Benjamin Avlund Timberlid and Petter Fossan Aas

Sequential investments in the shipping industry under a carbon tax

Master's thesis in Industrial Economics and Technology Management
Supervisor: Maria Lavrutich
July 2020

Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Economics and Management
Dept. of Industrial Economics and Technology Management

NTNU
Norwegian University of
Science and Technology

Problem description

This thesis considers the option to invest in emission-reducing technology under a carbon tax. We consider the shipowner's perspective and apply a real options approach to investigate the investment in a retrofit to LNG. Later, we include the option to invest in ammonia and create a combined option. We investigate how taxation affects the option values and investment timing.

Preface

This thesis was written as a concluding part of our Master's degree in Industrial Economics and Technology Management in Norwegian University of Technology and Science. The specialisation of our study programme is Financial Engineering.

We would like to offer our gratitude to our supervisor, Associate Professor Maria Lavrutich, for valuable guidance and suggestions throughout the Spring of 2020.

Oslo, July 2, 2020

Benjamin Avlund Timberlid   Petter Fossan Aas

Abstract

The shipping industry has an ambitious goal of reducing greenhouse gas emission by 50% within 2050. For this to be possible, shipowners has to abandon oil-based fuels and invest in green technology. As zero-emissions technologies for long-haul shipping are not yet commercially available, shipowners must look into strategies to gradually reduce their emissions. This can be done by considering available technology that offers modest CO_2 reductions in the short run and invest in zero-emission technology once it becomes available. A first step can be the use of LNG as a marine fuel. The technology offers CO_2 reductions in the range of 20-30%. To achieve further reductions, ammonia is considered to be a promising alternative for zero-emission shipping. Implementing a carbon tax can affect the shipowners investment decisions, and may trigger investments in LNG technology. Furthermore, it incentivizes shipowners to expedite the development of zero-emission technologies.

By applying real options valuation, this thesis investigate the shipowner's behaviour under a carbon tax. We consider the investment decision of a LNG retrofit, as an initial step to reduce emissions. First, we consider a perpetual option with one source of uncertainty, namely the fuel spread. By finding an analytical solution to the problem, we achieve tractable results. This is used as a benchmark. Next, we introduce a finite lifetime to the investment problem and solve the investment decision numerically using Least Square Monte Carlo. We then include two additional uncertainties: a stochastic carbon tax and downward jumps in the investment cost. By applying the models to a case study, we find that the perpetual model overvalues the investment decision significantly. We also find that the volatility does not affect the option value in the finite lifetime options, in contrast to traditional option theory. By including jumps in the investment decision, the results show that the investment timing is highly dependent on the arrival of the jump for tax levels below $35. For tax levels above, investments are undertaken immediately.

Lastly, we investigate the effect of adding the opportunity to invest in zero-emission technology once it becomes available. This is modelled as an embedded option in the LNG investment decision. The zero-emission technology under consideration is ammonia. We find that the inclusion of the embedded ammonia option significantly increases the value of investing in LNG. Furthermore, we find that earlier arrival of the ammonia technology increases the option value. This result implies that investing in R&D can be highly valuable and accelerate the adoption of ammonia technology.

Sammendrag

Shippingindustrien har satt seg et ambisiøst mål om å redusere klimagass-utslippene med 50% innen 2050. For at dette målet skal nås er man avhengige av en omstilling, hvor oljebasert drivstoff fases ut og erstattes med grønne alternativer. Ettersom utslippsfritt drivstoff ikke er tilgjengelig i stor skala må skipsredere undersøke muligheten for å redusere utslippene gradvis. Dette kan gjøres ved å investere i teknologi som har en moderat reduksjon i utslipp på kort sikt, med ytterligere investeringer i grønnere teknologi når det blir tilgjengelig. Det første skritte kan være å investere maskineri som går på flytende naturgass (LNG), ettersom denne teknologien reduserer CO_2-utslipp med 20-30%. I fremtiden er amoniakk som drivstoff et lovende alternativ for å oppnå nullutslipp. Ved å innføre en karbonskatt kan man fremskynde det grønne skiftet. En slik skatt kan gjøre investeringer i mer miljøvennlige alternativer lønnsomt på et tidligere tidspunkt. Samtidig gir det insentiver for investeringer i nullutslippsteknologi.

Vi benytter oss av realopsjonsmetoden for å undersøke hvilke beslutninger en skipsreder tar dersom en karbonskatt innføres. Vi ser på investeringsmuligheten for å retrofitte et skip til å gå på flytende naturgass. Først ser vi på den tidsubegrensede opsjonsverdien til investeringen. Her er den eneste usikkerheten prisforskjellen mellom Marine Gas Oil (MGO) og LNG. Ved å se på dette tilfellet kan vi komme frem til en analytisk løsning, som brukes som sammenlikningsgrunnlag videre i oppgaven. Deretter setter vi en tidsbegrensing på opsjonen. Dette problemet må løses numerisk. Vi løser det ved hjelp av Least Square Monte Carlo-metoden. Deretter legger vi til ytterligere to usikkerheter: hopp i investeringskostnaden, modellert som en Poisson-prosses, og en stokastisk karbonskatt. Vi finner at den tidsbegrensede opsjonen har en betraktelig lavere verdi enn den tidsubegrensede. Vi finner også at økt volatilitet ikke påvirker den tidsbegrensede opsjonsverdien nevneverdig, noe som motsier tradisjonell opsjonsteori. Ved å inkludere fall i investeringskostnaden finner vi at investeringstidspunktet er høyst avhengig av når fallet kommer for skattenivåer under \$35. For høyere skattenivåer vil man investere umiddelbart.
Avslutningsvis undersøker vi konsekvensene av å legge til en opsjon på videre investering i ammoniakk i LNG-investeringen. Vi finner at den amoniakk-opsjonen øker verdien av LNG-opsjonen betraktelig. Vi finner også at en fremskynding av kommersialiseringen av ammoniakk, øker opsjonensverdien til LNG-investering. Dette resultatet impliserer at investeringer i R&D i amoniakk kan være verdifulle.

Contents

1 Introduction

Freight transport by sea has been widely used throughout recorded history. With increasing globalization and trades between continents, the shipping industry has bloomed, as it accounts for 80-90% of global trade (GL, 2019). The majority of ships run on diesel-based fuels, causing high emission levels of greenhouse gases. In total, the industry is responsible for 3% of global emissions. Increasing engagement in climate change among the public has put pressure on governments and companies to slow down these emissions. The International Maritime Organization (IMO) has taken an active role to reduce emission emissions in the marine industry. This is evident by the introduction of what is popularly called *IMO 2020*, a regulation limiting the SO_x and NO_x emissions from the ship's exhaust. More action is expected. IMO's outspoken strategy is to reduce CO_2 levels by 50% compared by 2008 levels within 2050. To achieve this ambitious goal, most ships would have to abandon the diesel-based fuels. The use of Liquefied Natural Gas (LNG) as an alternative fuel has increased in recent years. In 2010, there where 18 LNG propelled ships in operation. In 2020, there are 169[1]. LNG is a safe alternative for shipowners due to mature technology and a decent bunkering infrastructure. The fuel also emits 20-30% less CO_2 compared to diesel-based fuels. This is not sufficient to reach IMO's target. Therefore, zero-emission technologies are being researched and tested on a grand scale. Hydrogen is a promising energy carrier, especially in the form of ammonia. However, this technology is still in an early stage of development. This has not stopped shipping companies from setting ambitious targets and conducting zero-emission pilot projects. Maersk, a large logistics and container shipping company, is aiming to have carbon-neutral vessels by 2030 in order to reach emissions targets[2]. In Norway, Eidevik Offshore will install ammonia-driven fuel cells on one of their ships in 2024[3]. Shipping companies' engagement is an important factor for reaching the IMO targets, but to achieve broad adoption of emission-reducing technology, there have to be financial incentives. An international carbon tax for the shipping industry can increase the profitability of these investments and thereby speed up the transformation. It is an ongoing debate about the implementation of a carbon tax in the industry. To inform the debate, The International Monetary Fund (IMF) conducted a study, identifying such a tax as a straightforward method to reduce emissions.[4]. The two main methods of taxing carbon, is through a flat tax or a cap and trade system. Both systems are implemented in other industries and have proven to be an efficient measure to reduce emissions.

In our thesis, we will investigate the effects of a carbon tax on the investment

[1]Source: DNV GL Alternative Fuels Insights platform, *https://afi.dnvgl.com*

[2]Source: https://www.maersk.com/news/articles/2019/06/26/towards-a-zero-carbon-future

[3]Source: https://www.equinor.com/no/news/2020-01-23-viking-energy.html

[4]https://www.imf.org/en/Publications/WP/Issues/2018/09/11/Carbon-Taxation-for-International-Maritime-Fuels-Assessing-the-Options-46193

in emission-reducing machinery. By applying a real options approach from the ship owner's perspective, we compare a perpetual and a finite lifetime option to invest in emission-reducing technology. In addition, we investigate a flexible investment strategy for reducing emissions gradually, by considering a sequential option to invest in zero-emission technology. Our focus is on the potential cost savings that can be achieved through these investments. Through this approach, we gain an understanding of the investment behaviour of ship owners under different tax scenarios. We argue that this is valuable for the policymakers, who commonly base their decisions on the net present value approach. This approach can yield misleading results, as it does not take into account managerial flexibility, such as delaying the investment. By accounting for this flexibility in the real options approach, we argue that this better reflects the shipowner's investment decision making. We find the project value and investment timing, insights that can be used to anticipate shipowner's reactions to the implementations of a carbon tax.

The thesis contributes to the real options literature by considering an option with a finite lifetime, where the project lifetime decreases constantly, regardless of the investment decision. By applying this model to an example from the shipping industry, we offer insight into how such decisions differ from more traditional investment problems, where the project lifetime begins at the time of investment. Implementing an embedded option to this type of limited lifetime problem has, to the best of our knowledge, not been done before. Furthermore, the thesis contributes to the literature on emission abatement by considering the economics of an embedded option in the LNG investment. As the embedded option, we consider a retrofit into ammonia. To our knowledge, this thesis is the first to investigate the value of an ammonia retrofit using real options. Lastly, we contribute to the policy debate in shipping by offering a real options perspective. We offer insights into the implications different tax levels have on our case study.

The thesis consists of seven sections. In Section 2, we present a background for the problem by discussing emissions, technology and regulations in shipping. A review of the literature on the subject is presented in Section 3 In Section 4, we present models for a perpetual and finite option to invest in emission-reducing machinery. These models are applied to a case study in Section **??**. The option to invest is then expanded to an embedded option in Section 4.4. In Section 7 we discuss the implications of our results and suggests further research.

2 Background

In this section, we present a short summary of the most important aspects that concern emissions and regulations in shipping. This is meant to give the reader an overview of the shipping industry's emission and the solutions for reducing these. We also describe IMO's role as a regulator and previous initiatives. Lastly, we discuss the two main methods for taxing and present some experiences from the implementation of a carbon tax in other industries.
The highest growth was seen in containerized cargo, where volumes have risen by 8% between 1980-2018. (UNCTAD, 2019). This development makes it challenging to reduce the industry's GHG emissions. However, initiatives/engagement, noen utforsker ny teknolog/det finnes teknology.

2.1 Current situation

The global maritime trade has experienced a yearly average growth of 3% between 1970 and 2017 (UNCTAD, 2019). This has made the shipping industry to a large global emitter, accounting for 3% of the total global greenhouse gas (GHG) emissions. More specifically, the industry emits to 1.1 billion tonnes CO_2 annually. In addition to this, the industry emits 3.2 million tonnes of NO_x and 2.3 million tonnes of SO_x (Balcombe *et al.*, 2019). This is due to the widespread use of Heavy Fuel Oil (HFO), a residual from the refining process of crude oil. This is the most common fuel in shipping due to historical low prices, reliable engine technology and a well-developed bunkering infrastructure. In the later years, the industry has been concerned about the high sulphur emissions from HFO and its negative effect on air quality in cities. On the 1st of January 2020, the International Maritime Organization (IMO) introduced a strict limit of 0.5% of sulphur content in the fuel, a reduction by over 80% [5]. Under this limit, HFO is not compliant and shipowners that wanted to keep their existing machinery were presented with two strategies. They could continue the use of HFO and invest in a scrubber, a device that cleans the exhaust of the engine. Alternatively, switch to Marine Gas Oil (MGO) or Very Low Sulphur Fuel Oil (VLSFO) without engine modifications. MGO and VLSFO are both refined products of HFO, with a higher production cost than HFO. This has raised concern for shipowners, as fuel costs make up a large proportion of operating costs. The increased cost of fuel, combined with an increased focus on the industry's environmental impact from regulators, customers and the public in general has caused the shipowners to investigate alternatives for engine propulsion.

2.2 Technology Alternatives (Rough)

A well-developed alternative fuel is Liquified Natural Gas (LNG). As LNG carriers (ships that transports LNG) has used this technology for some time, the

[5] Source: http://www.imo.org/en/mediacentre/hottopics/pages/sulphur-2020.aspx

technology has matured. This type of propulsion has a higher investment cost, but operating costs are reduced, as the fuel is less costly. Another benefit with LNG is that the CO_2 emissions reduce by 20-30%. From 2010 to 2018, the total number of LNG operating vessels has increased from 18 to 169. Currently, there are also 61 ships on order with LNG propulsion. This indicates a great interest in the technology. In addition, the infrastructure has improved in the later years, making LNG widely available in ports.[6] Some shipowners have opted for the alternative to make a new ships LNG ready. This means that the new build runs on diesel oil, but is prepared to be retrofitted to LNG in the future at a lower cost. This translates into a real option on LNG. However, as the technology only offers modest CO_2 emissions, LNG is only part of the solution to reach a zero-emission industry.
A promising zero-emission alternative is the ammonia fuel. This technology is not yet commercially available. Lack of infrastructure regarding bunkering and standardisation are some of the challenges. However, pilot projects are under development, and the first ammonia fueled vessel, Viking Energy, is expected to be launch in 2024[7]. In January, a collaboration between the German MAN energy and international shipping groups announced a project to create an ammonia-fuelled tanker within the next 4 years (MAN kilde). In addition, Color line has launched a project of retrofitting on of their vessels to ammonia propulsion [8] These initiatives may pave the way for further ammonia investments.

