiting and gaining more information increases with uncertainty. Subsequently, it can be confirmed that if the customers are less waiting-time averse, less capacity is needed, and because the project is more attractive due to higher generalised costs, the port will want to invest earlier. Finally, if the cost advantage of the leader is small enough, both ports compete for the leader role, as they are seeking to preempt each other. If the cost difference is large enough however, the cost-advantaged port is guaranteed the leader role, so that it can invest at its unrestricted leader threshold. Additionally, it will be easier for the leader to secure the monopoly position for a longer time. Hence, policy makers that want to benefit as much as possible from the advantages of inter-port competition, are advised to reduce investment cost differences between different ports. This could for instance be done through taxes or subsidies.

Although not considered in this and the previous chapters, it takes time to build the infrastructure, during which the market evolves in an uncertain way. As a result, the exposure to uncertainty is larger in reality than accounted for in the presented model. Additionally, a difference in time to build between two ports, e.g., due to a different political and legal environment, may also impact competition and the determination of the leader and follower port. Moreover, this and previous chapters' models neglect the option to expand. When the port is already active, it might want to mitigate sooner the already present congestion, in order to increase the port operations' profitability in the future. The impact of time to build on the port expansion investment decision of one single port is studied in the next chapter.

Chapter 6

The impact of time to build and uncertainty on port expansion projects

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).[1] The previous chapters all dealt with greenfield projects too. One of the counter-intuitive findings was that higher congestion costs and waiting-time aversion lead to delaying the investment in a new port, which would be larger though. 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. 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 Saeftinghedok in Antwerp. The question can be asked whether the same conclusions hold for a port expansion project as for the investment in a new port. In the latter case, if port customers are more waiting-time averse, it is better to install a larger new port later. One could however expect that the management of the port would have an incentive to anticipate the investment in case of port expansion projects, in order to reduce the congestion already present among its customers when the instrument of congestion pricing cannot be exploited any further in a profitable way.

Additionally, it takes a lot of time to build large infrastructure projects like port capacity investment projects (Meersman & Van de Voorde, 2014a; Vanelslander, 2014; Aguerrevere, 2003). During the project 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

[1]Opposed to the theoretical literature using analytical models to study port investments, more (empirical) cost-benefit analyses for port expansions are available.

port's investment decision and needs to be considered. The available RO literature on time to build 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. He moreover 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 longer 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 chapter is to analyse the impact of time to build and the capacity already in place on the port capacity expansion decision under uncertainty. The following research sub-questions have been formulated: (RQ 6.1) What is the impact of time to build on the optimal capacity investment decision under uncertainty without competition? and (RQ 6.2) What is the impact of existing capacity on the optimal capacity investment decision under uncertainty without competition? The impact of the two model extensions that are introduced in this chapter, compared to Chapter 3, are analysed separately in Section 6.5. In this chapter, the port considered has the option to invest in one expansion project, which is fully deployed in one phase and which can only be used after completion. Hence, phased investment is not considered here. 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 verified in this different port setting. These additions to the literature will allow practitioners to make well-considered port investment decisions, taking into account as much relevant information as possible. However, port competition is left beyond the scope of this chapter, in order to focus on the impact of time to build on the (unrestricted) optimal expansion decision of one port. This approach moreover allows for better mathematical tractability of the model. In order to extend this chapter's model to a duopoly case, the approach of Chapter 5 can be followed.

The structure of this chapter is as follows. Section 6.1 reformulates the basic model from Chapter 3 to determine the value of an investment in a new port without time to build. This offers a basis for the model of this chapter. Section 6.2 introduces time to build and the evaluation of expansion projects in the model. Section 6.3 describes how the optimal investment decision is determined according to the real options approach in a port expansion context with time to build. The additional parameters used for the numerical simulations are given in Section 6.4. This is followed by a discussion of the results in Section 6.5 and the sensitivity of the results to previously studied economic parameters in Section 6.6. The final section contains the conclusion of this chapter.

6.1 Recapitulation of the basic model for determining the project value

The extended model in this chapter is based on the basic economic model from Chapter 3, as outlined in Section 3.1. This allows comparing the findings of this chapter with the previous chapters' findings. The profit generated in a newly built private port, operated by one single actor, was calculated by Equation (3.7). As discussed in Chapter 4, the port authority (PA) is not always privately owned. Also a public government could own shares of the PA. This was included in the PA's operational objective function, $\Pi(X,K,q)$, by considering spillover benefits for the local economy and consumer surplus partly or fully in Equation (4.6).

As indicated, throughput should always be greater than or equal to zero. As a result, q^{opt} is set to 0 if the optimal throughput level is below zero (Dangl, 1999). As opposed to the models in Chapter 3 and 4 but in line with the model of Chapter 5, a port's design capacity K is not considered as a hard constraint for the throughput level. It is however a soft constraint if the waiting cost at high occupancy rates is sufficiently high. This approach allows for the exceptional case wherein throughput exceeds capacity at a high cost.[2] As a result, q^{opt} is defined here in two mathematical 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 again leads to the optimal throughput level q^{opt} at each point in time (see also Chapter 3):

$$q^{opt}(X,K) = \begin{cases} 0, & X < c - s_G\lambda, \\ \dfrac{[X-(c-s_G\lambda)]K^2}{2(AX+BK^2)-s_G s_{CS} BK^2}, & X \geqslant c - s_G\lambda. \end{cases} \tag{6.1}$$

Subsequently, the optimal $\overline{\Pi}(X,K) = \Pi(X,K,q^{opt}(X,K))$ is again calculated in the same two regions as well, which then allows calculating $V(X,K)$, the value of a greenfield project without time to build (see Section 3.3).

[2] It can be noted that the impact of omitting region R_3 as a result of relaxing the capacity constraint to a soft constraint only has a limited impact on the outcomes. In Table 6.3, the optimal investment strategy with K_0, θ, s_G and s_{CS} equalling zero, is (37.71 euro per TEU, 11.19 M TEU p.a.). In Chapter 3 with region R_3 included as a result of K being a hard constraint for q, the corresponding optimum was (37.63 euro per TEU, 11.17 M TEU p.a.), encompassing a difference of only 0.2%. Including region R_3 only unnecessarily complicates the calculations of the model for expansion projects due to additional mathematical regions R_j with boundaries involving K.

6.2 Economic setting and methodology: model extensions

In order to account for (i) the amount of capacity already present in expansion projects, and (ii) the lead time between the investment decision and the project completion, two model extensions are developed in this chapter. Both extensions need to be implemented in the expression for the value of the investment project. This new expression $\Delta V'$ is to be used instead of V in the dynamic programming methodology as described in Section 3.4.

6.2.1 Accounting for existing capacity in the value of expansion projects

The value of an expansion project of size ΔK with initial (existing) capacity K_0 can be calculated as the difference in value V after and before installing the expansion project at the moment where the demand shift parameter equals X:

$$\Delta V_j(X, \Delta K, K_0) = V_j(X, K_0 + \Delta K) - V_j(X, K_0), \tag{6.2}$$

with j indicating the mathematical region for X in which V is calculated and with $V_j(X,0) = 0$, so that $\Delta V_j(X, \Delta K, 0) = V_j(X, \Delta K)$.[3]

6.2.2 Accounting for the impact of time to build on the project value

As noted before, it takes time to build port capacity projects, once the investment decision is made. During this lead time, 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 project lead time θ 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, defined by growth and uncertainty parameters μ and σ, needs to be 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:

$$\phi(X, X_0, \theta) = \frac{1}{\sqrt{2\pi}} \frac{1}{X\sigma\sqrt{\theta}} \exp\left(-\frac{\left(\ln X - \ln X_0 - \left(\mu - \frac{1}{2}\sigma^2\right)\theta\right)^2}{2\sigma^2\theta}\right). \tag{6.3}$$

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 (Aguer-

[3] In that case, ΔK equals K from Chapter 3.

revere, 2003):[4,5]

$$\Delta V'(X,\Delta K,K_0,\theta) = e^{-r\theta}\left[\int_0^{c-s_G\lambda}\phi(X',X,\theta)\cdot\Delta V_1(X',\Delta K,K_0)\,\mathrm{d}X' + \int_{c-s_G\lambda}^{\infty}\phi(X',X,\theta)\cdot\Delta V_2(X',\Delta K,K_0)\,\mathrm{d}X'\right], \quad (6.4)$$

with r the discount rate. The integrals together calculate the weighted average project value V 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 of the investment decision and the start of port operations at the site after project completion.

6.3 Determining the optimal project investment size and timing

An analogous analysis to the one of Chapter 3 can be carried out to determine the optimal size and timing of the expansion project. To this end, Equation (3.28) here becomes

$$F(X) = \max\left\{\mathrm{e}^{-r\mathrm{d}t}\,\mathbf{E}(F(X)+\mathrm{d}F(X)), \max_K[\Delta V'(X,\Delta K,K_0,\theta) - I(\Delta K)]\right\}. \quad (6.5)$$

Using Equation (6.5) and the steps described in Section 3.4, the optimal size of the expansion project $\Delta K^*(X,K_0,\theta)$ and the optimal timing, expressed as threshold $X_T^*(\Delta K,K_0,\theta)$, can be determined for an expansion project. Both are functions of existing capacity K_0 and time to build θ.

The optimal investment strategy involving both timing and size $(X_T^{**}(K_0,\theta),\Delta K^{**}(K_0,\theta))$ is finally determined through solving the system

$$\begin{cases} X_T^{**}(K_0,\theta) = X_T^*(\Delta K^{**}(K_0,\theta),K_0,\theta), \\ \Delta K^{**}(K_0,\theta) = \Delta K^*(X_T^{**}(K_0,\theta),K_0,\theta). \end{cases} \quad (6.6)$$

This optimal investment strategy also depends on K_0 and θ.

The equations making up the model are summarised in Table 6.1, whereas the assumptions are in Table 6.2. Table 6.1 also contains the numerical values for the different parameters. The base case parameters determined in the previous chapters have been retained.

[4]Note that in the special case that time to build is zero, $\Delta V'(X,\Delta K,K_0,0) = \Delta V_j(X,\Delta K,K_0)$, with j determined by the region R_j where X is located at that moment.

[5]Also note that time to build can be included in a new port project as well, where $K_0 = 0$. To this end, $\Delta V_j(X,\Delta K,K_0,\theta)$ needs to be replaced by $V_j(X,\Delta K,\theta)$, with ΔK the size of the project, i.e., K.

The additional parameters are determined in the next section. The sensitivity of the results to monetary scale factor A, growth rate μ, uncertainty σ, relative number of PA shares owned publicly s_G and relative share of total consumer surplus considered s_{CS} is discussed in Section 6.6.

6.4 Setting the additional model parameters

The expansion decision in this chapter deals again with a new container terminal with an annual capacity of about 8 to 14 million TEU per year. Due to the model extensions in Section 6.2, additional model parameters need to be determined, based on real port data. 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 time to build a new dock 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 more 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 chapter, time to build is varied between zero and six years, to study the impact of an increase in time to build on the investment decision.

6.5 Results and discussion

The numerical model solutions in Tables 6.3 - 6.5 allow analysing the impact of a number of project and economic characteristics on the final investment decision of a port. Each table corresponds to a specific ownership structure and considers the base case, together with some scenarios involving one different economic characteristic. In the following subsections, the effect of time to build and the impact of existing capacity are analysed in greater detail.

6.5.1 The impact of time to build

Port expansion 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

Table 6.1: Overview of Chapter 6's model and the selected parameters.

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 scale 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 (i.e., growth)
$\sigma(=0.1)$	=	drift variability of Z (i.e., uncertainty)
Total cost $TC = cq + c_h K$		
$c(=1)$	=	constant marginal operational cost
$c_h(=0.5)$	=	cost to hold one unit of capacity 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 the port owned by the government
$s_{CS}(\in[0;1])$	=	share of total CS taken into account by the government

Table 6.2: Overview of Chapter 6's model assumptions.

	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: available after completion
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, which evolve with the market (i.c., increasing)
	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)

*: 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 TOC).
Focus on lumpy investment in port infrastructure and irreversible elements of superstructure.

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 decision, 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 decision, especially compared with cases with an investment decision threshold that is already relatively high. This can be explained by the fact that time to build also encompasses an incentive to anticipate the investment decision. The reason is that the present value of the future profit flow will be relatively lower due to this construction lag between the investment decision 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 flow 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:[6]

Result 6.1. *Under the assumptions given in Table 6.2, 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 and timing decision is observed. In Table 6.3 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 at a higher threshold, but the size of the project is smaller than if there is no construction lead time. As explained in Chapter 4, such an observation of two strong effects is uncommon in the RO literature, where the positive relationship between investment size and timing often dominates. 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 6.3. If the project lead time were one year, a port with existing capacity of 15 million TEU per year would install a smaller project, at a lower threshold than in the case without time to build. Oppositely, a greenfield project with one year of 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). Hence, each port is advised to analyse its own investment options

[6]This result holds for expansion projects, as well as for the installation of new ports.

Table 6.3: Optimal investment strategies $(X_T^{**}(K_0,\theta), \Delta K^{**}(K_0,\theta))$ under different project 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 6.4: Optimal investment strategies $(X_T^{**}(K_0,\theta), \Delta K^{**}(K_0,\theta))$ under different project 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			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(36.07, 11.22)	(29.80, 10.02)	(36.07, 10.41)	(45.41, 11.08)
Time	$\theta = 1$	(36.93, 11.23)	(30.18, 10.01)	(36.24, 10.38)	(45.40, 11.02)
to	$\theta = 2$	(37.83, 11.24)	(30.57, 10.00)	(36.43, 10.34)	(45.40, 10.97)
build	$\theta = 4$	(39.76, 11.26)	(31.43, 9.99)	(36.87, 10.29)	(45.48, 10.87)
	$\theta = 6$	(41.87, 11.28)	(32.38, 9.98)	(37.38, 10.23)	(45.64, 11.77)

A set to 4.

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

σ set to 0.15.

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

μ set to 0.02.

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

μ set to -0.01.

		Existing capacity			
		$K_0 = 0$	$K_0 = 5$	$K_0 = 10$	$K_0 = 15$
	$\theta = 0$	(36.19, 9.27)	(30.51, 8.06)	(35.78, 8.00)	(43.13, 8.12)
Time	$\theta = 1$	(38.03, 9.29)	(31.73, 8.08)	(36.96, 8.00)	(44.40, 8.12)
to	$\theta = 2$	(39.98, 9.32)	(33.02, 8.10)	(38.20, 8.01)	(45.71, 8.13)
build	$\theta = 4$	(44.27, 9.36)	(35.81, 8.14)	(40.86, 8.03)	(48.52, 8.13)
	$\theta = 6$	(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 6.5: Optimal investment strategies $(X_T^{**}(K_0,\theta), \Delta K^{**}(K_0,\theta))$ under different project 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: $A = 5, B = 1, c = 1, c_h = 0.5, \mu = 0.015, \sigma = 0.10, r = 0.06, FC_I = 80, \gamma_1 = 180, \gamma_2 = 19, \gamma_3 = 0, \gamma_4 = 0.12, s_G = 1, s_{CS} = 1, \lambda = 0.4$.

using the described methodology. This allows finding the optimal point in the trade-off between higher discounting and an increased customers' willingness to pay due to investment postponement, respectively decreasing and increasing the project value.

6.5.2 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 6.3-6.5 and is summarised as follows:[7]

Result 6.2. *Under the assumptions given in Table 6.2, it takes more time before a port with a higher current capacity becomes too highly occupied. Hence, it is possible in such a port 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 new port (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 investment, 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. This is in line with the finding of Chronopoulos et al. (2017), 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 addition to the positive effect of a later investment on the investment size, the capacity in place has a negative effect on the size of the port expansion project. This analysis indicates the importance of accounting for the amount of existing capacity in the investment analysis. This highlights the added value of this analysis, compared with Chen & Liu (2016).

[7] This result holds for projects with and without time to build.

6.6 Sensitivity analyses

In order to verify the impact of the type of port projects studied on some of the results derived in Chapters 3 and 4, this section contains some sensitivity analyses. Congestion costs, ownership structures, growth rates and the size of the uncertainty are altered, to verify the impact of these elements on port expansion investment decisions and to compare with the impact on the decision to invest in new ports. To this end, the base cases in Tables 6.3 - 6.5, are compared with the situations in which one additional parameter is altered. These altered parameters are respectively the monetary scale factor, the uncertainty and the growth rate.

6.6.1 Sensitivity of the results to congestion costs and waiting-time aversion

For the once-and-for-all greenfield projects in the previous chapters, a positive relationship between costs of congestion and investment size and timing has been found. Such port projects for customers or goods that are more time-sensitive, resulting in a higher user cost of congestion and hence a reduced willingness to pay for the same service level, are installed later. This is a reaction to the reduced project attractiveness due to this lower willingness to pay. Additionally, more capacity is installed to reduce occupancy rates and hence the more costly congestion.[8]

Oppositely, many expansion projects with a sufficiently high existing capacity and current throughput level 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 6.3. *Under the assumptions given in Table 6.2, 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 on average 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 soon enough to avoid fully occupied capacity and to dispose of sufficient free capacity in order to attract the shipping lines. Consequently, the timing decision of expanding an existing port such as the Port of Antwerp entails different incentives than the timing decision of the investment in a new port, like in Africa or Brazil.

[8] Here, phased investment is not considered. This leads to constructing a larger port at the moment of investment, which will be later. Oppositely, a first phase of a phased investment might be smaller and completed sooner, since a follow-up investment can take place later in order to expand the initial capacity (Chronopoulos et al., 2017). This reasoning is supported by the remainder of this section.

6.6.2 Sensitivity of the results to public ownership

If welfare is taken more into account in the 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 Chapters 4, 5 and 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.

However, as argued, disposing of additional port capacity becomes more urgent in the 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 6.4. *Under the assumptions given in Table 6.2, the timing of the expansion will be a lot sooner in the case of higher public money involvement. Because of the sooner timing's downward pressure on size, the net impact of increased public ownership on the investment size will on average be slightly 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.

6.6.3 Sensitivity of the results to 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 project lead time, the impact of increased uncertainty on timing can become negative. This finding is confirmed empirically by Marmer & Slade (2018) in the U.S. copper mining industry with considerable construction lead times. Since 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 6.3 - 6.5 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 chapter's model as well. The following small example

Table 6.6: 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:

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

with a substantially higher project lead time is used. In the base case from Table 6.3, expanding a private port with an existing capacity of 10 million TEU per year ($K_0 = 10$) and a project 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.

The findings from Chapter 3 with respect to negative growth rates are confirmed here. 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 demand decrease during the project lead time. Hence, if the economy is expected to decline, investment will only take place at a moment that demand is sufficiently large to make up for the declining future profits. The project would also be smaller compared with cases with positive economic growth, as the negative demand growth would lead to a declining demand and lower future occupancy rates. It is also apparent that an increase in time to build in the case of negative growth results in an increase in the project size. This is due to the sharp increase in the investment threshold in such a case. Additionally, with negative growth in the port sector, it might be preferred to use public money in other sectors in order to create more welfare.