To reach the 50% GHG emission reduction, shipowners will have to implement technologies, such as LNG and ammonia. As these alternatives come with high investment costs and may be undeveloped, shipowners have few incentives. Such incentives can be made by industry regulators and in shipping IMO has introduced several regulations on the maritime industry to reduce emissions.

2.3 Regulations in shipping

The shipping industry has proven notoriously hard to regulate and tax, mainly due to shipping companies opportunity to register their ships anywhere in the world. This is known as Flag of Convenience and refers to the shipowner's opportunity to choose the flag state that has the most beneficial terms. This has made taxation of the industry difficult, as the states imposing the tax are risking shipowners to flag out. In the later years, The International Maritime Organization (IMO), an agency of the United Nations, has proven its ability to regulate the players and to address the challenges associated with being an inherently international industry. They aim to 'level the playing field', and prevents shipowners from compromising safety, security and environmental efficiency[9]. This is done through the administration of conventions between its

[6] https://sea-lng.org/lng-as-a-marine-fuel/availability/
[7] Source: https://www.equinor.com/no/news/2020-01-23-viking-energy.html
[8] https://www.ammoniaenergy.org/articles/maritime-ammonia-ready-for-demonstration/
[9] http://www.imo.org/en/About/Pages/Default.aspx

174 member states. Efforts to reduce marine pollution is done through the International Convention for the Prevention of Pollution from Ships (MARPOL). The first MARPOL Convention was adopted in 1973 and it took 10 years before the first Annex was entered into force in 1983. This annex addressed the risk of serious oil spills and made double-hulls on oil tankers mandatory. [10] Later MARPOL annexes has treated noxious liquids, sewage and garbage in addition to air pollution. The enforcement of implemented regulations is conducted by an international network of surveyors and inspection of country officials. The most recent initiative is the Prevention of Air Pollution from Ships (Annex VI), which addresses the air emissions from ships and has been amended several times since the introduction in 2005. A special focus has been given to sulphur oxides, a compound that reduces the air quality in cities and is associated with exacerbation of respiratory diseases and an increase in deaths from respiratory and cardiovascular diseases (Brunekreff and Holgate, 2002). Strict limits on the sulphur content of the ship's fuel oil were first introduced in Emission Control Areas (ECAs) in 2010. This was expanded in 2020, with a global sulphur limit of 0.5% and is estimated to have affected 70,000 ships. For the shipowner to be compliant, investment in new machinery or switching to low-sulphur fuel is necessary. Thus, the regulation has had severe financial implications on the shipping industry. Furthermore, the implementation of the sulphur cap proves IMO's ability to be an efficient policymaker. Other notable initiatives are the IMO Data Collection System, requiring ships to collect fuel consumption data and the Energy Efficiency Design Index, an efficiency standard that new ships need to meet.

The sulphur limit is an important first step in IMO's ambitious GHG strategy. The aim is to reduce CO_2 emission by 40% within 2040 compared to 2008 levels. Additionally, they will pursue efforts to reach a 70% reduction within 2050. To reach these goals, investment in already existing emission-reducing technology is essential. Furthermore, substantial resources need to be put into RD in promising solutions that can reduce emissions further. IMO has initiated several initiatives, such as a trust fund for GHG reducing technologies and GreenVoyage-2050, a collaboration between IMO and the Norwegian government to test new solutions [11]. However, these efforts will not be enough to reach the outspoken emission goals. Furthermore, The International Monetary Fund argues that a carbon tax is necessary to give shipowners financial incentives to invest in emission-reducing machinery Parry *et al.* (2018). The introduction of a carbon tax is a natural next step to reach IMO's targets. The organisations established role as a policymaker and proven ability to enforce policies through its member states also suggest that the organisation is able to introduce this policy successfully.

[10] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/OilPollution/Pages/Default.aspx
[11] http://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

2.4 Carbon tax

A carbon tax increases the cost of using diesel-based fuels and makes its less carbon-intensive alternatives more attractive. The tax is paid for the amount of carbon emitted into the atmosphere, usually an amount per tonnes. There are different ways of designing a flat carbon tax. One way is to pay a fee for every tonne of CO_2 emitted into the atmosphere. An example of such tax is the carbon taxation of gasoline in Norway. The taxation is also applied to diesel, mineral oil and oil and gas extraction. Another model is a flat carbon tax above a given benchmark. In this regime, an industry standard is decided, and all emissions above the industry standard are imposed with a fee. An example of this is the new CO_2 emission regulations for passengers cars, implemented by the EU. The car manufacturers need to have an average CO_2 emission of 95 g/km from the cars sold. If a manufacturer exceeds this level, the manufacturer has to pay a fee of €95 per gram per car. A similar industry standard may be implemented in shipping.

Another alternative is a cap and trade system, also known as an emission trading scheme. This is a marked-based system for regulating emissions in carbon-intensive industries. Under a given cap of total emissions, companies can buy or sell allowances for CO_2 emissions. The total allowances bought by a company must be equal to their total emissions at the end of the year. Set up in 2005, the largest scheme is the EU Emissions Trading System (EU ETS), which covers the EU countries, Norway, Lichtenstein and Iceland. EU ETS includes 45% of EU's total GHG emissions and governs energy-intensive industries and airlines operating between inside EU. Other examples of emission trading schemes are found in South Korea, New Zealand and some states the U.S. Globally, these markets cover 4.6 billion tons of CO_2 emissions, 13% of the world ' total GHG emissions. [12] The total amount of allowances, i.e. the cap, is reduced each year in line with the EU's emissions goal. A company exceeding its yearly emissions receives fines. The ETS grants flexibility to the businesses by allowing them to choose the least costly path to meet the emission target, either by buying allowances or investing in new technology. Dechezleprêtre *et al.* (2018) suggests that the EU ETS has lead to a 10% reduction in carbon emissions between 2005 and 2012.

[12] https://ec.europa.eu/clima/policies/ets

3 Literature Review

Due to an increased focus on the environmental impact from shipping, a strand of literature investigating the profitability of new technology has emerged. Before IMO's 0.5% sulphur cap was introduced on the 1st of January 2020, several authors investigated the shipowner's investment strategy: either switch to a low-sulphur fuel or continue using heavy fuel oil in combination with a scrubber that removes SO_x from the exhaust. Lindstad *et al.* (2017) analyses the best response under different scenarios and conclude that the continuation of using HFO in combination with a scrubber is the best alternative. This is done using a static valuation method. Rehn *et al.* (2016) considers flexible strategies combining HFO with a scrubber, MGO and LNG. Using real options analysis and simulation, they conclude that a flexible strategy including making the ship technically ready for LNG is advantageous. Acciaro (2014) studies an LNG retrofit as a response to the sulphur limit using real options. By considering the value and optimal timing of the investments, the retrofit is not found profitable due to the current fuel and investment cost. Both Rehn *et al.* (2016) and Acciaro (2014) uses real options in their valuation and are able to value flexibility in their strategies. This is evident in the strategy recommendation of Rehn *et al.* (2016), which includes preparing the ship for a retrofit in the future. Our thesis contribute to the academic literature on technology choice in shipping. We revisit the assumptions of an LNG retrofit in the aftermath of IMO 2020, as it is no longer possible to run on HFO alone. The alternative low-sulphur diesel oils are distillates and come at a premium compared to HFO. Furthermore, we investigate the economics of the retrofit decision to ammonia-driven propulsion. This adds to the scarce literature of green technology in shipping.

The traditional way of valuing investment decisions is the Net Present Value method. This is a simple and straightforward approach, but with some considerable shortcomings. In reality, investment decisions include some form of flexibility, such as delaying or making sequential investments. These features are not compatible with the NPV method. By applying option pricing theory on real investments managerial flexibility can be included, in addition to price dynamics. Early examples of real options applications are Mossin (1968) and Brennan and Schwartz (1985), which finds thresholds in the commodity price for stopping and resuming production. McDonald and Siegel (1986) considers the optimal timing of investments and emphasizes the importance of the value of waiting in project valuation. Dixit (1989) gives a more general framework and considers the option to switch between an active and idle firm, resulting in two thresholds for switching between the two states. The notion that an option to invest includes an embedded option is a powerful method that makes it possible to value investments that can be done in several stages. Trigeorgis (1993) studies the differences between the addition of individual option values and the options combined. An important finding is that the value of flexibility and the cash flows may be in simillar order of magnitude for the combined option. Dixit and Pindyck (1994) considers sequential investment problems that have to be performed in a specific order. However, the focus is large projects with a long time horizon and the cash flows are not received until the final investment is made. Flexibility is very important in shipping, due to prominent business cycles in the industry and uncertainty in the regulatory approach to achieve emission reduction. The ability to include these factors make real options a natural modeling approach. In addition to modeling an option to invest, taking into account the option to defer, we also consider a sequential investment. Trigeorgis (1993) and Dixit and Pindyck (1994) both model projects with cash flows received when the final investment is done. We consider an option where the cash flows changes for each investment made.

In shipping, real options theory has been used in several applications. The uncertain freight rates, which move in prominent business cycles, makes this an appropriate valuation method. Dixit and Pindyck (1994) studies the decision of whether to lay up, reactivate or scrap a ship using dynamic programming and finds optimal rate levels for undertaking the actions. Bjerksund and Ekern (1995) uses real options to value an option on a time-charter contract for a cargo ship and models the underlying cash flows as an Ornstein-Uhlenbeck process. Applying the switching option framework of Dixit (1989), Sødal *et al.* (2008) values a combination carrier with the possibility to switch between the bulk and tanker market under stochastic freight rates. Similar models have been used to take advantage of freight rate differentials between different shipping markets (Sødal *et al.* (2009), (Adland *et al.*, 2017a), Adland *et al.* (2017b)). Naturally, the real options theory in shipping is concerned with the maximising of income, represented by the freight rates. We take another approach, by modeling the potential savings in costs that are obtainable from undertaking investments. In our thesis, we also investigate the effects of a carbon tax on the investment decision. The shipping industry has traditionally been subject to low taxation. Due to this, there are few examples in the academic literature that studies the effect of carbon tax schemes in shipping. One of the few is Haehl and Spinler (2020), which applies a real options approach to evaluate the choices of capacity and technology under regulation uncertainty to a fleet of ships. By the inclusion of both a flat emissions tax and a cap-and-trade market, they find the latter to reduce emissions more effectively. In contrast to Haehl and Spinler (2020) which solves a capacity problem, we consider are concerned with the investment decision for a single ship. To study the shipowner's investment behaviour under a carbon tax, find the option values and investment timings.

In the fields of renewable energy and power plants, different tax and subsidy systems have been present for several years. There exists a broad field of literature that applies real options to evaluate investment decisions in new projects and the retrofit decisions to carbon capture and storage (CSS) equipment under tax schemes. These investment decisions are characterised by high investment costs and uncertain profit. Furthermore, the investments reduce GHG emissions which traditionally have not been assigned a monetary value. These characteristics coincide with the investment decision shipper's face when looking to invest in emission-reducing machinery. Thus, it is natural to study this field of literature. To trigger investment in renewable energy, policymakers have introduced several mechanisms to account for the high investment cost and uncertainty. Most notable are the feed-in tariffs (FIT), which secures a fixed price per kWh of renewable electricity sold in the market, and Tradable Green Certificates (TGC), evidence that a specified amount of electricity is produced by a renewable energy source. Boomsma *et al.* (2012) investigates the effect of FIT and TGC on investment timing and project size by solving a dynamic programming model with up to three sources of uncertainty. The results show that FIT facilitates earlier investment, while TGC yields larger projects when an investment is undertaken. Kitzing *et al.* (2017) comes to a similar conclusion, looking at wind energy with the profit as the only source of uncertainty. The article concludes that FIT leads to 15% smaller projects than TGC, but that TGC triggers investments at 3% higher profit margins than FIT. Fuss *et al.* (2008) applies real options simulation to investments in CSS for a power plant and finds that the uncertainty of the carbon prices under a trading scheme results in earlier investments than if the price had been known beforehand. Looking at flat tax and EU ETS for investment in power plants, Compernolle *et al.* (2020) finds that a trading system stimulates investment in low-carbon technology for low carbon prices. This is due to the positive correlation between electricity prices and carbon prices, resulting in lower volatility. The flat tax is preferred to postpone investment in carbon-intensive technology. The varied results from the energy field show that deciding between flat and marked-based subsidies may be challenging. In their modeling approach, the TGC and a cap and trade system is similar. The same holds for the FIT and a flat tax. We leverage this similarity in the modeling approach for our thesis, where we model the savings in carbon tax as a cash flow. To see the effects of a theoretical carbon tax on the shipping industry, we study the effects of both a flat tax and a cap and trade system.

In our thesis, the uncertain fuel prices have an important role. In the modeling of fuel prices, several authors find mean-reverting properties. Bessembinder *et al.* (1995) finds a strong mean reversion in oil prices by applying an empirical test for equilibrium prices. Schwartz (1997) also finds strong evidence for mean-reverting properties in the oil price and apply real options to future contracts with underlying Ornstein-Uhlenbeck processes. One of the main findings is that a real options approach results in too high investment thresholds when mean reversion in prices is neglected. Laughton and Jacoby (1993) also suggests that disregarding mean-reversion and use of a Brownian motion instead, will lead to a bias in the option value. This is in part due to the mean reversion, which reduces the probability of positive fluctuations caused by the volatility. Other applications of mean-reverting processes are Hahn and Dyer (2008), which models oil and gas prices as Ornstein-Uhlenbeck processes to value a switching option. Based on the empirical evidence in Bessembinder *et al.* (1995) and Schwartz (1997), modeling fuel prices as a mean-reverting process is appropriate. This is also motivated by the possible bias that can arise by ignoring mean-reversion found by Laughton and Jacoby (1993). An important modeling assumption is the choice of the project's lifetime. In the vast majority of the academic option literature, the lifetime is assumed perpetual. Additionally, the literature that models finite options, consider projects where the remaining lifetime starts to decrease after investment. In our project, the lifetime decreases independently of the investment timing. In such investment problems, the literature is scarce.