Finally, the conclusions about the joint impact of an increase in uncertainty and a resulting decrease in the discount rate from Section 3.5 can be confirmed here as well, using Table 6.6. An increase in uncertainty followed by an interest rate decrease would lead to an even larger increase in the size of the expansion than in the case of neglecting this effect on the interest rate. Again, it can be observed that the impact on the timing of the investment is ambiguous and needs to be analysed for each specific investment case. To this end, the models from this thesis and next chapter's tool can support the PA's management.

6.7 Conclusion of this chapter

In this chapter, time to build and expansion of existing capacity have been added to 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 investing later on the size, next to the negative impact of a less attractive project. One general result has been derived: 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. As 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, larger waiting-time aversion of port customers leads to anticipating the port expansion decision, which will be of a slightly smaller size. This 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 chapter 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. It moreover increases the exposure to uncertainty. This may among other things lead to further postponing the investment decision. As a result, large projects encompass 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 profits, sooner investment and often slightly 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 models derived in this and the previous chapters allowed deriving new theoretical insights into the optimal investment decision in port infrastructure and superstructure under uncertainty. However, next to theoretical insights, port managers also need to be enabled to implement these models in practice. Moreover, they need to be aware of the potential benefits and costs of applying RO in practice. This is discussed in the next chapter.

Chapter 7

Moving from theoretical real options models to decision making in practice: required steps, opportunities and threats

The characteristics of the economic environment, the port type and the investment project type all have an influence on the optimal port capacity investment decision. The models developed in Chapters 3 to 6 allow deriving theoretical insights into this optimal decision. The theoretical directions of these influences provide useful information for port managers at the moment when the economic environment changes. For example, when demand starts to grow stronger, the results from Chapter 6 show the management of a single actor-port that they would be better off by delaying port expansion and investing in more capacity.

The question however remains: How can a specific port implement the developed models to derive its own optimal investment decision in reality? A second question that remains is: What are the potential gains and costs of implementing RO, compared with currently used decision making methods. In practice, the NPV approach is often used to evaluate port investment projects. However, as was already indicated in Chapter 2, this approach neglects the value of flexible options in irreversible projects and uncertainty, such as the option to delay investment. Even if uncertainty is low or absent, the NPV decision rule can be (very) wrong, because the irreversible investment decision is considered as a now-or-never decision (Dixit & Pindyck, 1994). In order to apply the RO models developed in this thesis in ports, two conditions need to be fulfilled. On the one hand, the port management needs to have the information at hand to derive and estimate the values of the model parameters. On the other hand, the user needs to be able to apply advanced econometric methods in order to calculate the optimal investment timing and size, possibly supported by external econometricians (Dikos, 2008). This latter condition is less straightforward, as Marmer & Slade (2018) illustrate. They use the model of Bar-Ilan & Strange (1996) with time to build and apply it to the U.S. copper mining industry using advanced econometrics on reduced forms of a set of theoretical equations.

In this chapter, the necessary input for the RO models is discussed, as well as a possible, basic programming approach to transform the model into an optimal real-life port investment decision. The required steps that are needed to move from the complex, theoretical models, described in this thesis, to a more applicable, user-friendly implementation are discussed. These steps are gathered in a blueprint for a practical tool that can help to come one step closer to the practical implementation of the developed models, since the complex calculations are left for the algorithm. Hence, this tool should be seen as a simplified approach to yield a first approximation of the optimal investment strategy for a port expansion project, based on the RO models developed in this thesis. This tool could also support transforming the port management's input into the model parameters. Nevertheless, the quality of the input, such as the complex estimates of economic characteristics such as demand growth and uncertainty, will always be important and are left for the human user. The entered parameters are then transferred to the RO model yielding an approximation of the optimal investment size and timing in terms of observable decision variables. It is however not the objective of this chapter to explore the large number of complex estimation techniques for the parameters. These are nonetheless required to accurately implement the RO models from this thesis. More advanced econometrics and further model extensions (e.g., including phased investment) will be crucial objects of further research to increase the realism and the applicability of RO investment analysis in ports. As for every model, also for this tool holds the wisdom: “Rubbish in, rubbish out". A subsequent discussion of the advantages and disadvantages of RO models allows quantifying the potential gains and determining the costs as compared with an NPV approach.

In this chapter, the specific model of Chapter 6 has been chosen as an illustration, because the majority of port capacity investment decisions are expansion decisions (De Langen et al., 2018) and involve considerable time to build. Moreover, ports can be owned privately or publicly. Both types are accounted for in this model. Although this model does not explicitly model port competition, it is still useful to gain insight into the unrestricted optimal investment decision of a single port and to illustrate the model implementation in practice. To take into account the competition of nearby ports, the insights and different strategies of Chapter 5 need to be considered afterwards. Subsequently the aggregate optimal investment decision (from a service port model) might have to be translated into the decision of multiple actors in a port. To this end, the approach of Chapter 4 can be followed. This requires insights into the revenue and cost structures of the port authority (PA) and the terminal operating company (TOC) in order to derive their shares (the α's of Chapter 4) in the total revenue and costs generated in the port. Moreover, Chapter 6's model is based on a number of assumptions that do not necessarily all hold in the cases that are to be studied in practice. In order to relax the most inappropriate assumptions, the RO models developed in this thesis need to be manually extended with the characteristics of the situation at hand. This can be based on Chapter 2's framework. Only after this manual extension, the new RO model can be calculated or programmed.

This chapter is structured as follows. The next section discusses the blueprint of the practical tool to implement a simplified version of the developed RO models for port managers to get a first idea about their optimal investment decision. Subsequently, Section 7.2 provides a reflection on the advantages and difficulties of using RO in a port context. These advantages are discussed and quantified for the scenario studied in this chapter. This chapter ends with a short conclusion and potential extensions of the tool, based on future research outcomes.

7.1 A real options tool blueprint for port capacity investment decisions

The next subsection provides an overview of the required inputs and how they can help to derive the parameters of Chapter 6's model. Section 7.1.2 illustrates how the tool should work, using a realistic application for an existing private port that focuses on the own unrestricted optimal investment decision. This model moreover accounts for time to build. In addition, it illustrates how a port's management could use the output of the tool to take an optimal port capacity expansion decision under demand uncertainty without neglecting the option value of waiting.

7.1.1 Input required to calculate real options model parameters

Some model parameters are relatively easy to obtain, as they can be based on information that is available for the management of the port, for example from their accounting. These include the marginal operational cost (c) and the holding cost to maintain the capacity in place ($c_h K_0$). Dividing the latter by the current design capacity (K_0) yields the capacity holding cost per TEU. Also the (expected) time to build (θ) can be anticipated by the port management, making abstraction of the construction lead time uncertainty. For the discount rate (r), the long term interest rate of state obligations is often used as a proxy for the risk-free rate of return (Dixit & Pindyck, 1994). If a government (partly) owns the port, they are expected to dispose of an estimation of the spillover benefits per TEU for the region (λ) (see e.g., Gueli et al. (2019)) and the share of total consumer surplus considered by this government (s_{CS}).[1] Finally, the relative number of shares held publicly (s_G) can be derived from the PA's ownership structure.

[1]The government could ask the National Bank or another external consultant to provide these values for them.

For a number of other parameters, more complex calculations with the provided data are required. In reality, they can be executed or supported by econometricians. For the tool however, they need to be simplified and carried out automatically in order to approximate the outcome of the complex RO analysis for a PA. This yields a first idea of their optimal investment decision. Subsequent and more detailed calculations can be performed by external consultants and econometricians.

In order to approximate the demand growth rate (μ) and uncertainty (σ) in a specific port in a specific period, the regression analysis approach of Chapter 3 could be used. The growth can be estimated using the exponential model

$$\ln(TEU_t) = \alpha + \mu t + \varepsilon_t, \tag{7.1}$$

with TEU_t a port's throughput at time t, while the root-mean-square error (RMSE) of the regression can be used as a proxy for σ. This analysis can be based on a time series of the port's throughput, which is widely available for port managers (Vlaamse Havencommissie, 2016). An important condition however is that the supply of capacity is constant, to eliminate this impact on the realisations of the demand curve. Moreover, an alternative approach could be using a time series of p, the prices paid in the port by the shipping companies to have their goods handled.

An important drawback of the regression analysis to estimate the growth rate and uncertainty, is that historical data are used. In periods where structural breaks take place and where the uncertainty and the growth rate are expected to change, more forward-looking estimation techniques may be preferred. Examples of such techniques include qualitative methods on the one hand, such as expert interviews, the Delphi method and surveying the market. Quantitative examples on the other hand include forecasting demand, based on regression analysis involving other forecasted variables, such as GDP, and use this demand forecast to estimate the uncertainty and the growth rate.

The investment cost function needs to be determined as well. More specifically, the fixed cost FC to carry out preliminary studies and to transport machinery to the construction site determines the intercept of the investment cost function. The shape and height of the function can be determined through information about a number of investment projects of different sizes. To this end, a trend line of the most appropriate shape needs to be fitted to the situation at hand. Next to the fixed investment cost, the investment costs of port projects need to reflect three characteristics. The cost is increasing and exhibits economies of scale. Finally, there is a boundary beyond which further expansion becomes very costly, since expropriation is needed to enlarge the port perimeter. In this thesis, a situation with a fourth-order polynomial has been assumed, using the following specification:

$$I(\Delta K) = FC + \gamma_1 \Delta K - \gamma_2 \Delta K^2 + \gamma_4 \Delta K^4 + \varepsilon. \tag{7.2}$$

However, if there are not sufficient data of projects of different sizes, it might be needed to assume additional data points to estimate a fourth-order polynomial. The first data point required is the fixed cost (i.e., the cost of a project of 0 TEU). Two additional data points are the cost of the smallest and the largest project considered. In order to account for larger projects being infeasible due to size restrictions, two fictional, additional points with more than linear cost increases can be assumed and added to the dataset. Also a fictional project of half the size of the smallest project, with a cost higher than $[I(\min\{\Delta K\}) - FC]/2$, needs to be added to account for economies of scale in the investment cost over the first part of the domain of the investment cost function. Nevertheless, it is noteworthy that if another functional shape for $I(\Delta K)$ better fitted the data, replacing it in the calculations would not impact the technicality of the calculations, as long as the function is differentiable with respect to ΔK.

The final parameter that needs to be set, is the monetary scale factor of the congestion cost, A, in order to translate delays into user costs. These costs depend on the port users' average value of time and reduce their willingness to pay for port services. For the developed tool, this can also be estimated using regression analysis. The formula needed, is derived as follows under the simplifying assumption of a normalised slope of the inverse demand curve ($B = 1$) and the assumptions in Table 6.2:

$$
\begin{aligned}
p &= X - q - \frac{AXq}{K_{tot}^2} \\
&\Updownarrow \quad (X = \rho + q) \\
p &= \rho + q - q - \frac{A(\rho + q)q}{K_{tot}^2} \\
&\Updownarrow \\
\frac{A(\rho + q)q}{K_{tot}^2} &= \rho - p \\
&\Updownarrow \\
A &= \frac{(\rho - p)K_{tot}^2}{(\rho + q)q}, \qquad (7.3)
\end{aligned}
$$

with p the price corresponding to an optimal throughput level q, K_{tot} the total design capacity of the considered port and ρ the price that the port could ask at the same throughput level if there were no impact of congestion. By retrieving this information from a market analysis or survey for different throughput levels (e.g., the current level, a level slightly lower, a level slightly higher than current throughput and a level close to full occupancy), A can be fitted using OLS on the following formula:

$$\frac{(\rho - p)K^2}{(\rho + q)q} = A + \varepsilon. \qquad (7.4)$$

It is here that the impact of competition is partly accounted for in the calculations. When less competition is present, port users have fewer alternatives. By consequence, their willingness to pay will be reduced less due to congestion and delays in the considered port.

Hence, the actual port price will deviate less from the price without congestion. This results in a smaller value for A in a less competitive market, even when the average aversion to waiting of the port's customers is similar.

A summary of the required inputs is given in the third column of Table 7.1. Moreover, this table shows in its second column the questions that can be used in the computer tool or application to gather the data. The final column shows the calculations required to derive the model parameters. This is discussed in the next section, together with how these calculations can be used to approach a first estimate of a specific port's optimal investment decision in terms of observable decision variables.

7.1.2 An application of the investment decision tool

In order to transform the input into an optimal investment decision, an algorithm based on three steps is proposed. The first step will collect the input and transform it into the parameters that are required for the RO model, as described above. This information is passed on to the second step where the optimal investment decision is calculated. In the third step, the calculations are outputted as relevant decision variables. In this section, the three steps with their different sub-modules are described and applied using an example of a private container port. As no complete real-life data set of one port could be obtained, some realistic assumptions have been made in the previous chapters, based on the limited amount of data that is available. These are retained here. In the considered hypothetical example, the considered private port's current annual container throughput capacity is assumed to be 9 million TEU per year. The port moreover considers investing in an expansion of 8 to 10 million TEU p.a.

The first step of the algorithm needs to collect the input from the port authority and transform it into the parameters of the RO model where necessary. First of all, the existing theoretical (design) capacity of the port K_0 at the time of using the algorithm needs to be entered into the program, together with the current price p (assumed on average 14 euro per TEU, including port dues and terminal handling charges) and annual throughput q (assumed 5.5 million TEU p.a.). The parameters c (1 euro per TEU), $c_h K_0/K_0$ ($4.5/9 = 0.5$ euro per TEU), θ (5 years), r (6%), λ, s_G and s_{CS} can be derived directly from the input by the algorithm.[2] The derivation of these parameters has been explained in Chapters 3, 4 and 6. Subsequently, a regression module can extract the parameters μ and σ from the time series of a port's container throughput, as in the example in Table 7.1. In the previous chapters, a μ of 0.015 and a σ of 0.1 have been obtained. Alternatively, the user could enter the growth and uncertainty values that result from a more forward-looking estimation method.

[2]The latter three are disregarded in this specific example due to the application to a private port maximising profit.

Table 7.1: Step 1 of the algorithm: input.

Line	*Question*	Input	Derived parameters
1)	*Current annual throughput?*	5.5 M TEU per year	$\rightarrow q$
	Current capacity?	9 M TEU per year	$\rightarrow K_0$
	Current price per TEU?	14 euro per TEU	$\rightarrow p$
2)	*Current operational cost per TEU?*	1 euro per TEU	$\rightarrow c$
3)	*Current annual cost to maintain the capacity?*	4.5 M euro per year	$\rightarrow c_h (= 4.5/K = 0.5)$
4)	*Expected time to build the project?*	5 years	$\rightarrow \theta$
5)	*Discount factor to be used?*	6%	$\rightarrow r$
6)	*Public ownership? Yes / No?*	NO	
	$\hookrightarrow$ If Yes:		
	Relative number of government owned shares?	0%	$\rightarrow s_G$
	Spillover benefits per TEU?	0.4 euro per TEU	$\rightarrow \lambda$
	Share of total consumer surplus considered?	0%	$\rightarrow s_{CS}$
7)	*Throughput of the port over the last years? (Table)*	***Year t*** | **Throughput *q* (M TEU)** *2009* | 5 ⋮ | ⋮ *2015* | 5.5	$\overset{OLS}{\rightarrow} \ln(TEU_t) = \alpha + \textcircled{\mu}\, t + \varepsilon$ $\hookrightarrow \mu (= 0.01)$ $\hookrightarrow RMSE = \sigma (= 0.1)$
8)	*Investment costs? (Table)*	***Size ΔK (M TEU p.a.)*** | **Investment Cost *I* (M euro)** *Fixed cost? → 0* | 50 *Smallest project? → 8* | 800 *Largest project? → 10* | 1200 *Additional data points generated:* *4* | 500 *11* | 1500 *12* | 2000	$\overset{OLS}{\rightarrow} I = FC + \gamma_1 \Delta K - \gamma_2 \Delta K^2 + \gamma_4 \Delta K^4 + \varepsilon$ $\hookrightarrow FC = 50.2; \gamma_1 = 174;$ $\gamma_2 = -17.2; \gamma_4 = 0.113$
9)	*Cost of congestion? (Table)*	***Annual Throughput q (M TEU per year)*** | **price *p* (euro)** | **price *ρ* w/o congestion (euro)** *5.5 (current)* | 14 | 21 *5* | 12 | 17 *6* | 17 | 27 *7.5* | 32 | 57	$\overset{OLS}{\rightarrow} \frac{(\rho - p) K_{tot}^2}{(\rho + q) q} = A + \varepsilon$ $\hookrightarrow A = 4$

Another regression module is required to approximate the parameters of the investment cost as a function of the new capacity that is to be installed. First, the user of the algorithm needs to specify the fixed cost of the investment, which is 50 million euro in the example. Next, the port management needs to determine the range of capacity expansion sizes considered and provide the cost of the smallest and largest project considered. In the example, a project with an annual capacity of 8 million TEU is expected to cost 800 million euro, whereas a project with a capacity of 10 million TEU per year is expected to cost 1.2 billion euro. If available, the port can also specify the cost of intermediate project sizes.

With this information at hand, the algorithm can add three more points to the dataset for the regression of the fourth-order polynomial. The first point is an additional point in the middle between size zero and the smallest project size considered. The cost to be added, is some upward rounded linear extrapolation between the fixed cost of expansion and the cost of the smallest project. For a project with a capacity of 4 million TEU per year, a cost of 500 million euro is added to the dataset, which is (800+50)/2 rounded to the higher hundredfold of million euro, to be able to model the economies of scale for the first part of the investment cost function's domain. The next two points to be added need to account for the boundary beyond which further expansion is very costly. These are costs of two fictional projects that are larger than the largest project considered by the port. In the example, these are projects with a capacity of 11 and 12 million TEU per year. The price increase compared with the project with a capacity of 10 million TEU per year needs to be larger than the increment from the second largest project to the largest project considered.[3] That increment was 200 million euro per million TEU per year. Hence the algorithm adds 300 million euro to the cost of a project with a capacity of 10 million TEU per year to yield the fictional cost of a project with a capacity of 11 million TEU per year, i.c., 1.5 billion euro. For the cost of a project with a capacity of 12 million TEU per year, a more than proportionally increased increment is added again, i.e., 500 million euro per million TEU per year, yielding 2 billion euro. Using this dataset, the OLS estimation of Equation (7.2) yields the coefficients $FC = 50.2$, $\gamma_1 = 174$, $\gamma_2 = -17.2$ and $\gamma_4 = 0.113$. The third-order term is omitted (see Chapter 3).

A final module is required in the first step to determine the value for parameter A, which is the most difficult one to estimate. The user of the algorithm already entered the port's current capacity, throughput and price. Only the price that could have been asked under the absence of congestion still needs to be added to the first observation to estimate A more accurately. For the example, it is assumed to be 7 euro per TEU more than the current price, yielding a ρ of 21 euro per TEU. For a smaller (5 million TEU per year), and a larger annual throughput level (6 million TEU per year), the user of the program needs to provide the same information. If the port is able to provide this information for other throughput levels, it is possible to add more lines to the dataset to estimate A. In the example in Table 7.1 (line 9), information for an annual throughput of 7.5 million TEU per year is also added.

[3]i.e., from the 8 to the 10 million TEU project.

This final observation provides very useful information about the congestion costs, as it involves a high occupancy rate.