In summary, our thesis considers the option of investment in emission-reducing technology. There is limited academic literature that considers the valuation of such technology using real options. In similarity to Acciaro (2014), we consider the option to invest in LNG but include a carbon tax in the form of flat tax and a cap and trade system. Also, we include an embedded option to invest in ammonia. To our knowledge, this has not been done before. Thus, we contribute to the literature on green technology. The inclusion of a carbon tax in real options applications in shipping gives important insights to the ongoing debate about taxation in shipping.

4 Model

4.1 Modeling the shipowner's investment decision

In the investment decision, the shipowner faces high capital costs and a high degree of uncertainty in the income and fuel prices. Operating under volatile freight rates that follow prominent cycles, shipowners have always been trying to time their investment decision to make a profit. This will be no different under a carbon tax. Fuel costs make out a large proportion of a ship's operating costs and a levy on the fuel consumption will force the shipowner to investigate alternatives. As the shipowner generally has no market power, increases in the profit margin must come from cost cuts. Looking at carbon tax, a long-term solution for reducing this is the retrofitting of existing machinery running on diesel to less carbon intensive machinery. We investigate the shipowner's behaviour under a different carbon tax schemes and if such schemes gives incentives for the shipowner to make investments in emission-reducing machinery. We do this by investigating the profitability of such investments under two different carbon tax schemes, a flat tax and a cap and trade scheme. In particular, we calculate the option value and the corresponding investment threshold. Furthermore, we find the probability of investing under the tax schemes in relation to IMO's emission goals. In our model, we consider one scenario with a flat tax and another scenario with a cap and trade scheme. The latter scenario only differs in that the carbon tax is taken as uncertain.

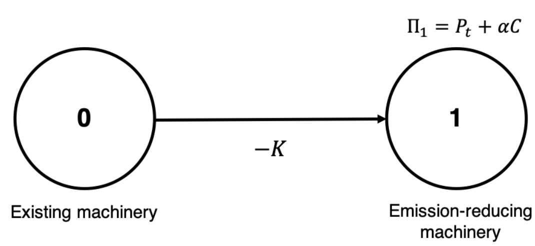


Figure 4.1: Figure of the investment decision and profit flows in each state

4.2 General setup

In our model, we consider an irreversible option to invest in a less CO_2 intensive propulsion system. By paying the investment cost K, the shipowner receives the spread P_t between the two fuel types. Furthermore, the shipowner receives the reduction in carbon tax αC_t. The constant α is equal to the portion of carbon dioxide reduced in the retrofitted state, compared to the original state. The value of α depends on the investment under consideration. C_t is the carbon tax per tonne CO_2 emitted. The total cash flow is denoted Π_1 and is not an actual cash flow, but rather the potential savings by investing. The states and its associated cash flows is summarised in Figure 4.1. The optimal stopping problem of the shipowner is given by

$$F(\tau, S_\tau) = \sup_{\tau \geq 0} \mathbb{E}\left[\int_\tau^T ((P_t + \alpha C_t) - K)e^{-\rho t}dt\right] \tag{1}$$

where C_t reduces to the constant C under the flat tax scheme. We assume the fuel prices to follow Ornstein-Uhlenbeck processes, as commodities often show mean-reverting properties. (Dixit and Pindyck, 1994) According to Sødal *et al.* (2008), the spread between such processes is itself an Ornstein-Uhlenbeck process. The spread is given by

$$dP_t = \mu(m - P_t)dt + \sigma dW_t \tag{2}$$

where μ is the mean-reversion rate, m is the mean, σ is the volatility and dW_t is a Wiener process. A high μ will quickly revert the price back to its mean, in the case where the price is far away from the mean. We solve the model with a flat tax and a cap and trade scheme separately in the following sections.

4.3 Option to invest under a flat tax

To investigate the investment decision under a flat tax, we consider a perpetual option to invest. With only one source of uncertainty, we are able to derive a numerical solution to the investment problem. This solution also serves as an important benchmark for both optimal spread and tax level. The option to invest maximises the stopping problem given by Equation 1, but considers the carbon tax as a constant, C. With only one source of uncertainty, the fuel spread P_t , a numerical solution is obtainable if an infinite project lifetime is assumed. To account for the actual project lifetime, from now until scrapping, we adjust the discount rate ρ. As a result, the maximisation problem can be written as an infinite integral given by

$$F(\tau, S_\tau) = \sup_{\tau \geq 0} \mathbb{E}\left[\int_\tau^\infty ((P_t + \alpha C) - K)e^{-\rho t}dt\right] \tag{3}$$

The evolution of the value in the project can be written as

$$\frac{1}{2}\sigma^2 V''(P) + \mu(P - m)V'(P) + \rho V(P) + P + \alpha C = 0 \tag{4}$$

Sødal *et al.* (2008) finds a general solution to Equation (4). This differential equation can be written on the form:

$$zy''(z) + (b - z)y'(z) + \theta y(z) = 0 \tag{5}$$

Equation (5) is known as the Kummer equation. According to Slater (1960), this equation can be solved by the hypergeometric function of the first kind, also called the Kummer function. This has the following series representation:

$$H(\theta, b, z) = \frac{\theta}{b}z + \frac{\theta(\theta+1)z^2}{b(b+1)2!} + \frac{\theta(\theta+1)(\theta+2)z^3}{b(b+1)(b+2)3!} + ... \tag{6}$$

The general solution of V becomes:

$$\begin{aligned} V(P) = AH\left(\frac{\rho}{2\mu}, \frac{1}{2}, \frac{\mu}{\sigma^2}(m-p)^2\right) \\ +B(m-p)H\left(\frac{1}{2}(1+\frac{\rho}{\mu}), \frac{3}{2}, \frac{\mu}{\sigma^2}(m-p)^2\right) \end{aligned} \tag{7}$$

Where A and B are constants. Furthermore, we find the present value of the investment decision which is the specific solution of Equation 4. First, the expected value of P_t following the Ornstein-Uhlenbeck process is:

$$\mathbb{E}[P_t|P_0] = m + (P_0 - m)^{-\mu t} \tag{8}$$

Applying the results in Equation 8 yields the specific solution for the option value:

$$\mathbb{E}\left[\int_{\tau}^{\infty}(P_t - \alpha C)e^{-\rho(t-\tau)}dt\right] = \frac{m+\alpha C}{\rho} + \frac{P-m}{\mu+\rho} \tag{9}$$

The solution of the option value is thus given by:

$$\begin{aligned} V(P) = AH\left(\frac{\rho}{2\mu}, \frac{1}{2}, \frac{\mu}{\sigma^2}(m-p)^2\right) \\ +B(m-p)H\left(\frac{1}{2}(1+\frac{\rho}{\mu}), \frac{3}{2}, \frac{\mu}{\sigma^2}(m-p)^2\right) + \frac{m+\alpha C}{\rho} + \frac{P-m}{\mu+\rho} \end{aligned} \tag{10}$$

where A and B are unknown constants that has to be determined by the boundary conditions of V. As the $P \to -\infty$ the option to invest becomes worthless. To determine the value of the constants so they satisfy this condition, we have to consider the value of the Kummer function at the boundaries. The asymptotic behaviour of the Kummer function is given by Slater (1960):

$$\lim_{z\to\infty} H(\theta, b, z) = \frac{\Gamma(b)}{\Gamma(\theta)}e^z z^{\theta-b} \tag{11}$$

Using 11, Sødal *et al.* (2008) finds the appropriate values of B given in terms of A:

$$B = -\frac{\sqrt{\mu}}{\sigma}\frac{\Gamma(\frac{1}{2})\Gamma(\frac{1}{2}(1+\frac{\rho}{\mu}))}{\Gamma(\frac{3}{2})\Gamma(\frac{\rho}{2\mu})}A \tag{12}$$

In order to find the switching thresholds P_L and P_H, value matching and smooth pasting conditions needs to be applied:

$$F(P) = V(P) - K \tag{13}$$

$$F'(P) = V'(P) \tag{14}$$

Considering equations (D.2-14), we have three equations with the three unknowns, P, A, and B. P^* is the spread value where the shipowner choose to invest. This becomes an important variable in the following analysis. The procedure for solving this system of equations is given in the Appendix. The solutions are then obtained by using a numerical solver in Python.

4.4 Finite investment problem

In the previous section, we considered an option with an assumed infinite lifetime. This overstates the project value, as the cash flows are received in perpetuity once the the option is exercised. In order to adjust for the actual lifetime of a ship, we specify a time period that represents the opportunity window of the investment, that is the remaining lifetime of the ship. An important tradeoff now arise. The limited lifetime of the ship, means that the investment has to be undertaken within this period. We further assume that the investment does not extend the lifetime of the project. Thus, by delaying the investment and waiting for new information, the shipowner experienced a decline in the remaining project lifetime along with the associated cash flows. In this section we will implement a flat carbon tax and cap and trade system over a limited time span. In the cap and trade system, the carbon price is uncertain. In addition, it is expected that the investment cost will decrease over time, due to increased shipyard efficiency stemming from retrofit experience and technology improvements (SEA-LNG, 2020). We assume a decreasing investment cost to account for this.

4.4.1 Model

The finite investment problem is similar to the problem presented in Section 4, but differs by three important factors: 1) a finite lifetime T, as opposed to the perpetual lifetime, 2) the investment cost is considered a stochastic variable and 3) in the cap and trade scenario, the carbon price is also considered a stochastic variable. Once a finite lifetime is assumed, an analytical solution is harder to obtain. Because of this, we apply a simulation approach. This also gives flexibility to incorporate more stochastic variables. The optimal stopping problem is given by Equation 15:

$$F(\tau, S_\tau) = \sup_{\tau \geq 0} \mathbb{E}\left[\int_\tau^T ((P_t + \alpha C_t) - K)e^{-\rho t} dt\right] \tag{15}$$

In the comparison of the two tax systems, we consider two scenarios:

1. **Flat tax** where the carbon price $C_t = C$. This is similar to the analytical model.

2. **Cap and trade system** where the carbon price is uncertain as carbon allowances are traded in a market. We assume that the carbon price C_t follows a GBM process given by

$$dC_t = \alpha C_t + \sigma_C C_t dW_t \tag{16}$$

   Where C_t is the carbon price at time t, σ_C is the volatility and dW_t is a Wiener process. For the assumptions behind this modeling choice, see Section 5.2.2.

The investment cost K is first considered constant for the comparison with the perpetual benchmark model. Later, when we expand the model to include the cap and trade system, jumps in the stochastic cost is also included. We model the reduction in the investment cost K as discrete jumps following a Poisson process. The frequency of the jumps is λ. Then, by the Poisson process definition, the probability of a jump is λdt. The investment cost K is given by

$$K_t = K_{t-1} + dq_t \tag{17}$$

where K_{t-1} is the investment cost in the previous time period and dq_t is defined by:

$$dq_t = \begin{cases} -J & \text{if jump at time t} \\ 0 & \text{if no jump at time t} \end{cases} \tag{18}$$

As the jump size J is expected to vary within a certain interval, we assume J $\sim N(\mu, \sigma^2)$.

4.4.2 Least Squares Method

The model setup includes three stochastic process under the cap and trade system and two stochastic processes under a flat tax. For multidimensional options with a finite lifetime, there exists no analytical solutions. In order to obtain a solution to the problem, we need to apply a numerical approach. The Least-Squares Method presented in Longstaff and Schwartz (2001) is a computationally inexpensive implementation of Monte Carlo simulation, as it excludes in-the-money paths. The method uses backward-propagation to find the option value and compares the exercise value and the value of waiting. The value of waiting is estimated using least-square regression. Longstaff and Schwartz (2001) present several types of basis functions to be used in the regression and finds that a broad range of functions give accurate results. Moreno and Navas (2003) studies the robustness of this method for American put options, and find the method to be robust for the type and number of basis functions used in the regression. The method is also robust for multidimensional options. Cortazar *et al.* (2008) applies the LSM method on the Brennan and Schwartz (1985) switching model, both with one and three factors. Based on the these findings, we apply the LSM method on the finite model. Later, when we expand the model with an embedded option, we use the *Option on option* model presented in Gamba (2003).

We consider the option to invest as an American option. To calculate the option value, we assume a finite time horizon [0,T], corresponding to the lifetime of the ship. It is possible to invest at N discrete times, as investment during the voyage is impossible. The interval length corresponds to the length of a voyage. The set of stochastic variables S_t includes the spread P_t and investment cost K_t. In the GBM scenario the carbon price C_t is also included. Thus, we have the following discretized, maximisation problem:

$$F(t_n, S_{t_n}) = \max\left(V(t_n, S_{t_n}) - K_t, e^{-\rho(t_{n+1}-t_n)}\,\mathbb{E}[F(t_{n+1}, S_{t_{n+1}})]\right) \qquad (19)$$

where F is t, V is the option value at time τ, K is the investment cost and $S_t = (P_t, C_t, K_t)$.
In order to solve the maximisation problem, we begin by simulating ω paths of profit processes. Starting from the expiration date of the ship, T, we calculate the option value of all simulated paths. We then iterate backward, to t = T - T/N, comparing the exercise value with the continuation value, as described in Equation 19). As it is no continuation value in the last time step, we just check if the exercise value is positive in this point. The continuation value is approximated by regressing the future option value on the state variables in the current time step. If the exercise value exceeds the continuation value, a cash flow matrix is updated with the value of immediate exercise. The unknown continuation value function is assumed to be a linear combination of n basis functions. Several basis functions can be used, e.g. Laguerre, Legendre and Jacobi polynomials. As discussed in the literature, the LSM is robust for a broad range of basis functions. Thus, we use a set of Laguerre polynomials as the basic function, denoted L_j. The continuation value is given by

$$\mathbb{E}(F(S_{t+1})) = \sum_{j=0}^{J} \alpha_j L_j(S_{t+1}) \qquad (20)$$

where α is the constant coefficients for each regression. Once we reach time 0, the cash flow matrix contains the information of the investment timing and cash flows gained in each path. The option value is found by calculating the average of the discounted cash flows:

$$F(t_0, S_{t_0}) = \frac{1}{N} \sum_{n=1}^{N} \left(V(\tau_n, S_{\tau_n}) - I\right) e^{(r(\tau_n - t_0)} \qquad (21)$$

5 Case study: LNG retrofit for a Neopanamax Container Ship

In this section, we apply the models presented in Section 4 and 4.4 on the decision to invest in a duel-fuel engine running on LNG. The ship under consideration is a 15,000 TEU Neopanamax container ship running on MGO.

5.1 Model parameters

Table 5.1: Base case parameters

	Parameter	Value	Unit	Description
	Days at sea	240	Days	
	Fuel consumption	1200	mt/trip	
K_1	Initial investment cost, LNG	33	million \$	
C	Tax	0-20	\$/mt	
ρ	Discount rate	0.003		Monthly rate
α	Tax rate LNG retrofit	0.8		
λ	Jump intensity, LNG	0.2		
μ_J	Expected jump size , LNG	3	million \$	
σ_J	Standard deviation, jump, LNG	0.5	million \$	

Based on this, we assume that the ship under consideration is between 5-10 years and a remaining lifetime of 20 years. We consider the retrofit decision to be taken monthly, as the retrofit cannot be undertaken mid-voyage. The cash flows are thus received monthly. The value of the option to invest is driven by the fuel spread, either between MGO and LNG or LNG and ammonia, depending on the option under consideration. It is important to note that this is not an actual cash flow, but rather the potential savings by switching to either one of the options. In the same way, the shipowner receives a proportion of the carbon tax, based on the reduction in carbon emissions. For LNG compared to other fossil liquids, Balcombe *et al.* (2019) estimate a reduction of 20-30% in CO_2. We assume a measure of 20% reduction in CO_2, to get a conservative reduction for the LNG retrofit. Combustion of ammonia emits no CO_2 but requires a secondary fuel to ignite (MAN, 2019). As the quantity of this fuel will be small and may be replaced by e.g. biodiesel, we assume 100% reduction in CO_2 emissions for this retrofit.

The fuel spread is modelled as an Ornstein-Uhlenbeck process in our model. The investment cost of the LNG retrofit is assumed to be \$30 million, similar to the recent retrofit of the Hapag-Lloyd ship 'Sajir' [13]. This investment cost assumes that technical preparations for the LNG retrofit have been done during

[13] Source: https://www.hellenicshippingnews.com/a-first-in-liner-shipping-hapag-lloyd-to-convert-ship-to-lng/

the building of the ship. The retrofit requires approximately three and a half months in a shipyard. To estimate the daily lost revenues, we use the average 6-12 monthly time charter rate for a 9,000 TEU ('Eco' design) Neopanamax, at $29,170/day [14]. For the three and a half month the ship is out of operation, this implies approximately $3 million in lost revenues. As we model the retrofit to happen immediately, we include the lost revenues in the investment cost. It is therefore set to a total of $33 million. We expect the investment cost to decrease over time, due to increased shipyard efficiency stemming from learning and technology improvements (SEA-LNG, 2020). With technological development, we refer to improvements in components and materials applied in the LNG retrofit. As there is still relatively few ships (and shipyards) that have completed a retrofit, the capital costs can be reduced by standardisation of units and the creation of "off-the-shelves" solutions. Although not directly comparable, McKinsey estimates that the capital cost of an LNG plant can be reduced by 5-10% due to prefabricated units.[15]. Furthermore, through experience with LNG retrofits, shipyards can increase their productivity. Thus, we assume that the combined reduction from experience and technology development will result in reductions in investment cost of around 10%. Furthermore, we assume the jumps to be of different size, but with an expected value of $3 million corresponding to the 10% reduction and a standard deviation of $0.5 million. Thus, J is assumed to follow a normal distribution $\sim N(3, 0.5^2)$. We assume a jump in the cost every fifth year, corresponding to a $\lambda = 1/5$ in the Poisson process.

We estimate the monthly discount rate to be 0.75%, based on a yearly, average industry cost of capital of 9.37% [16]. We assume 240 days at sea per year, corresponding to an average sea percentage for container ships of around 70% (Psaraftis and Kontovas, 2009). In the determination of the fuel consumption, we assume a constant consumption of 60 metric tonnes per day. The parameter is hard to measure as it depends on the efficiency of the engine, speed and route details. Furthermore, fuel data is rarely collected from private shipping operators making it hard to find average consumption for the ship type. We choose a conservative measure as a base case, to avoid an overvaluation of the option. The uncertainties in this measure will be addressed in the sensitivity analysis in Section **??**.

In our modelling approach, we exclude all positive impacts of switching to less polluting machinery, even though this has a significant value. An increased focus on the environmental impact through the entire value chain has caused large brands to start including environmental pricing into their contracts with shipping companies. (SEA-LNG, 2020) This advantage is hard to quantify but will increase the value of both options. The retrofit is not assumed to add any-

[14]Source: Clarkson's Shipping Intelligence Network

[15]Source: *Setting the bar for global LNG cost competitiveness, McKinsey & Company, 2019, https://www.mckinsey.com/industries/oil-and-gas/our-insights/setting-the-bar-for-global-lng-cost-competitiveness*

[16]Source: http://people.stern.nyu.edu/adamodar/New_Home_Page/datafile/wacc.htm

thing to the scrap value of the ship. Hence, we do not include the scrapping value of the ship at the end of the lifetime in our analysis as this is equal no matter the decisions made. An important barrier to invest in a retrofit in LNG is the availability of bunkering infrastructure in ports. As of today, only the biggest ports offers LNG. The number of ports offering LNG is expected to increase drastically in the next years, lowering the barrier to invest.

5.2 Stochastic processes

5.2.1 Fuel spread dynamics

In this section, we argue that the modelling of the spread between two fuel prices as an Ornstein-Uhlenbeck process is appropriate. Mean-reversion in commodity prices also has an economic intuition. High fuel prices will attract suppliers trying to take advantage of the increased profits. On the consumer side, high prices will reduce demand. Both of these effects result in downward price pressure. The opposite holds for low fuel prices. Assuming that the dynamics of two fuel prices can be represented as two O-U processes, the differential between the two processes is itself an O-U process (Sødal *et al.*, 2008). In addition to reduce the number of stochastic factors in our problem, we argue that the spread is a more relevant measure for the shipowner for undertaking the investment. Thus, we conclude that the modelling of the spread as an Ornstein-Uhlenbeck process is appropriate and continue with an empirical analysis of the relevant fuel data.

In the case study, we investigate the investment in a retrofit to a duel fuel engine with LNG as the main fuel. Thus, we are interested in the spread between the initial fuel and LNG. As initial fuel, we choose Marine Gas Oil (MGO) as it is compliant with the sulphur restrictions following the introduction of IMO 2020. This fuel has a long history and is considered a more reliable fuel than the newly introduced fuel Very Low Sulphur Oil (VLSFO). However, VLSFO is at the time of writing selling at lower price levels than MGO, resulting in lower profits for the LNG investment. We use weekly price data in dollar per metric tonne for MGO in Singapore. The LNG prices are given in dollar per mmBTU for natural gas delivered in Asia. Both time series are collected from Clarksons Shipping Intelligence Network. To compare prices between the two fuels, we have to perform a conversion. This is done by converting from mmBTU to metric tonnes and adjusting for the different energy density. The resulting LNG price is given in dollar per MGO equivalent ($/MGOe).

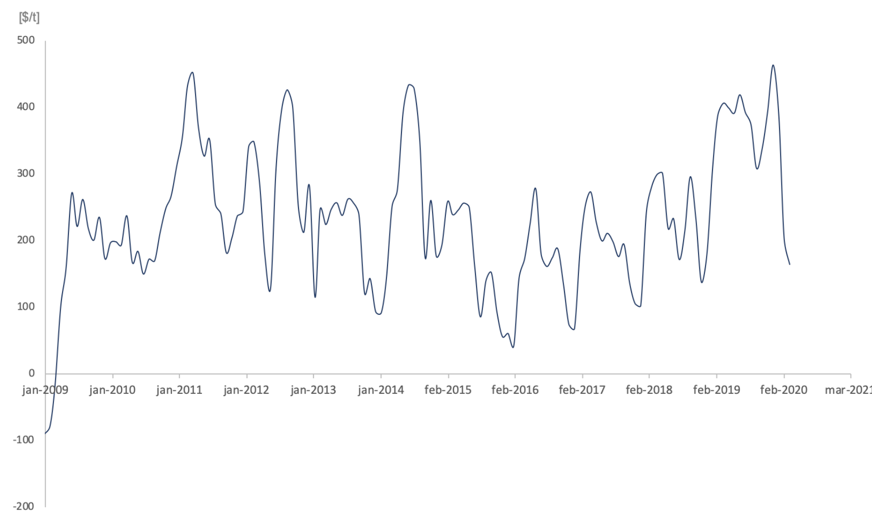


Figure 5.1: Historical levels of the price spread between MGO and LNG, given in tonnes. Source: Clarkson's Shipping Intelligence Network

The time series in Figure 5.1, shows the spread between the fuel price of MGO and LNG from 2009-2020. A visual investing suggests mean-reverting properties, with a mean spread fluctuating around $250.
In addition to the theoretical reasoning and visual investigation, we formally test the data for mean-reversion. An important property of the Ornstein-Uhlenbeck model is constant volatility. To investigate if the time series exhibit volatility stationarity, we perform an Augmented Dickey-Fuller (ADF) test. The test has a null hypothesis stating that the time series is non-stationary, while the alternative hypothesis suggests a stationary time series. The null hypothesis is rejected if the test statistic τ_{ADF} is less than the ADF critical values for a given significance level. We perform the test on the monthly spread from 2009-2020, a total of 135 observations. In the determination of the number of lags, we use the Bayesian Information Criteria (BIC). The resulting test statistic $\hat{\tau}_{ADF}$ = -5.278 is well below the 1% significance level of -3.480. Thus, we can reject the null hypothesis of a non-stationary time series. Additionally, we calculate a Hurst Exponent of $H = 0.0172$. This value suggests a strong mean-reversion in the data. Based on these results, we assume that the spread can be modelled as an Ornstein-Uhlenbeck process given by

$$dP_t = \mu(m - P_t)dt + \sigma dW_t \tag{22}$$

where P_t is the fuel spread, μ is the mean-reversion speed, σ is the volatility and dW_t is a Wiener process. As done by Dixit and Pindyck (1994), we run an OLS regression on the following form

$$P_t - P_{t-1} = a + bP_{t-1} + \epsilon_t \tag{23}$$

Here, a and b are constants, while ϵ_t is assumed iid and $\sim N(0, \sigma)$. Both estimates for a and b has p-value well below the 5% level and we conclude the variables to be statistically significant.

Table 5.2: Estimation of parameters by OLS regression

Parameter	Value	t-statistic	p-value
a	53.21	4.224	4.421E-05
b	-0.2215	-4.470	1,659E-05
Standard error	60.17	-	-

To estimate the actual parameters in Equation 22, we use the following formulas given in Dixit and Pindyck (1994):

$$\hat{m} = -\frac{\hat{a}}{\hat{b}} \tag{24}$$

$$\hat{\mu} = -log(1 + \hat{b}) \tag{25}$$

$$\hat{\sigma} = \hat{\sigma}_\epsilon \sqrt{\frac{log(1 + \hat{b})}{(1 + \hat{b})^2 - 1}} \tag{26}$$

The results is given in Table 6.2.

Table 5.3: Parameters for the fuel spread modelled as an Ornstein-Uhlenbeck process

	Parameter	Value	Units	Description
$\hat{m}$	Mean	240.18	\$/tonne	
$\hat{\mu}$	Mean-reversion rate	0.109		
$\hat{\sigma_P}$	Volatility	31.61		Monthly
P_0	Current spread	244.08	\$/tonne	June estimate

5.2.2 Carbon price process

In a cap and trade scheme, carbon allowances are traded frequently and the prices are thus uncertain. The stochastic process used to model the carbon price should capture the characteristics of the actual price movements in such a market. As we consider a theoretical cap and trade scheme for the shipping industry as a whole, we look to an already existing market to get a proxy. The EU ETS, explained in detail in Section **??**, is the largest carbon market to this date with price data available. Furthermore, the market exhibits important characteristics that a theoretical shipping market should have. First, the carbon price should be uncertain and not able to take negative values. Furthermore, a mechanism called the Market Stability Reserve was introduced in 2018 (Parliament and the Council, 2015), removing allowances in the case of unforeseen demand drops. This is likely to happen in periods of low economic activity, such as the financial crisis in 2008. In the years following, the carbon price fell significantly, see Figure 5.2. Based on these two characteristics: uncertainty and a mechanism to avoid price jumps, the GBM seems to be an appropriate stochastic process for the carbon price. Furthermore, academic literature on energy investments often model the EU ETS and other trading schemes as a GBM (Compernolle *et al.* (2020), Boomsma *et al.* (2012), Fuss *et al.* (2008)).