All modules and inputs of the program's first step are summarised in Table 7.1. The output of step 1 is the set of derived parameters in the final column. This set can be passed on to step 2, the actual RO model calculations as described in Chapter 6. The outcome of this step is an optimal investment decision $(X_T^{**}(K_0,\theta), \Delta K^{**}(K_0,\theta))$. Using the input parameters as described in this section, the outcome would be (38.42 euro per TEU, 9.47 M TEU p.a.). Some additional calculations in a third step are however still needed to translate this outcome into meaningful decision variables for the PA's management.

First, it would be interesting for PA managers to dispose of the occupancy rate at which it is optimal to invest, given that the optimal price is charged at any moment in time. As discussed in the previous chapters, the optimal throughput of a profit-maximising port as a function of X and K_{tot}, $q^{opt}(X, K_{tot})$, can be obtained from the first-order condition for the port profit. Inputting the optimal investment threshold for X returned by the RO calculations and the capacity of the port before expansion (i.e., 9 million TEU per year) in this expression for $q^{opt}(X_T^{**}$, 9 M TEU p.a.) yields an optimal throughput level of 6.46 million TEU per year at the moment of investment. Divided by a capacity of 9 million TEU per year, it is found that investment optimally takes place at an occupancy rate of 72%. The optimal annual capacity of the expansion is 9.47 million TEU per year. After expansion, the optimal annual throughput would equal q^{opt}(38.42 euro per TEU, 18.47 M TEU p.a.) = 12.89 million TEU per year, corresponding to an occupancy rate of 69% of the new total capacity of 18.47 million TEU per year. This observation illustrates that new capacity is expected to attract additional throughput, as congestion and occupancy rates will fall. The optimal price can be lowered as well, while profit will be higher. (Zhang, 2007; Wan et al., 2013).

Another interesting output that the algorithm could present, is the time that will pass before the entire new capacity is expected to be fully utilised. According to Wilmott et al. (1993, p. 371), the following finite expected time can be calculated for a current X_0 to reach X_B, when X follows a GBM with parameters μ and σ and under the condition that $\mu > \sigma^2/2$:

$$t(X_0 \to X_B) = \frac{1}{\mu - \sigma^2/2} \ln(X_B/X_0). \tag{7.5}$$

Given that q^{opt}(66.93 euro per TEU, 18.47 M TEU p.a.) = 18.47 million TEU per year corresponds to full occupancy, the time for X to move from the investment threshold 38.42 euro per year to 66.93 euro per year can be calculated as 113 years. This implies that the utilisation of the total capacity after expansion is expected to remain below 100% for 113 years in the discussed private service port scenario, also due to the possibility to increase prices when demand and congestion increase.

The blueprint of the developed tool is summarised in Figure 7.1. The use of the tool applies to a situation where the port management wants to calculate the optimal time to

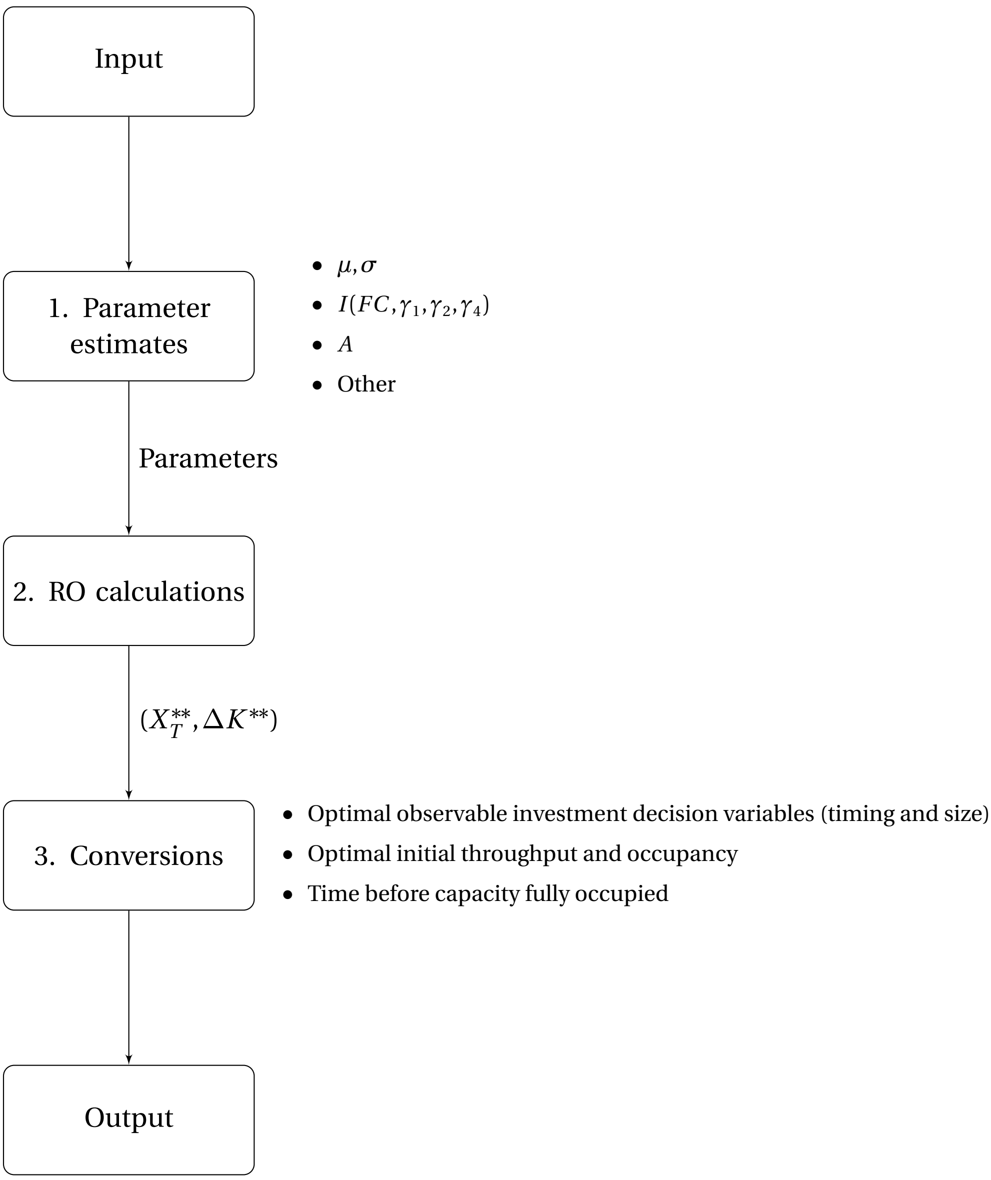


Figure 7.1: Summary of the RO tool blueprint.

exercise the option to invest and at the same time calculate the optimal size of this investment. If the size of the expansion is fixed ex-ante, a few algorithm adaptations are required. An estimation of the investment cost function I is no longer needed and can be replaced by the exact cost of the considered expansion project. As a result, the inner maximisation of the option value maximisation in Section 6.3, equating the marginal value and cost of adding capacity, is omitted. This only leaves the outer maximisation with respect to the investment timing. The outcome, $X_T^*(K_0, \Delta K, \theta)$, can subsequently be transformed into relevant and observable decision variables for the port management in a similar way as described above. On the contrary, when the port management deems it necessary to invest right away in additional capacity, no maximisation of the option value of waiting is needed. Only the equation of marginal value and cost of adding capacity remains to determine the optimal investment size.

7.2 A critical discussion of the advantages and challenges of real options for port capacity investment decisions

Many practitioners consider the RO methodology to be a complex methodology. Calculating the RO investment option is much more difficult than calculating NPV. However, next to additional costs of this approach, there are also considerable potential gains. The critical discussion in this section is hence made up of two parts. First, the potential gains from applying RO to the investment in new port capacity are quantified for the situation elaborated in the previous section. Afterwards, the differences between RO models and traditional NPV methods are discussed and related to the additional difficulties and costs of RO models.

7.2.1 Potential gains of using real options

In order to quantify the potential gains from applying RO, the expected difference in present value between the optimal RO decision and the worst decision that would be accepted by NPV is calculated. In Figure 3.11, it was already made clear that the NPV rule would lead to installing any project with a value V exceeding the investment cost I. Hence, the worst NPV decision possible would be expanding the port at a moment and of a size leading to a net value $V - I$ of 0 euro. However, the NPV approach does not involve optimisation of the timing or the size of the expansion. These decisions are predetermined, in an inflexible approach. Hence, two extreme scenario's exit. In reality, any situation between these two extrema is possible.

A first scenario would involve the port management applying the NPV rule at the moment that would be optimal from the RO perspective as well, i.c., when the reservation price X would equal 38.42 euro per TEU. In such a case, the port expansion project size could range between 0.3 and 14.31 million TEU per year to yield a positive net project value. The maximum net present value of the project is found by applying the RO rule. Installing 9.47 million TEU per year at this particular moment would yield a net present value of 1.714 billion euro. However, if 0.3 or 14.31 million TEU per year were installed, the net present value would equal zero. Hence, in the worst case, taking a decision supported by NPV could result in a net present value that is 1.714 billion euro less than what could have been achieved with RO. In the best case, the difference with RO is zero euro.

Second, a similar logic can be derived for the scenario where the size of the investment has been determined ex-ante. For instance, the port could be considering expanding the port infrastructure and superstructure with a capacity of 9.47 million TEU per year, which would be optimal under an RO decision rule. In such a case, if the NPV rule were applied at a moment that the reservation price X would equal 25.53 euro per TEU, the net present value of the expansion would again equal zero euro. However, compared with the optimal investment threshold $X_T^{**} = 38.42$ euro per TEU of the RO rule, a net present value of 397 million euro would be lost. This is calculated as $(25.53/38.42)^{\beta_1}(V - I)$. Only if the NPV rule was applied at the moment that the reservation price equals the optimum from an RO perspective, no loss would be encountered, compared with RO.

In conclusion, for the scenario discussed in this chapter, the potential present value gained from applying RO, compared with NPV, lies between zero and 1.714 billion euro. The actual foregone value resulting from applying the NPV rule however depends on the specific scenarios that are considered and analysed under this NPV analysis, as NPV analyses only consider a limited number of distinct scenarios with specific investments sizes and timings. In case the scenario with the optimal RO decision is included in the NPV analysis, it will result in the same present value as the RO analysis. Alternatively, some present value ranging from zero to 1.714 billion euro is foregone, depending on the specific investment sizes and timings considered in the analysed scenarios.

7.2.2 Additional complexities and costs of using real options

A number of RO model elements described in this thesis are not needed exclusively for RO analyses. For an NPV analysis, the costs of congestion are also needed. However, they can be specified more accurately under NPV, using the expected delay *times* the value of time of the goods *times* the throughput quantity. Since no optimisations are needed, the complexity of the functional expression is not bounded by potential complications of further calculations. This improves the realism and accuracy of the point estimates of expected congestion costs of the port expansion project in an NPV approach. Providing an accurate estimate of A in an RO approach may prove difficult and may involve hiring external econometricians at a high cost. Similarly, estimates about the other costs, such as operational and capacity holding costs, are needed under both approaches as well. These costs are less complicated to calculate, as they can be derived from the PA's accounting by the internal accountants.

In order to be able to estimate future revenues from port activities, an estimated relationship between prices and throughput quantities will also be needed for an NPV approach. This involves estimating the most realistic shape for the demand function, and the correct parameters, e.g., for the slope, influencing price elasticities. However, because no optimisations are made under NPV, this relationship between prices and quantities is only needed over a small part of the domain of the demand function. Often, the revenues are estimated directly as the product of the expected price and throughput, which are based on a number of assumptions, but without making use of an explicit demand function. In order to accurately estimate the demand function, the PA could again rely on costly, external econometricians.

To model uncertainty in an RO approach, dynamics need to be added to the model. This is what discerns RO models the most from NPV models. In the models developed in this thesis, cost functions are assumed fixed over time. Oppositely, the demand function has been chosen to evolve over time, following an uncertain pattern. Based on the literature, the assumption has been made that this pattern can be modelled using a GBM with individual parameters for growth and uncertainty. In practice however, it is on the one hand necessary to check whether the GBM is appropriate for the studied scenario. This is complex and costly and often involves external knowledge from econometricians. On the other hand, when the GBM has been proven to hold, it is even more complex to accurately estimate the parameter values for the growth and uncertainty. Also this involves advanced econometrics or insights from costly experts. If however, the GBM hypothesis is falsified in practice, the RO model needs to be adapted as well. Also this is often too complex for the staff of the PA. As a result, the costs of hiring external experts such as scholars and econometricians will be even higher in such a case. In addition, because the growth and uncertainty parameters in the RO model are assumed fixed over time, it is necessary to re-evaluate the model if the market changes significantly before the start of the construction of the port expansion.

Another element that discerns RO models from the NPV approach is the use of an investment cost function. Whereas NPV is often used to evaluate at most a few alternative scenarios of different sizes, potentially in a binomial tree approach, continuous-time continuous-state RO models involve an optimisation of the investment size. For NPV, it is sufficient to dispose of the cost of these individual projects. For RO, a continuous function needs to be elaborated, with a correctly specified absolute value and first-order derivative to allow for an accurate optimisation. Moreover, a boundary beyond which further expansion is impossible needs to be accounted for as well. Estimating this investment cost specification in practice is time intensive and hence costly, since information and costs of more project sizes need to be collected. However, the benefit of being able to optimise the investment size over a continuum of potential port expansion projects can be very high, as was discussed in Section 7.2.1.

Finally, RO models include and attribute value to the options of flexibility on a project (i.e., a flexible investment decision) and in a project (i.e., the option to flexibly adapt operations) (T. Wang & De Neufville, 2005). In this thesis, the focus has been on options on a project. However, in practice, port expansion projects also involve options in the project. For example, the option to deploy the terminal at the new dock in phases can be considered an option in the project. Without necessarily evaluating the net present value of this approach, the port of Rotterdam successfully uses this phased investment option for the development of Maasvlakte 2. The new docks are constructed using the technique of rainbowing sand. Initially, after constructing the first dock, the terminal has only been developed partly. Paving and cranes are only installed on the area closest to the entry of the dock. The remainder can be financed and developed later, when the demand for extra capacity is expected to become present. Such an option of phased investment reduces the lumpy character of port capacity investment decisions. In this way, value can be generated (and calculated), as the time between income and expenses can be reduced. However, accounting for such options is complex and costly, as they need to be embedded in the project on the one hand, and they need to be included in the RO model calculations on the other hand. The latter implies a further complication of the model, but can be based on the RO framework from Chapter 2. At the same time, it involves an interesting approach for further research.

7.3 Conclusion of this chapter

In order to transfer the theoretical insights from the previous chapters to practical calculations for a port's optimal investment decision, this chapter has presented the description of a possible algorithm to simplify the calculations of the optimal investment decision in terms of observable decision variables. This is considered an important step to give complex RO modelling a place in practical decision making. To this end, the port management's input is transformed into RO model parameters, which are subsequently used for the RO calculations. Subsequently, the output of the RO model needs to be transformed into observable decision variables for the port management.

Using an RO approach to find the optimal investment decision potentially implies gaining a lot of money, compared with applying NPV. Depending on the scenarios and specific projects considered, these gains can largely outweigh the costs of hiring external scholars, consultants or econometricians. They could provide the necessary knowledge to further adapt the developed RO models and to estimate the parameters of the RO models. In this way, this external staff can further fine-tune the first approximation of the optimal investment decision returned by the developed tool.

However, the RO calculations are impacted by the assumptions of the RO model. One of the most challenging aspects is estimating the correct shape of the demand function, which is assumed linear additive in this thesis. In case a linear additive curve is realistic, the external econometricians will need to empirically estimate the slope of the inverse demand curve. However, if a linear additive demand curve is not suitable and sufficiently realistic to make real-life calculations, adaptations to the RO model will be needed as well. They can be based on the RO framework from Chapter 2. It is especially important that the right elasticities of demand are included for the range of considered capacities and throughput levels. Next to the demand function, also correct representations of the specific port's congestion costs and investment costs need to be included in the model and verified by the hired staff. A similar reasoning holds for the process to model demand uncertainty, i.c., the GBM with a growth and uncertainty parameter.

Chapter 8

Conclusions, implications and future research

The conclusion of this thesis is split into three sections, each relating to a type of additions to the existing state-of-the-art in port capacity investment decisions. First, new theoretical insights from this thesis are brought together in Section 8.1. This section relates the derived theoretical knowledge and the developed models back to research sub-questions RQ 2.1 to 6.2, the theoretical part of the main research question. Subsequently, the practical implications and limitations of the methodology developed in this thesis for real-life port capacity investments are discussed in Section 8.2. These are based on the answers to research sub-questions RQ 7.1 and 7.2 from Table 1.3. Avenues for future theoretical and empirical research are discussed in Section 8.3. This further research can augment the applicability and accuracy of the RO models even more in practice.

8.1 Theoretical findings and results

Ports are crucial for an economy as a whole and for the logistics sector. They facilitate economic growth and regional development, as well as trade. Investing in ports is indispensable to provide sufficient capacity to handle the goods. This thesis focuses on the irreversible capacity investment in lumpy port infrastructure and superstructure for container throughput. Because of the uncertainty present in the port, which originates from many different sources, RO models have been identified as an accurate methodology to decide about these investments. Useful characteristics of continuous-time continuous-state RO models with demand uncertainty have been described. Already available port investment models show the importance of considering congestion costs for the users of the port capacity, i.e., the shipping lines, in the analysis. The combination of both types of models resulted in a framework that allows building new RO models and judging the applicability of already developed RO models in a port setting.

In order to uncover the impact of project- and port-related economic characteristics on port capacity investment decisions, new RO models have been developed in this thesis. The models of Chapters 3-5 deal with the construction of new ports. These models stand out among other models in the literature, as they introduce congestion costs more accurately in port investment models considering demand uncertainty. Moreover, the different decisions of the port authority (PA) and the terminal operating company (TOC) and inter-port competition have explicitly been taken into account. Next to that, in Chapter 6, new insights into port expansion investments with time to build have been derived.

A crucial new finding of this thesis deals with the impact of waiting-time aversion of port users on the investment decision in a new port. The larger the delay costs for the port's customers, the later the optimal investment timing and the larger the optimal investment size. This finding has been confirmed in different models for new ports. Moreover, a frequently observed RO finding has been proven to hold in different port settings as well. When deciding about the investment in a new port, the higher the demand uncertainty, the more design capacity will be installed and the later the timing.

Moreover, it can be concluded that competition between two new ports drives investment threshold and capacity of the leader down, whereas the follower will invest later in more capacity. The reason is that competition has a negative impact on each port's option value of waiting. This impact of competition is however reduced by investment cost differences between the cost-advantaged port, who invests first, and the follower port. In a model ignoring time to build and phased investment within a landlord port, the investments of the PA and the TOC need to be geared to the same capacity and installed at the same time. This capacity and timing can be the optimum of a similar service port, which is reached in a landlord port after both actors mutually give in from their individual investment optimum. Alternatively, the PA can use its concession fee policy to force the TOC to invest in the first actor's optimum. Additionally, it has been found that ports with a larger share owned publicly invest earlier and in more capacity. This observation is uncommon in RO, where earlier (later) timing often goes hand in hand with less (more) capacity. The reason is that the profits and positive economic effects are needed soon enough, so that the growth of a region is not slowed down. To this end, a good port investment policy should facilitate sufficient capacity provision in order to avoid shortages slowing down economic growth.