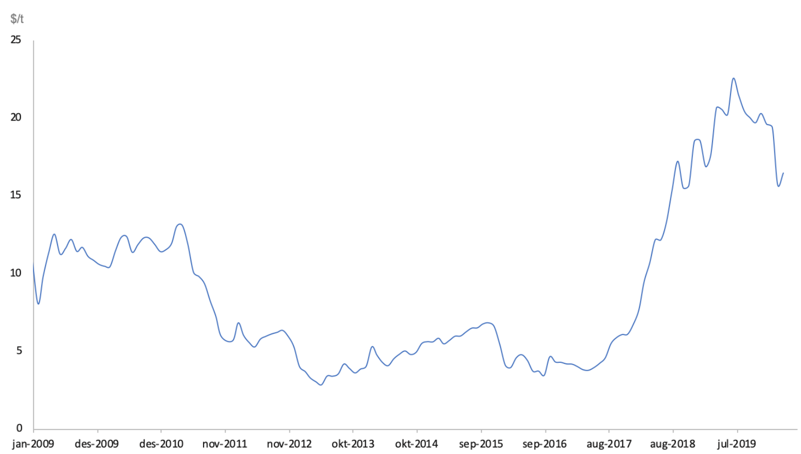


Figure 5.2: Historical price levels for CO_2 allowances in the EU ETS 2009-2020. Source: https://ember-climate.org/carbon-price-viewer/

The carbon prices are given in EUR, so a conversion to USD is necessary. We assume that the shipowner will hedge perfectly against any exchange rate risk, thus we try to exclude this risk from our analysis. Experimenting with different exchange rate regimes, especially considering the euro crisis in 2014, we find small differences in the carbon price levels. Hence, we use an average exchange rate for the period 2009-2020 equal to 0,8037 USD/EUR in the conversion. We repeat the ADF tests from the previous section to see if the time series contains a unit root. The test statistic is $\tau_{ADF} = -1.835$, above the 10% significance level of -3.147. Hence, we are not able to reject the null hypothesis, hence the process is not stationary. Supported by the academic literature presented above, we model the carbon price as a GBM. The parameters of the stochastic process are calculated by the formulas given in Appendix **??**, applied on the monthly carbon price for EU ETS allowances in the period 2009-2020. The resulting parameter values are given in Table 5.4.

Table 5.4: Carbon price process parameters

	Parameter	Value	Units	Description
C_0	Current price	20.90	\$/tonne	Date: 01.06.2020
α	Drift	0.007	\$/tonne	
$\hat{\sigma_C}$	Volatility	0.102		

Real option analysis

In this section, we analyse the investment decision applying real options valuation methods. We use the models presented in Section 4, that is the investment problems with an infinite and finite project lifetime. The perpetual model is a traditional real options model and can be solved with relative ease. We use the model as a benchmark, but more importantly, to point out the differences between the perpetual and finite model. Furthermore, we compare the investment thresholds with the NPV method, as the method is often used by policymakers to investigate the effects of new regulations. This will give us a holistic understanding of the investment problem and the effects of tax.

5.3 Perpetual investment problem

We now apply the parameters in Table 5.1 to the perpetual investment problem with tax levels ranging from \$0-\$20. The option values with the corresponding investment thresholds are given in Table 5.5. Considering the current spread of \$244, the investment would have been postponed for all of the tax levels. The effects of increasing tax can be seen in Figure 5.3. By increasing the tax level from zero to \$10, the option value increases by \$0.99 million. More importantly, the investment threshold reduces by \$11.2. The investment thresholds mark the points where the option value is equal to the net present value, as the value matching condition in the model indicates. When the spread reaches the investment threshold, the investment is undertaken. As the level of spread is lower than the investment threshold, the investment would be delayed.

Table 5.5: Perpetual model: Option values for different tax levels

Tax level	Threshold	Option value
0	\$271.2	\$5.52m
\$10	\$260.0	\$6.51m
\$20	\$249.5	\$7.52m

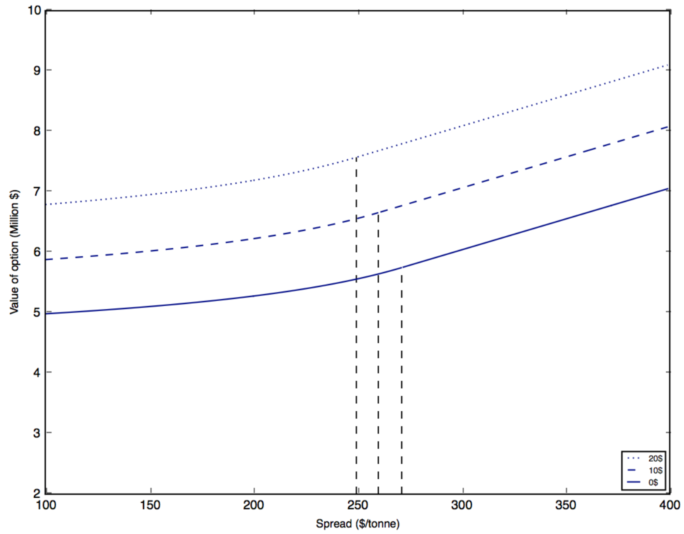


Figure 5.3: Option value for given spreads

5.3.1 Sensitivity to spread volatility

We now investigate the impact that varying the fuel spread volatility has on the investment. As Figure 5.4 shows, the option value before investing increases with increased volatility. This is visible from the upwards shifts in the option value for increasing volatility. The investment thresholds are also increasing with the volatility. For a doubling of the volatility compared to the base case, the threshold increases from $249.5 to $296. Furthermore, the option value increases from $7.6 to $8.2 million, an increase of $0.6 million. This is consistent with traditional option theory, presented in e.g. Dixit and Pindyck (1994). As the volatility in the spread increases, there will be larger fluctuations in the spread and a higher upside for the future profit flow. As the option is lower bounded by zero, i.e. not investing, the upside from the fluctuations increases more than the downside. Because of this, the option value increases with volatility. The investment thresholds are also affected, by the same reasons. In order to maximise the profits, the investor takes advantage of the large fluctuations caused by the increased volatility and wait until the option is further in the money. Larger fluctuations also increase the downside of the profit flows. However, this does not affect the option as the value is bounded by zero. Considering the current spread of $244, reducing the volatility by 50% would result in an immediate investment. For this scenario, the investment threshold is $210.

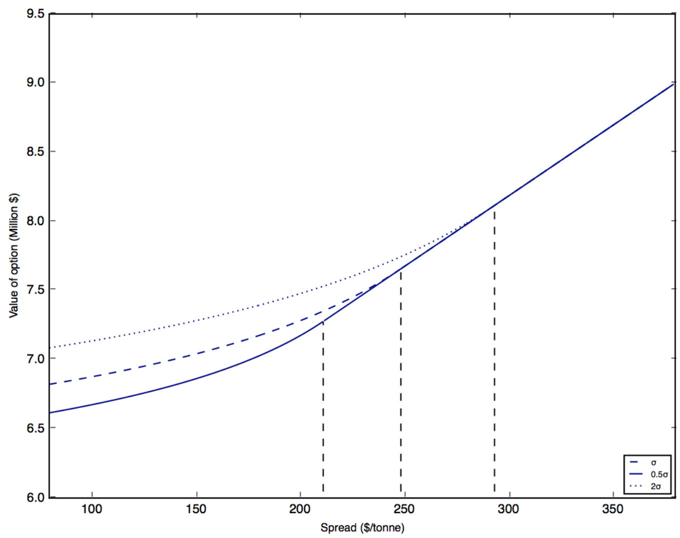


Figure 5.4: Option value for different volatilities on spread

5.3.2 Sensitivity to investment cost

The investment cost of undertaking a retrofit is in the analytical model assumed to be constant. This assumption is worth investigating, as the cost may vary due to several factors. As mentioned in Section 5.1, the investment is expected to decrease due to technology improvement and improved shipyard efficiency. Furthermore, the variable can also vary due to other factors, such as individual negotiations between the shipowner and the yard or subsidies from the government. These factors suggest that a constant investment cost may not be a good assumption. To address the effects of variations in the investment cost, we test the model for decreases in the parameter. The option values for different spread levels are plotted for three levels of investment costs in Figure 5.5. As expected, a decrease in investment cost increases the option value. The thresholds also decrease with the investment costs. Considering Figure 5.5, a reduction in the investment cost from $33 to $30 million increases the option value for all spread levels. The investment threshold with an investment cost of $33 million is $249.46/tonne. At this spread level, the option value increases with $3.1m by reducing the investment cost to $30 million. The threshold at this investment cost is$221.3/tonne.

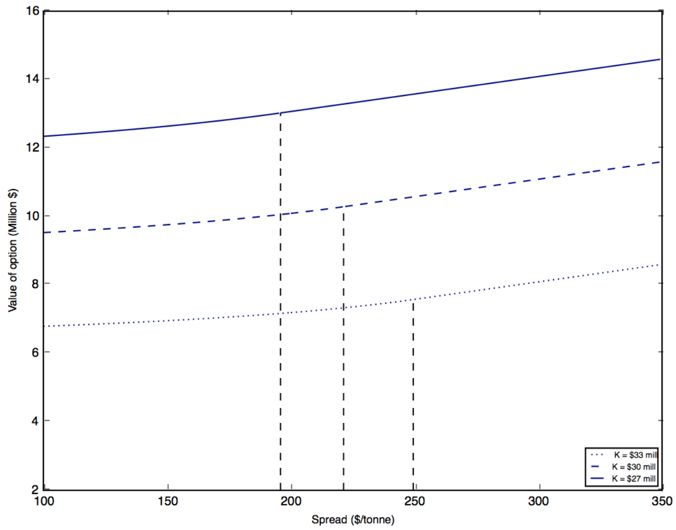


Figure 5.5: Option value for different levels of investment costs

5.4 A limited finite investment problem

In this section, we apply the finite lifetime model presented in Section 4.4 to the case study. For now, the only variable that changes the lifetime of the project. The two additional stochastic processes, carbon price as a GBM and the jump process for the investment costs, is introduced later. We do this is in order to analyse the differences between the infinite and finite model. In the following section, we produce similar calculations as done with the analytical model. In the calculations, we use Monte Carlo simulation with 50,000 simulations.

5.4.1 Option values under different tax levels

We first study the effects of different tax levels in the finite model. This is done by calculating the option value for different spread levels under three different tax levels. The result is presented in Figure 5.6. Increases in the tax level directly affect the cash flows and the value of the investment opportunity increases. In Figure 5.6, consider the zero tax scenario. The investment is only valuable as the spread reaches levels above $330, where it follows the NPV. The increase of the tax level reduces the spread level for where the investment is profitable. An introduction of a $10 carbon tax will lower these levels by approximately $100. The fact that the option is worthless until the inflection point, means that there is no value in deferring the investment. By comparing to the perpetual option, we see that the implementation of a finite opportunity window significantly reduces the project value. In addition, the value of delaying the investment vanishes.

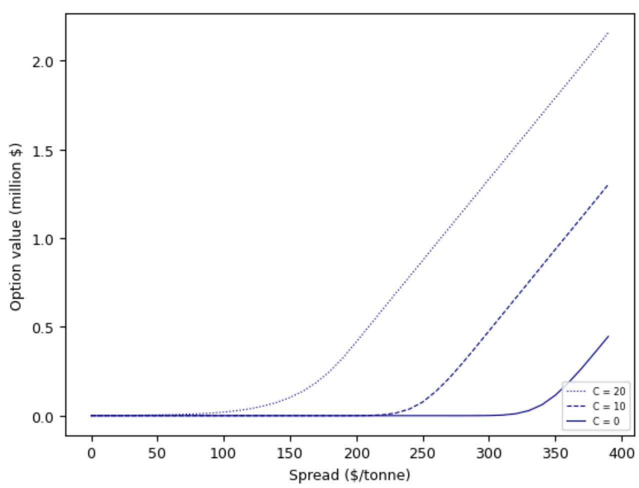


Figure 5.6: Option value given fuel spread level for different tax levels

5.4.2 Option value's sensitivity to volatility

To study the fuel spread volatility's impact on the investment problem, we again calculate the option values but for different volatilities. The result is shown in 5.7, which shows that the option values for all volatility scenarios coincide. This is in contrast to traditional option theory, that an increase in the volatility will increase the option value and the optimal threshold (Dixit and Pindyck, 1994). This effect was shown for the analytical benchmark in Section 5.3.1. In this case, the option value does not change notably for variations in the volatility. From Figure 5.7, a doubling of the volatility, from 31.61 to 63.22, only increase the project value slightly in the inflection area. This result is due to the option's dependence on the remaining lifetime of the ship, as the delaying of the investment results in lost cash flows that can never be recovered. Consider an increase in the volatility, ceteris paribus, this will increase the profit's upside and thereby the option value. But in order to capitalise on this volatility increase, the investor would have to wait. Thus, the change increases the value of waiting. For the finite lifetime option, the increased upside has to be greater than the actual loss of cash flows incurred by waiting. As this option is highly dependent on a limited amount of cash flows, volatility does not impact the option value notably, in contrast to the results found in the perpetual model.

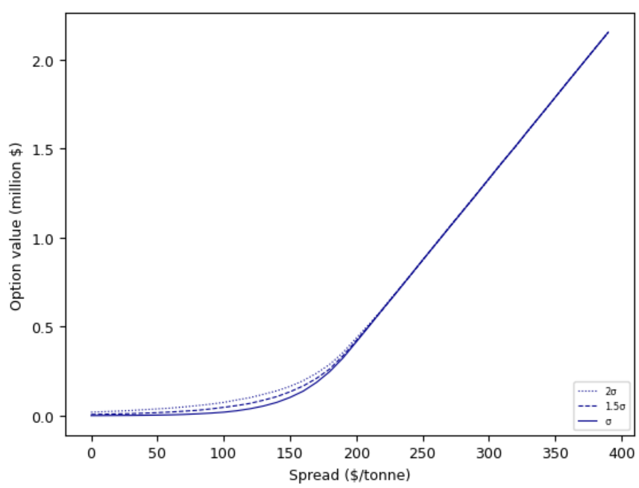


Figure 5.7: Option value for different volatilities on fuel spread. C = 20

5.4.3 Sensitivity: Investment cost

As there is significant uncertainty regarding the actual investment cost of the decision, we investigate the effects of a reduced investment cost on the option value. As discussed in the assumptions, we also expect the investment cost to decrease due to technological development in components and processes. In Figure 5.8, the option values have been calculated for three investment costs, the base case, $30 million and $27 million. The increase of the investment cost results in upwards shifts for the project values. Considering the project value with an investment cost of $30 million, the value increases by approximately $2.38 million for a spread of $0 compared to the base case. Furthermore, this is no longer a now-or-never decision. At a spread level of $0, the investment is undertaken after 11 months. The time to invest decreases until a spread of $170, where investment is done immediately. Under an investment cost of $27 million, the option value is $5.18 and the investment occurs after 8 months for a spread of $0. It is worth noting that the investment thresholds is dramatically reduced for all investment costs compared to the perpetual option.

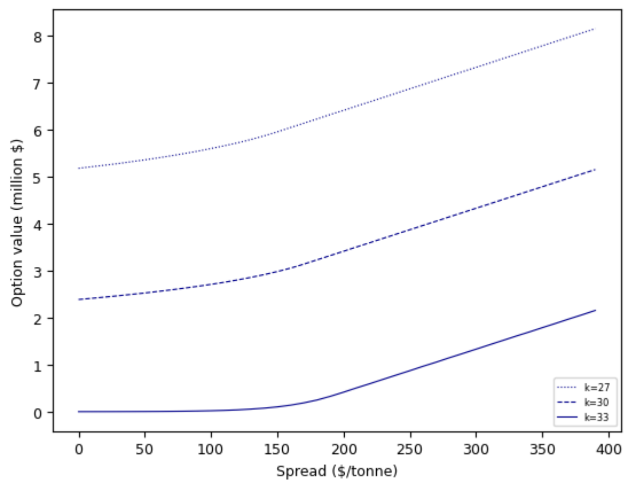


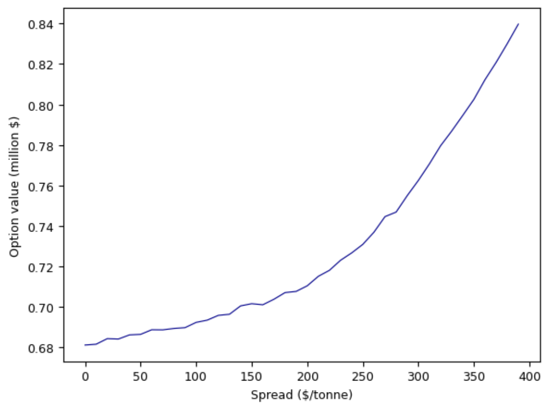
Figure 5.8: Option value for given fuel spread levels for different investment costs

5.5 Finite investment problem included jumps

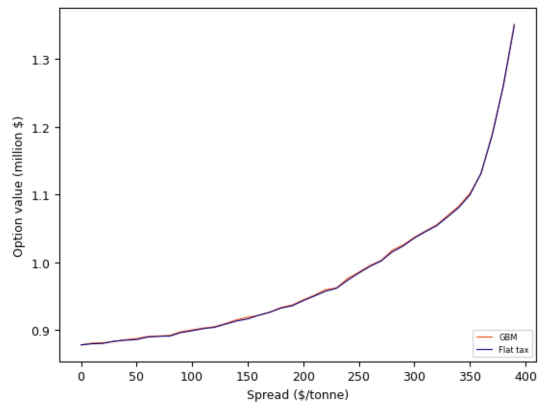
We now apply the full finite model presented in Section 4.4 for the parameters presented in Table 5.1. We expand the finite model from the previous section with two changes: a stochastic carbon price and jumps in the investment cost. We assume the investment cost to decrease due to technological innovation and improved learning in shipyards, in contrast to the previous section where we assumed this to be constant. We argue that with these model changes, we achieve some critical features to model to better approximate the dynamics in the investment decision. Applying Monte Carlo simulation to solve the model, we calculate the option values under the different tax systems. Furthermore, we address the models sensitivity to changes in the volatility, jumps in the investment cost and fuel spread parameters. It is important to note that the option values are calculated for a ship with a remaining lifetime of 20 years. As time passes, the remaining lifetime of the option will decrease with the ship's lifetime. This property also results in significant option value reduction associated with delaying investment, as the foregone cash flows will not be collected at a later stage. We have used 50,000 simulations in the calculation of the results.

5.5.1 Option value under different tax systems

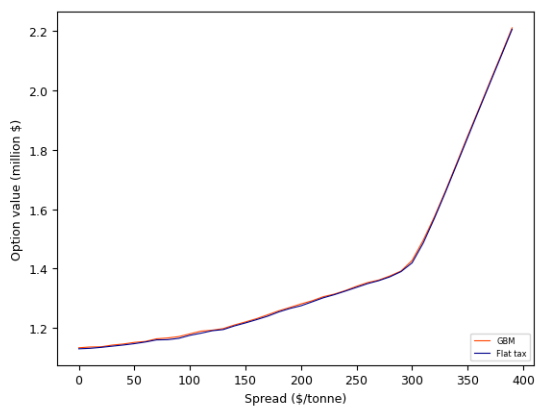
The effects of a carbon tax under a flat tax and a cap and trade system on the option value is presented in Figures 5.9a-5.9c. The option values for the flat tax and the cap and trade system are plotted for different values of fuel spreads. This is done for three flat tax level scenarios: no tax, \$10 and \$20. For the cap and trade system, the starting value for the carbon price corresponds to these levels. The graphs behave as expected, with option values that increase with the fuel spread. Figure 5.9a-5.9c shows that the spread level that triggers immediate investment decreases for increases in the tax. This level is around the inflection area of each graph. This is visible in Figure 5.9b and 5.9c. In Figure 5.9a this area is not visible, meaning that the investment threshold is above \$400/tonne



(a)



(b)



(c)

Figure 5.9

The fuel spread levels for immediate investing has increased significantly compared to the limited finite model presented in Section 5.4. This can be explained by the presence of discrete jumps in the investment costs. Once the jumps occur, the project value increases significantly.

Figure 5.10 illustrates the time to invest for different tax levels. With no tax, time to invest would not drop to zero at the spread levels presented, as the value of waiting for a jump will exceed the value of investing immediately. This confirms the result in 5.9a, where the option value never follows the NPV. With a tax level of $10, the time to invest drops suddenly at a spread level of $350. At a spread level of $390, the threshold is reached, and the investment happens

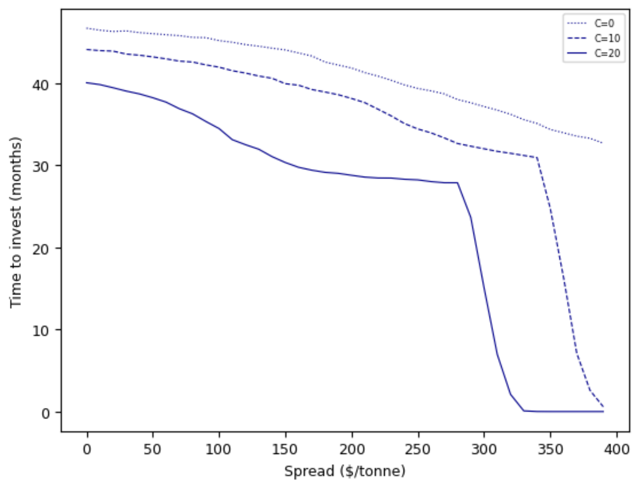


Figure 5.10: Time to invest in months for different spread levels

immediately. At this point, the cash flows received from investing immediately exceed the value of waiting for a jump. To explain the sudden drop, we need to consider a tax level below and above the threshold. For tax levels above the threshold, the investment happens instantaneously. However, if the threshold is not reached, the investment is delayed until a jump occurs. In theory, this drop in investment timing is instant. However, by running simulations, there would be a rapid, but not instant, decline, as most of the paths are in the money immediately, but some have a higher value of waiting. When considering the tax level of $20, the same dynamics apply. However, the drop arrives at a lower level of spread, as the foregone cash flows increase with the increased tax levels. Looking at Figure 5.9b and 5.9c the option value under the flat tax and the cap and trade system coincide. Thus, it seems that there is no considerable difference between the two tax systems. This result stems from at least two factors in the model. First, tax makes out a small proportion of the profit flow. The retrofit results in a 20% reduction in CO_2, which gives a corresponding 20% reduction in the carbon tax. Even though the combustion of one tonne fuel results in 3.2 tonnes of CO_2 emitted, the resulting proportion of the tax is 0.64. Hence, for a $20 carbon tax, the total tax savings is $12.8. By comparison, the fuel costs saved per tonne is on average the mean of the spread ($240). Secondly, the calculated carbon price volatility is particularly low. To investigate the effects this volatility on the option value, we test for different volatility levels in the next section.

5.5.2 Sensitivity to carbon price volatility

To visualise the option values sensitivity to volatility in the carbon price, we consider three scenarios with volatilities 0.5σ and 2σ in addition to the base case. In Figure 5.11 shows the option values plotted for given fuel spreads under the three scenarios. There are no notable differences between the three scenarios. Differences before the inflection in the graphs is due to variations in the simulations. This indicates that the differences between a flat tax and a cap and trade system is negligible for our case study. This is because the taxes contribution to the profit flow is rather low. An increase in the tax volatility would slightly increase the value of waiting. However, the increased value of waiting is not sufficient to compensate for the lost cash flows. As increases in the volatility does not affect the option value, we will not pursue the cap and trade scenario with a modified volatility. Furthermore, the inclusion of the cap and trade significantly increases the computational time needed to produce meaningful results. Due to the combination of these factors, we continue using only flat tax in the following sections.

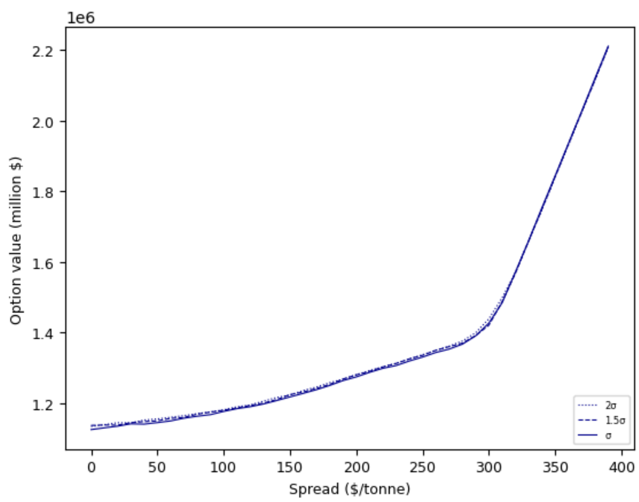


Figure 5.11: Option values for different carbon tax volatilities

5.5.3 Sensitivity: Jumps in investment cost

In the finite model, the expected variations in investment cost is represented a Poisson process. The occurrence of an investment jump is determined by the arrival rate, which is assumed to be 1/5 in the base case, or one jump every fifth year. To investigate the effects of changes in the arrival rate, we vary λ to represent a scenario with a rapid ($\lambda = 1/3$) and no technological development ($\lambda = 0$). The former represent a scenario where a large proportion of the global fleet undergoes retrofits and resources into R&D increases. The latter is an extreme case, where no technological development happens. This is not realistic, but compared to the other scenarios it highlights the dynamics of adding a jump process to the model. Figure 5.12 illustrates the options values for given tax levels under the three arrival rates. We now focus on the tax levels rather than the spread, as we want to investigate the tax level's effect on the option values in this model. The dynamics is the same as for the spread. The option values increase with the tax levels. As expected, the shape of the graph for $\lambda = 0$ resembles the ones presented in Section 5.4.1. Under a flat tax, the investment jump is the only difference between the limited finite and the finite model.

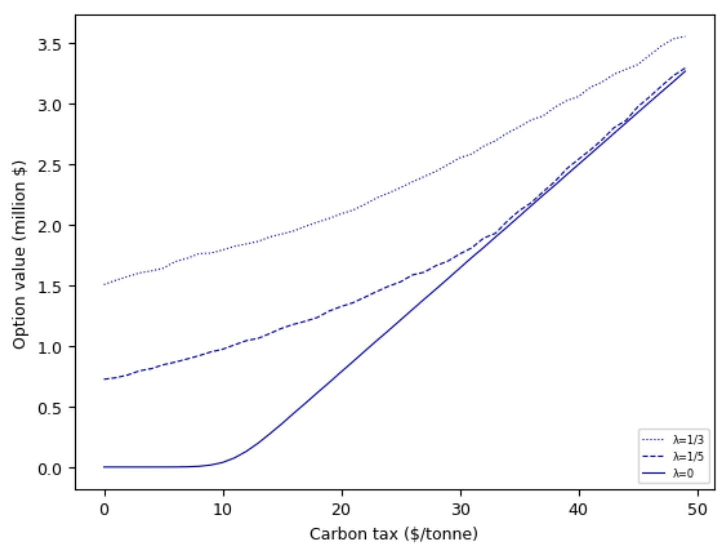
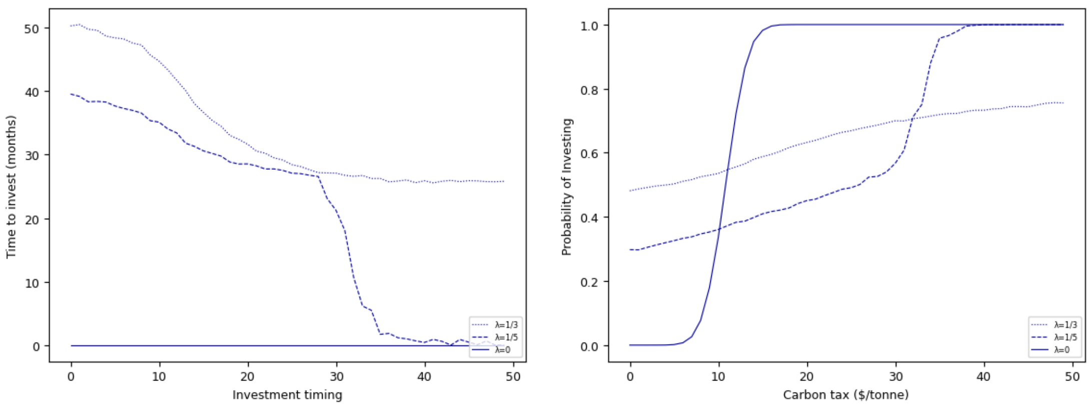


Figure 5.12: Option value for different jump frequencies

Furthermore, an increase in the arrival rate causes upwards shifts in the option values. Consider Figure 5.12 and a carbon tax of \$10. For the scenario where $\lambda = 1/5$, the option value is \$0.7 million. When λ is increased to 1/3, that is one arrival every third year, the option value increases by \$1.78 million.