In port expansion investment decisions subject to time to build, the impact of the aforementioned factors is slightly different. If congestion involves larger costs for the port users, the PA experiences a larger incentive to anticipate the expansion investment in order to avoid such costly congestion in the current operations. As a result, the optimal expansion timing will be earlier than in a case with lower congestion costs. The impact on the size of the investment is however limited. The same conclusion holds for the impact of increased public ownership, which in some cases could be crucial to beneficially invest in the port project and realise its full potential. The incentive to overcome current capacity shortages slowing down economic growth is even larger than in the case of a new port. As a result, public ownership anticipates the investment decision a lot, compared with a privately owned port. This has a reducing impact on the size of the investment. The impact of the amount of demand uncertainty remains the same in expansion projects, if time to build is neglected. However, time to build can alter the impact of uncertainty. With a lot of time to build and high uncertainty, a further increase in uncertainty may lead to an anticipation of the optimal investment, instead of postponing the investment. The installed capacity will however still be larger. The direct impact of time to build on the investment is more ambiguous. Since time to build reduces the attractiveness of a project, investment will take place later or will be smaller.

8.2 Practical implications and limitations

The previous theoretical conclusions relate to the answers to research sub-questions RQ 2.1 to 6.2 and explicate the impact of changes in the economic environment on the optimal timing and size of the capacity investment. These theoretical insights can prove useful for policy makers to create optimal circumstances for beneficial port investments. However, these results also have implications for port investment decision makers implementing these insights. These are defined in the answers to research sub-questions RQ 7.1 and 7.2. Only by combining all these answers, the main research question of this thesis can be solved and the full added value of this thesis becomes apparent.

Although in practice many port capacity investment decisions are based on the net present value (NPV) rule, this thesis confirms the statements of Dixit & Pindyck (1994). They argued already more than 20 years ago that NPV could lead to very wrong decisions when irreversible, large-scale investment decisions are studied under uncertainty. The reason is that NPV considers such an investment as a now or never investment. The findings of this thesis confirm that the flexibilities of investment size, investment timing and throughput level add value to the project. If more information and more options can be used, this leads to better decision making.

Nevertheless, these options explicitly need to be evaluated in the investment decision to optimise the project's value and take an optimal investment decision, even if uncertainty is low. Information about the uncertainty and the resulting distributions of the port's cash flows need to be incorporated in the investment decision as well. This allows determining the size of the required investment postponement wedge, protecting the port sufficiently from the negative impact of demand uncertainty. To this end, a blueprint of a tool to implement the RO model in real-life port capacity investment decisions has been proposed. This tool allows port managers in practice to approach the optimal timing and size of a real project in terms of observable decision variables, based on a number of collectable inputs and simplified calculations. This highlights the practical added value of this thesis, which is also quantified and compared to the costs of applying RO.

As the results in this thesis unveiled, the RO decision rule leads to a later investment than the NPV rule. At this later moment of investment, higher profits can be generated. If the market then experiences negative growth over a period, sufficient reserves can make up for reduced profits. Through such a protecting wedge, the project remains profitable even if the realised profit is less than the expected value. The net gains from implementing RO can become very large, depending on the specific project. Nevertheless, estimating the exact shape and the parameters of the uncertain demand function, the congestion costs or the investment cost function for RO models might involve high costs for the port management, especially if external econometricians are to be hired. This is the first of two major RO model limitations. Second, the rather theoretical RO models will always involve some simplifications of reality, as they are based on a relatively large set of assumptions. Relaxing these assumptions or considering additional options involves adapting the RO model. Such a complex task is also very costly and may require additional research.

The question is then to be posed if the advantages of RO outweigh the costs, especially compared to the costs and benefits of the NPV approach. The latter approach involves less econometric estimations of functions. In order to calculate NPV, the expected values of the different cash flows, including their expected growth, are the most important input. Using scenario analysis, the sensitivity of a specific project's profitability to economic growth or decline can be calculated too. However, the NPV rule does not enable decision makers to benefit from the project's built-in flexibilities. Using NPV, only one project can be evaluated at a time. Hence, it is impossible to determine the optimal investment size and timing using NPV. It would be too time consuming and hence practically infeasible to calculate the NPV of all investment sizes and timings of the capacity project under consideration and then invest in the most profitable option. As a result, a lot of money could be lost by installing a wedge against uncertainty that is profitable according to NPV, but that is too large or too small according to RO. By consequence, deciding on the investment through RO allows port managers to take the most beneficial decision and find an optimal point in the trade-off between costly over- and undercapacity. The high potential gains in many cases can make up for the additional costs and complexities of RO models.

Since previously developed RO models were not able to accurately account for port-specific characteristics, such as congestion costs, developing the port models in this thesis has been an important step towards the implementation of RO in real-life port capacity investment projects. Although RO models are theoretical in nature and based on a large number of assumptions, making them as realistic as possible is required to make those models applicable to real-life situations and improve port investment decision making. Even though the future is uncertain, well-developed RO models allow making the best ex-ante decision possible while taking into account the embedded project flexibility and the information available at that moment of decision. A simple analogy allows clarifying this point. Suppose there are two decision options when drunk after a party: drive yourself or call a taxi. The uncertainty is situated in the probability of having an accident. RO allows evaluating all options at once and taking the decision that is ex-ante perceived as the best. This would be to call a taxi. Even if this taxi then got involved in an accident while you were in it and you got injured, this would still have been the best decision.

8.3 Suggestions for future port-related real options research

The RO models developed in this thesis explicate the impact of economic, port and project characteristics on optimal port capacity investment decisions under uncertainty. Moreover, the added value of real options for investment decision makers has been made explicit, in addition to a potential, simplified application. Nevertheless, some limitations to the practical implications have been identified. Overcoming these limitations while further improving model realism and applicability gives rise to some future port-related RO research.

Considering the decision of one port operator (the TOC or the PA), opens up some viable ways for future research. First of all, asymmetrical information between parties may exist, or some parties might not dispose of perfect information (Delaney, 2019). This has not been included in this thesis. The impact of a relaxation of this assumption would be an interesting topic of a new analysis. Moreover, to model the difference in bargaining power of actors, Schneider et al. (2010) propose among other things a Nash bargaining game. In cases where a winner-take-all approach is not appropriate, this could be an interesting approach to define the concession fees optimising the actors' discounted project values in a specific situation. Subsequently, the impact of intra-port competition following the presence of multiple competing operators in a non-cooperative setting, as well as the impact of the actual or potential vertical integration between TOCs and other logistics chain actors, such as shipping lines or hinterland companies, would be interesting to analyse (De Borger & De Bruyne, 2011; Huisman & Kort, 2015).

In the analysis of inter-port competition, the fixed investment cost provided the basis for the cost advantage of the leader port. However, studying a different capacity holding cost per port could be an interesting approach to analyse the impact of different public private partnerships (PPP) on the different costs and the final investment decision in competing ports. Also other differences between the two ports are relevant, such as different objectives and ownership shares. Future research might prove whether the port with a higher public ownership share would indeed invest earlier in more capacity than a competitor with a lower public ownership share. The reason is that the project would be more attractive for the former because of social welfare being considered to a larger extent.

Moreover, port investment decisions are influenced by the government's port development doctrine. Where the duopoly model accounts for the properties of the Anglo-Saxon and European (Continental) doctrines with individual ports, respectively private and at least partly public ports, the results may well be different under the Asian doctrine (see e.g., Bennathan & Waters (1979) and Lee & Flynn (2011)). Considering the centrally planned development of multiple ports and potential cross-subsidisation may alter the findings. Hence, this would be an interesting extension of the results found in this thesis, for example to allow for comparison with Chen et al. (2017).

In this thesis, the time to build has been assumed to be known ex-ante. It could be interesting to study the impact of uncertain time to build on the timing and the size of the investment decision. For this, 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 the Chi-squared distribution could be used. Moreover, the expected value of the time to build could also be related to the size of the investment.

From an empirical viewpoint, well-developed models allow econometricians to calculate the parameters empirically and make better real-life port investment decisions, using the models at hand. However for specific applications, implementing more accurate functional representations of demand and cost functions would be a beneficial step to increase the applicability of the RO approach. This would limit some of the simplifying assumptions underlying the developed models.

Additionally, the developed models need further extensions to improve their realism and applicability to a port setting. An important extension would be incorporating the option of phased investment, e.g., starting from the port expansion model of Chapter 6. In that case, the dock or the terminal is not to be installed at once, as is assumed in the developed models of this thesis. Section 2.4.4 already discussed the modelling approach of phased investment, which is slightly different from the approach used in this thesis. Considering phased investment in future research would be beneficial, since previous research already demonstrated the significant value of this option. Stepwise investment increases the project value and the amount of capacity installed if final capacity is flexible. Moreover, the first investment often takes place earlier (Chronopoulos et al., 2017; Kort et al., 2010). However, what remains unclear is the interaction between this phased investment option and the impact of congestion costs on the investment decision(s).

Once this model is developed, the insights and other model characteristics from this thesis can be added to this phased capacity expansion model including uncertainty, congestion costs and time to build. First, a competing port could be added to the model again, as was done in Chapter 5 to study the impact of competition on the phased investment decision in a duopoly. Once the investment decision of an individual port is obtained, the approach of Chapter 4 can again be used to distinguish between the decision of the PA and the TOC and to calculate a concession fee that satisfies the pursued objectives of the PA.