In Figure 5.13a the time to invest in the different scenarios are presented. With no jumps, the investment is a now or never decision. In the base case scenario, the timing depends on the arrival of a jump, until the tax threshold of $35 is reached and investment happens immediately. For tax levels higher than this, the inclusion of jump does not have a big effect on the option value, as shown in 5.13. As we investigate jumps every 3 years, a threshold is not reached, and the value of waiting for the jumps before investing exceeds the value of receiving the cash flows until the jumps arrive.



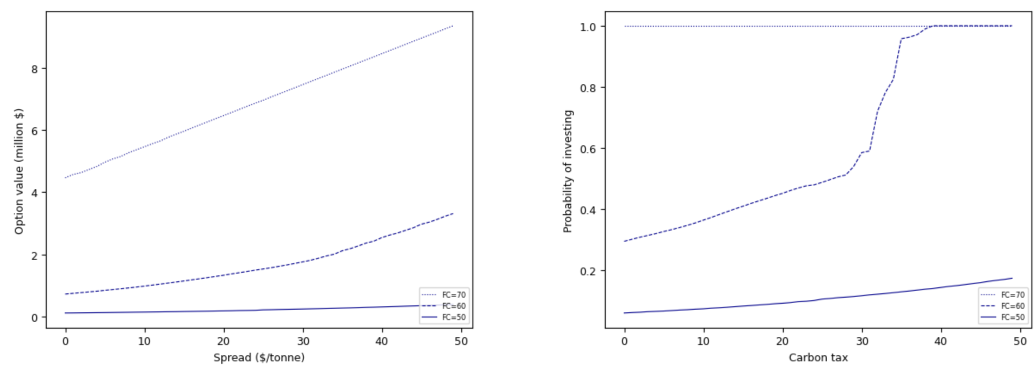
(a) (b)

Figure 5.13: Panel (a): Time to invest for different jump frequencies, Panel (b): Probability of investing for different jump frequencies

To further investigate the impact of different arrival rates in the jumps process, we calculate the probability of investing during the lifetime of the option. Considering the increase in the option value for increasing arrival rates, we expect the probability of investing to increase as well. The probabilities for different tax levels are plotted in Figure 5.13b. Considering the scenario with no technological development ($\lambda = 0$), the probability of investing increases with the carbon tax. As tax level increases from $9 to $12, the probability of investing goes from 0 to 1. In the same tax interval, the probability of investing in the base case has a modest increase of 0.05. This can be explained by the following rational: As the investment is delayed, the investment decision is highly dependent on the arrival of jumps in the investment cost. While waiting for the investment jumps, cash flows are lost. If the jump arrives too late, it will not compensate for the lost cash flows. Therefore, the investment would not be undertaken. For higher level than the tax threshold of $35, the probability of investing would be 1. The same dynamics holds for jumps every 3 years. However, as stated in the paragraph above, the threshold is never reached for this λ, and the probability of investing would never reach 1.

5.5.4 Sensitivity to fuel consumption and spread mean

As mentioned above, the savings on fuel consumption is the greatest contributor to the value of the option. In this section we will investigate the consequences of changing spread mean and fuel consumption. Figure 5.14a illustrates the option values with different levels of spread and figure 5.14b shows the probability of investing in the different scenarios. The value of the option increases significantly when the fuel consumption increases from 60 to 70 tonnes per day. As Figure 5.14b shows, all of the simulated paths are in the money for all tax levels. The investment happens immediately, which explains why the option value is following the linear NPV value. Since all paths are in the money, an incorporated tax would not impact the investment decision, it would only make the investment more profitable. The opposite holds for a decrease in fuel consumption.



(a) (b)

Figure 5.14: Panel (a): Option value for tax level. Three scenarios for fuel consumption: 50, 60 and 70 tonnes, Panel (b): Probability of investing of paths for different fuel consumption

Figure 5.15 shows the option value with three different levels of the mean spread. We can see that the same dynamics appear. As the mean of the spread increases, the expected value of future cash flows increases, making the project more valuable. With a mean spread of $270/tonne, the investment would be undertaken immediately for all tax levels, meaning that the implementation of the tax would not affect the decision. A decrease in the spread mean shows that the investment decision would not be undertaken for any tax level.
These results show that the investment decision is highly dependent on the savings from the reduced fuel costs. As ships have different fuel consumption, this is an important parameter to investigate before making the investment decisions.

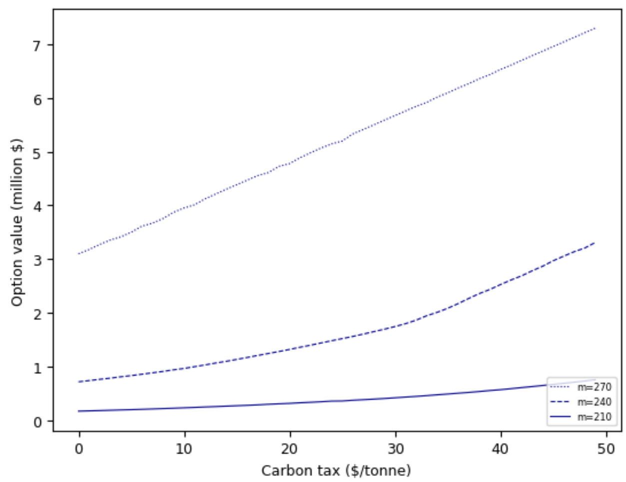


Figure 5.15: Option value for different level of means

6 Sequential investment problem

In this section, we will expand the model in the previous section to include the arrival of new, improved emission-reducing technology. Although some emission-reducing technology is readily available today, most technology that offer a substantial reduction in emitted carbon dioxide is further away in time. Such technologies, some of them discussed in Section 2, may not be available due to its technological maturity, bunkering infrastructure and/or price. By implementing a second option in the investment problem, the model is able to capture any additional value by doing the investment sequentially. The second investment opportunity will represent a technology that offers lower emission than the first investment. For example, consider the initial investment in an LNG retrofit includes the option to do further modifications on the engine to run on ammonia. Further assuming that exercising this second option will have value at some point in the investment horizon, this will make the total investment opportunity more valuable. An important intention of a carbon tax is to incentivise investments in carbon-reducing technology. The inclusion of a second option makes it possible to investigate the effects of a tax on a long-term investment strategy that includes not yet available technology. This is paramount in the shipping industry, where there exists no commercially available technology that is compatible with IMO's emission goals, at least not for long-haul shipping. The model is not limited to the application presented in our case study but can be applied to calculate the value of a sequential investment decision as described above.

6.1 Model

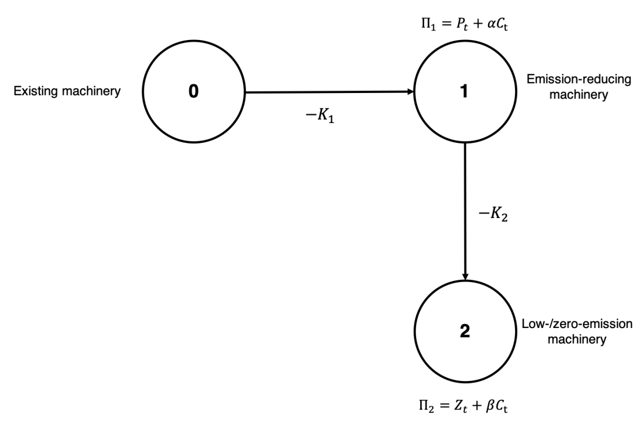


Figure 6.1: Figure of the investment decision and profit flows in each state

In the model, we consider the sequential investment in two technologies. The investment in the first technology gives the shipowner the option to invest in a second technology through a retrofit. The decision is shown in Figure 6.1. In the modelling of this American-style option, we consider the shipowner's decision to not invest at all, invest in the first technology or invest in both technologies sequentially. The model extends the model from Section 4.4 with another state. By making an irreversible investment cost K_2, the shipowner receives the spread between the fuel price in the first and second state. In addition, the reduction in carbon emission between the two states is also earned. The spread Z_t is modelled as an Ornstein-Uhlenbeck process given by:

$$dZ_t = \mu_Z(m - Z_t dt + \sigma_Z dW_t \tag{27}$$

where μ is the mean reversion rate, m is the mean, σ is the volatility and dW_t is the increments in a Wiener process.
Hence, the resulting cash flow Π_2 is

$$\Pi_2 = Z_t + \beta C_t \tag{28}$$

Where Z_t is the spread, β is the CO_2-reduction and C_t is the carbon price. We assume that the second retrofit has to become available, before an investment is possible. To model this, we assume the investment cost to be a jump process with only one jump. Before the jump occurs, the investment cost has an infinitely large value:

$$I = \begin{cases} \infty & \text{if no jump has occurred} \\ K_2 & \text{if jump has occurred} \end{cases} \tag{29}$$

The compound option at time t_n has a value $F_1(t_n, S_t)$, depending on the value of the state variables in the set $S_t = (P_t, Z_t, C_t)$. In time steps $t < T$, the option can be exercised, yielding the exercise value denoted by $\Pi_1(t_n, S_{t_n})$ and the second option $F_2(t_n, S_{t_n})$ or wait. We assume that the value of the second option is known. Thus, the option value of the compound option in time $t = T - h$ is given by the maximisation of the exercise value and the continuation value

$$F_1(t_n, S_{t_n}) = \max\left\{\Pi_1(t_n, S_{t_n}) + F_2(t_n, S_{t_n}), e^{-r(t_{n+1}-t_n)}\,\mathbb{E}[F_1(t_{n+1}, S_{t_{n+1}})]\right\} \tag{30}$$

According to Longstaff and Schwartz (2001), we estimate the continuation value with a regression on a set of basis functions, denoted $\Phi(t_n, S_{t_n})$. Discussion of the choice of basis function is left for the Appendix. The second option value is found similarly and has the following maximisation problem

$$F_2(t_n, S_{t_n}) = \max\left\{\Pi_2(t_n, S_{t_n}), \Phi_2(t_n, S_{t_n})\right\} \tag{31}$$

To find the investment timing τ_1 and τ_2, we again apply the LSM algorithm with the implementation for compound options described in Gamba (2003). Iterating backwards from $t = T$, we consider both Equation 30 and 31. The investment timing for the compound option is found when the exercise value exceeds the continuation value:

$$\Pi_1(t_n, S_{t_n}) + F_2(t_n, S_{t_n}) \geq \Phi_1(t_n, S_{t_n}) \tag{32}$$

The investment timing for path ω, is the earliest time $\tau_1(\omega)$ where Equation 32 is satisfied.

6.2 Parameter calibration

Table 6.1: Base case parameters

	Parameter	Value	Unit	Description
	Days at sea	240	Days	
	Fuel consumption	1200	mt/trip	
K_1	Initial investment cost, LNG	33	million $	
C	Tax	0-20	$/mt	
ρ	Discount rate	0.003		Monthly rate
α	Tax rate LNG retrofit	0.8		
β	Tax rate ammonia retrofit	0		
λ	Jump intensity, LNG	0.2		
μ_J	Expected jump size , LNG	3	million $	
σ_J	Standard deviation, jump, LNG	0.5	million $	
K_2	Investment cost, ammonia	5	million $	If jump occurs

6.2.1 Ammonia price process

The value of the option to invest in an ammonia propelled machinery is driven by the spread between LNG and ammonia. As ammonia is not yet adopted as a marine fuel, there exists no price index that is perfectly transferable to the prices expected in the future. Applications of ammonia today is mostly in the agriculture sector, where it is used as an essential component in fertilizers. In the production of ammonia today, 1.2-1.6 tonnes of CO_2 is emitted per tonne of ammonia as the the feedstock is natural gas Argus (2020). An important prerequisite for ammonia to be a truly carbon-free alternative, is substituting the natural gas with renewable energy. The decrease in cost of renewable energy supports the future profitability of the production of green ammonia. For example, the levelised cost of solar energy fell by 87% in the 2010s (Economist, 2020). Ignoring this fundamental difference, we use the Ammonia FOB Yuzhny index as an approximation for the price process, an established index for ammonia from the Black Sea port (Insight, 2020). Figure 6.2 shows the historical, weekly price levels for ammonia and LNG from 2009-2020.