In order to add even more realism to the RO model and limit model simplifications as much as possible, it would be beneficial to investigate in a follow-up study the option of two subsequent expansions. In 1999, when the Port of Antwerp considered the investment in the Deurganckdok, it already contemplated the construction of a second tidal dock, Saeftinghedok. Adding such a second expansion option would further reduce the myopic character of the developed RO models, which consider only one investment.

Moreover, additional sources of uncertainty could be accounted for in the models, such as a variable discount rate, ex-ante uncertainty about the time to build and cost uncertainty, next to the already included demand uncertainty. Also disaster, political, technological and legal uncertainty could be included in the analysis. However, information about the interactions between the different sources of uncertainty would then be required. In addition, different processes would be needed to model these different sources of uncertainty. It is important that these processes' accuracies in representing realistic situations are tested and validated. Nevertheless, these additions would substantially complicate the mathematical calculations of the RO model, as well as the empirical estimations needed. In any case, a good balance between model realism and (exact or approximate) solubility needs to be maintained in future research. Moreover, different port investment types might have to be combined in one decision making process model.

The newly developed models can be used in a subsequent research phase to enhance the tool proposed in Chapter 7. This will allow increasing realism and taking better and more realistic decisions in two competing ports such as Antwerp and Rotterdam in the Hamburg - Le Havre range. However, due to the increased model complexity, also the complexity of the estimation techniques might increase. Using case studies, for example on finished projects, the correctness of the developed models can be assessed and further improvements can be made.

Finally, the approaches and models developed in this thesis offer useful insights for other sectors as well. For example, the available capacity investment decision making models for airports do not explicitly account for the impact of congestion. The approach and insights presented in this thesis can be used to incorporate this characteristic, that is also present in airports, in airport capacity RO models (see e.g., Balliauw & Onghena (2018)). Of course, those characteristics distinguishing airports from ports need to be taken into account as well, before transferring any model components or findings. Next to airports, also other industries might benefit from this research. For instance, the insight of adding a fourth-order investment cost function could be useful for other investment decisions that are limited in space as well. As an example, one could think of the investment in warehouses or football stadiums. However, here again, accounting for the relevant industry characteristics is a prerequisite for finding valid and reliable optimal investment decisions under uncertainty.

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Appendix A

Solution to differential equation (3.19), determining a new port's project value

In this Appendix, the solution to differential equation (3.19) is derived. To this end, the following equation is solved:

$$\frac{\sigma^2}{2}X^2\frac{\partial^2 V}{\partial X^2}(X,K)+\mu X\frac{\partial V}{\partial X}(X,K)-rV(X,K)=-\overline{\pi}(X,K) \tag{A.1}$$

where $\overline{\pi}(X,K)$ is either a constant or rational function:

$$\pi(X,K,q^{opt}(X,K))=\overline{\pi}(X,K)=\begin{cases}\overline{\pi}_1(X,K)=-c_hK, & X\in R_1,\\ \overline{\pi}_2(X,K)=\dfrac{(X-c)^2K^2}{4(XA+BK^2)}-c_hK, & X\in R_2,\\ \overline{\pi}_3(X,K)=(K-A)X-(BK+c+c_h)K, & X\in R_3.\end{cases} \tag{A.2}$$

First, the homogeneous equation is considered:

$$\frac{\sigma^2}{2}X^2\frac{\partial^2 V}{\partial X^2}(X,K)+\mu X\frac{\partial V}{\partial X}(X,K)-rV(X,K)=0. \tag{A.3}$$

Note that the second-order derivative has a coefficient that is quadratic in X, and likewise for the other terms. Hence, if V is given by a power function, all terms in the differential equation will prove to be the same power functions. Thus, the two independent solutions will be given by power functions. Plugging $V=X^\beta$ into the equation, it can be simplified to the quadratic equation

$$\frac{\sigma^2}{2}\beta(\beta-1)+\mu\beta-r=0, \tag{A.4}$$

which has the two distinct real roots β_1 and β_2 given in Equation (3.22). Note that the condition $r>\mu$ means that $\beta_1>1$ and $\beta_2<0$. Hence, the solution to the homogeneous equation in the j-th region ($j = 1, 2$) is given by

$$V_{h,j}(X,K) = G_{1,j}(K)X^{\beta_1} + G_{2,j}(K)X^{\beta_2}. \tag{A.5}$$

In region R_1, the right-hand side of differential equation (A.1) is a constant. A constant particular solution is then:

$$\overline{V}_1(X,K) = -\frac{c_h K}{r}. \tag{A.6}$$

In region R_2, the right-hand side is more complicated:

$$\begin{aligned} \overline{\pi}_2(X,K) &= \frac{(X-c)^2K^2}{4(AX+BK^2)} - c_h K \\ &= \frac{K^2}{4A}X - \left[\frac{K^2}{4A}\left(2c+\frac{BK^2}{A}\right) + c_h K\right] + \frac{K^2(c+\frac{BK^2}{A})^2}{4A}\frac{1}{X+\frac{BK^2}{A}}. \end{aligned} \tag{A.7}$$

This right-hand side consists of a polynomial part (of degree one) and a rational part. Finding a particular solution for the polynomial part is straightforward: if $V = aX + b$ is entered into the differential equation, the following equation is obtained:

$$\overline{V}_{2,\mathrm{pol}}(X,K) = \frac{K^2}{4A(r-\mu)}X - \frac{1}{r}\left[\frac{K^2}{4A}\left(2c+\frac{BK^2}{A}\right) + c_h K\right]. \tag{A.8}$$

For the final part of the solution, it is easier to consider the monic form of the differential equation, i.e., dividing (A.7) by $\sigma^2 X^2/2$. In order to find a particular solution for the remaining rational (in X) part,

$$\overline{\pi}_{2,\mathrm{rat,mon}}(X,K) = \frac{K^2\left(c+\frac{BK^2}{A}\right)^2}{2A\sigma^2}\frac{1}{X^2\left(X+\frac{BK^2}{A}\right)}, \tag{A.9}$$

the method known as variation of parameters or constants is used. That is, a solution in the same form as the solution to the homogeneous equation is proposed, but now with coefficients that also depend on X:

$$\overline{V}_{2,\mathrm{rat}}(X,K) = C_1(X,K)X^{\beta_1} + C_2(X,K)X^{\beta_2}. \tag{A.10}$$

As a result of this method, the coefficients are given by

$$C_1(X,K) = \int \frac{1}{W}X^{\beta_2}\overline{\pi}_{2,\mathrm{rat}}(X,K)\,\mathrm{d}X, \tag{A.11}$$

$$C_2(X,K) = -\int \frac{1}{W}X^{\beta_1}\overline{\pi}_{2,\mathrm{rat}}(X,K)\,\mathrm{d}X, \tag{A.12}$$

where W is the Wronskian, i.e., the determinant of the two independent solutions to the homogeneous equation and their derivatives:

$$W = \begin{vmatrix} X^{\beta_1} & X^{\beta_2} \\ \beta_1 X^{\beta_1-1} & \beta_2 X^{\beta_2-1} \end{vmatrix} = (\beta_2-\beta_1)X^{\beta_1+\beta_2-1}. \tag{A.13}$$

Besides for integer values of β_1 and β_2, the integrals in equations (A.11)-(A.12) cannot be evaluated using elementary functions alone. Instead, their solution can be written in terms of hypergeometric functions (Abramowitz & Stegun, 1972). The solution

$$\begin{aligned}\overline{V}_{2,\mathrm{rat}}(X,K) &= -\frac{\left(c+\frac{B}{A}K^2\right)^2}{2\sigma^2 B(\beta_2-\beta_1)} \\ &\quad\times\left[\frac{1}{\beta_1}{}_2\mathrm{F}_1\left(1,-\beta_1;1-\beta_1;-\frac{AX}{BK^2}\right)-\frac{1}{\beta_2}{}_2\mathrm{F}_1\left(1,-\beta_2;1-\beta_2;-\frac{AX}{BK^2}\right)\right]\end{aligned} \tag{A.14}$$

is obtained and is valid for $X < BK^2/A$, or its analytic continuation for $X \geqslant BK^2/A$. The sum of the particular solutions for the polynomial and rational parts, found in (A.8) and (A.14) respectively, produces a particular solution for differential equation (A.1) in the region R_2.

If the solution of the homogeneous equation is added to this particular solution, a particular solution is still obtained. Consequently, a linear combination of X^{β_1} and X^{β_2} can be added to the particular solution. The reason for this stems from the analysis of the asymptotic behaviour of the solution. With a large X, the first hypergeometric function in (A.14) will increase as a constant *times* X^{β_1}. However, the next term in the asymptotic expansion at infinity will merely be linear, even if $\beta_1 > 2$. This can be shown by writing down the series expansion of the hypergeometric functions at infinity. Thus, this term in X^{β_1}, calculated as

$$\frac{\Gamma(\beta_1)\Gamma(1-\beta_1)}{(BK^2)^{\beta_1}}A^{\beta_1}X^{\beta_1},$$

is subtracted, in order to obtain the particular solution omitting speculative bubbles resulting from the term in X^{β_1} (see Dixit & Pindyck (1994), Chapter 6). For a behaviour near zero omitting speculative bubbles, no further steps are needed. Since the hypergeometric series is a power series around zero, it converges in the neighbourhood of zero and no divergent terms (i.e., terms in X^{β_2}) are present. Hence, no correction in X^{β_2} is required.

Finally, in region R_3, the right-hand side is polynomial in X:

$$\overline{\pi}_3(X,K) = (K-A)X - (BK + c + c_h)K. \tag{A.15}$$

Again, by plugging $V = aX + b$ into the differential equation,

$$\overline{V}_3(X,K) = \frac{K-A}{r-\mu}X - \frac{BK^2 + cK + c_h K}{r} \tag{A.16}$$

is obtained.

All these considerations lead to the particular solution given in Equation (3.23).