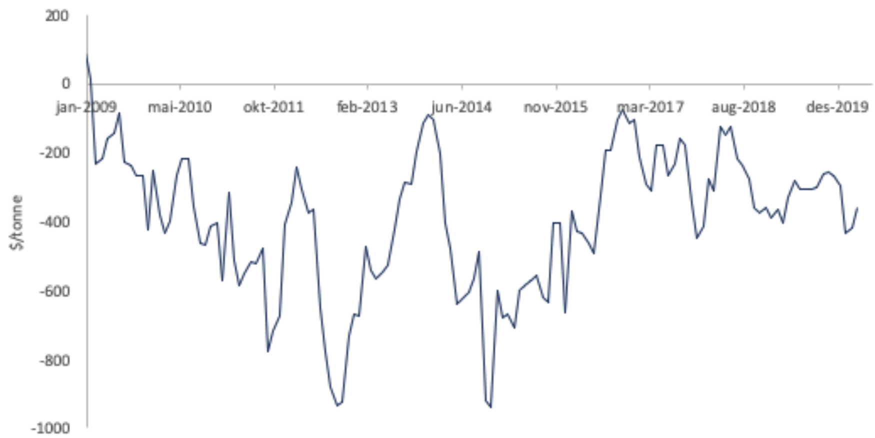


Figure 6.2: Historical differentials between LNG and ammonia. Source: Network (2020)

To formally test the time series for volatility stationarity, we perform an ADF test on the monthly spread between the LNG and ammonia price from 2009-2020, as seen in Figure 6.2, with a total of 135 observations. The resulting test statistic $\hat{\tau}_{ADF} = -3.861$ is below the 5% ADF critical value of -3.444. Thus, we can reject the null hypothesis of a non-stationary time series. Based on this, we conclude that the time series has mean-reverting properties and that the Ornstein-Uhlenbeck process is an appropriate model. Assuming that the spread between ammonia and LNG is mean-reverting, we estimate the parameters for the Ornstein-Uhlenbeck process as described in Section 5.2.1.

Table 6.2: Parameters for the LNG-ammonia spread modelled as an Ornstein-Uhlenbeck process

	Parameter	Value	Units	Description
$\hat{m}$	Mean	-414.6	\$/tonne	
$\hat{\mu}$	Mean-reversion rate	0.080		
$\hat{\sigma}$	Volatility	54.51		Monthly
P_0^S	Current spread		\$/tonne	

From the parameter estimation, we calculated a mean of -\$441, a value that will require unreasonable high tax levels to push into a profitable investment. A truly 'green' ammonia, is estimated to be priced between \$245-250 per tonne in 2040 (Argus, 2020). For the long-term LNG price, McKinsey (2019) predicts a supply gas by 2035 and a resulting price of \$7/MMBtu or \$330/MGOe. To reflect these forecasts, we use a mean spread of \$80/MGOe in the O-U process.

Furthermore, we investigate a low and medium mean scenario, with values of \$20 and \$140 respectively.

6.3 Case study: Sequential investment in LNG and ammonia

In this section, we apply the model presented in Section 6.1. We expand the option to invest in LNG with an embedded option to invest in ammonia. We look at the same ship as the case study in Section 5, with the same set of assumptions. As the ammonia technology is not yet available, we assume that the investment happens sequentially. The availability of the ammonia technology depends on a jump process.

We apply the LSM algorithm to solve the model and uses 10,000 simulations in our calculations. As the embedded option causes the model to become very computationally expensive, we present the analysis in the form of tables, comparing relevant values.

6.3.1 Value of the embedded option

To investigate the impact of increases in the tax level on the sequential investment decision, we calculate the option values. Furthermore, we calculate the timing and the probability of investing. We present the results for the sequential investment decision and the corresponding results form the finite model in Table 6.3 for comparison. For the no tax scenario, the option value of the embedded option is \$2.21, while the single option is worth \$0.72. This shows that including the option to retrofit to ammonia significantly increases the option value. By adding a \$10 tax, the value of the embedded option increases by \$2.06 million, compared to the modest increase of 0.26\$ in the single option. This can be explained by the reduced carbon tax. The LNG option reduces the carbon tax på 20%, whereas the reduction of tax will be %100 in the ammonia state.

As Table 6.3 shows, the time to invest for the embedded option increases with the tax level. The time to invest in LNG is almost 15 months with no tax and approximately 21 months for a tax of \$20. For the single option, the dynamic is the opposite. The timing decreases as the tax level increases. This can be explained by the increase in the second option value as tax rises. The embedded option value increases by \$2.06 million when the tax increases from \$0 to 10. For the single option, the value only rises by \$0.26 million. The increased profits of the second option increase the value of waiting and the timing. As the value of the investment increases, the probability of investing increases. The probability of investing increases by around 50% between the single and the embedded option for all tax scenarios. For example, with a tax level of \$20, 45% invest in the single option, compared to 83.0% in the embedded option.

Table 6.3: Comparison of finite and sequential investment problem

Tax level	Finite model			Extension		
	Value	Timing LNG	% invested LNG	Value	Timing LNG	% invested LNG
No tax	\$0.72	39.6	29.5	\$2.21m	14.62	65.0
\$10	\$ 0.98	34.7	36.3	\$4.27m	19.8	77.2
\$20	\$1.32	27.9	45.0	\$6.37m	22.8	83.04

6.3.2 Sensitivity to arrival rates in ammonia technology

As the time of commercialisation for ammonia is relatively uncertain, we vary the arrival rate in the Poisson process representing the ammonia technology arrival. In addition to showing results for the base case, $\lambda = 1/10$, we test for arrival rates of $\lambda = 1/7.5$ and $\lambda = 1/12.5$. The option value, timing and probability of investing obtained from the simulation is shown in Table 6.6 and 6.7 for a tax level of \$10 and \$20 respectively. The option values increase when the arrival happens earlier for both tax levels. Earlier arrivals of the ammonia technology means that cash flows from this option begins to arrive sooner. This increase the value of the embedded option, which also increases the value of the combined option. As Table 6.6 shows, an increase in arrival rate from the base case to $\lambda = 1/7.5$, the option value increases by \$0.67 million for a tax level of \$10. In Table 6.7, the same increase in arrival rates changes the option value by \$0.96. This is due to the higher tax level, which affects the cash flows directly. The probability of investing also increases with arrival rate for this reason. This demonstrates that a decrease in the time to arrival from 10 to 7.5 years, has a positive impact on the investment decision. The opposite holds for a reduction in arrival rate. Furthermore, the value of accelerating the arrival of ammonia is larger for higher tax levels. This has important implications for the shipping industry. Under this type of investment decisions, the option value can increase by investing in more R&D on relevant technologies. For higher tax levels, the impact of R&D on the option value is higher. This may be of interest when setting the tax level. Conversely, failing to invest in R&D reduce the option value, in addition to the probability of investing.

Table 6.4: Option sensitivity to different arrival rates with C = 10

λ	Value	Timing LNG	% invested LNG
0.08	\$3.86	20.0	74.9
0.1	\$4.27	19.8	77.2
0.133	\$4.94	19.7	81.3

Table 6.5: Option sensitivity to different arrival rates with C = 20

λ	Value	Timing LNG	% invested LNG
0.08	\$5.83	23.6	80.1
0.1	\$6.37	22.8	83.04
0.133	\$7.33	23.25	85.7

6.3.3 Sensitivity to investment cost

As ammonia technology is at an early stage of development, the investment cost is highly uncertain. Furthermore, the price is likely to vary as there will be no off-the-shelf solutions when the technology is introduced. Therefore, we perform a sensitivity analysis on the investment cost. We calculate the option values for the base case investment cost of \$5 million, in addition to \$2.5 and \$5 million. Table 6.6 shows the results for a tax \$10, Table 6.7 for a tax level of \$20. The sequential option increases in value as investment cost decreases. As Table 6.6 shows, the option value increases with \$1.3 million by decreasing the investment cost from \$5 million to \$2.5 million. This result can be explained by looking at the embedded option. As the only thing that is affected is the strike of the ammonia option, the value of the option will increase. This will again increase the value of the sequential investment. As the value of the embedded option rises, the value of waiting for the ammonia arrival increases, hence the delayed timing of the LNG investment. As an increase in the investment cost, reduces the value of the embedded option. This, in turn, reduces the value of waiting. Hence, the investment timing in LNG decreases with higher investment costs in ammonia.
By comparing these results with the finite model presented in Table 6.3, we see that the embedded option gives an additional value of to the LNG investment even for an increase in the investment cost \$7.5 million. For a tax level of \$10, the finite option value was worth \$0.98 million, while the combined option is worth \$3.08 under said investment cost.

Table 6.6: Option sensitivity to different levels of investment cost with C = 10

Investment cost	Value	Timing LNG	% invested LNG
\$2.5m	\$5.57m	23.04	80.96
\$5m	\$4.27m	19.8	77.15
\$7.5m	\$3.08m	16.64	72.3

Table 6.7: Option sensitivity to different levels of investment cost with C = 20

Investment cost	Value	Timing LNG	% invested LNG
\$2.5m	\$7.80m	25.38	84.4
\$5m	\$6.37m	22.8	83.04
\$7.5m	\$5.22m	20.78	77.4

6.3.4 Sensitivity to LNG-ammonia spread mean

As described in Section 6.2.1, the costs of producing green ammonia are strongly dependent on the costs of renewable energy. Furthermore, the price of green ammonia is dependent on the level of adoption in shipping and other industries. Thus, we consider the long-term ammonia price estimate fairly uncertain. To address this, we examine how changing the mean for the LNG-NH_3 spread affects the embedded option. Based on the level of uncertainty, we test for means of \$40 and \$120, in addition to the base case. The results for a tax level of \$10 and \$20 is presented in Table 6.8 and 6.9 respectively.

Table 6.8 show that the option values increase with the mean for tax levels of \$10. The same dynamic is present for the investment timing and the probability of investing. As the LNG-NH_3 mean increase, so does the value of the cash flows from the ammonia investment. This results in higher project value for the ammonia retrofit and in turn the embedded option. Given a mean of \$40, the option value is \$0.99 million. This is equal to the value of the single option for \$10, presented in Table 6.3, indicating that the embedded option is worthless. Considering the same value for a \$20 tax in Table 6.9, the probability of investing increases to 78.4%. The option value is \$3.95 million. Thus, a tax increase of \$10 gives an additional option value of \$2.97 million. For means of \$80 and \$120, the option values increase significantly by increases in the tax level. However, the probability of investing is not affected notably. These results show that an increase in the tax level can trigger ammonia investments, even for spread means as low as \$40. By triggering the ammonia investment, the probability of investing in LNG increases significantly. The tax can therefore heavily impact the investment decision. For the higher means, the increased tax gives a higher option value, but the investment decision is not affected notably. This result can be important for policymakers, as their goal should be to incentivize investments, not to add excess value to the projects.

Table 6.8: Option sensitivity to different levels of LNG-NH_3 mean with C = 10

Mean LNG-NH_3	Value	Timing LNG	% invested LNG
\$40	\$0.99m	13.0	36.6
\$80	\$4.27m	19.8	77.2
\$120	\$6.78m	24	82.4

Table 6.9: Option sensitivity to different levels of LNG-NH_3 mean with C = 20

Mean LNG-NH_3	Value	Timing LNG	% invested LNG
\$40	\$3.95m	17.5	78.4
\$80	\$6.37m	22.8	83.04
\$120	\$9.07m	26.8	83.3

7 Conclusion and further research

Due to an increased focus on emissions, a carbon tax is likely to be introduced in the shipping industry in the nearest future. This thesis proposed real options models for investment in emission-reducing technology under different tax levels. We considered a retrofit decision for a ship where the profit is driven by saved fuel costs and reduced carbon tax. First, we considered a perpetual option with a flat carbon tax and a fixed investment cost. Later, we introduced a finite lifetime to the option for comparison. We used Least-Square Monte Carlo simulation to calculate the option value. To account for more realistic assumptions, we expanded the model with downward jumps in the investment cost. A stochastic carbon price was also included to model a cap and trade system. To investigate additional value from retrofits to zero-emission propulsion, we created an embedded option by adding the opportunity for a second investment. The models have been applied to a case study where we considered the retrofit of a Neopanamax vessel. The models can be used by shipowner's who want to find the value of potential retrofits to abate emissions. This can give important insights to the policymakers about the shipowner's investment decisions.

The main results can be summarized as follows. In the perpetual option model, we found that the LNG retrofit is not profitable under the current spread levels, even with carbon tax levels up to \$20. Introducing the finite lifetime model to the same investment decision, we found that the option value was strongly reduced. This shows that the perpetual model significantly overstates the option value compared to the more realistic finite lifetime assumption. This result calls for cautiousness when assuming an infinite option lifetime, an assumption made by an overwhelming proportion of the academic literature. Even though perpetual models often yield analytical and tractable results, our results show that this is not a good approximation. Thus, we argue that the use of simulation is necessary to include the more realistic finite lifetime assumption. The sensitivity analysis of the limited finite lifetime model revealed that the fuel spread volatility does not affect the option value notably. The result is in contrast to the option theory for perpetual models, where the option value increases with volatility. This is due to the trade-off between the non-recoverable cash flows and the increased value of waiting caused by higher volatility.

By expanding the model to investigate downward jumps in the investment cost and a stochastic carbon price, we get some new insights under more realistic assumptions. The results showed that jump in investment cost delays the investment and that the investment timing is strongly influenced by the arrival of the jump. Also, the probability of investment decreased for tax levels lower than \$35. After including the stochastic carbon tax, we found no significant differences between the cap and trade system and the flat tax. As the profits from the investment are mainly driven by the savings on fuel costs, the differences in the tax schemes where negligible. This was also the case when doubling the volatility for the GBM process in the sensitivity analysis. The sensitivity analysis demonstrated the importance of the fuel spread parameters. By increasing the daily fuel consumption from 60 to 70 tonnes, the investment would have been undertaken immediately for all tax levels. This shows that the investments decision is highly dependent on fuel consumption. A similar result is derived by investigating the mean. Increasing the mean from \$240 to \$270 results in immediate investment for all tax levels. The high dependence on the mean stems from the effects of the Ornstein-Uhlenbeck model, which pulls deviating spreads back to the mean.

The inclusion of the embedded ammonia option increased the option value substantially regardless of the carbon tax. Under a carbon tax of \$10, the inclusion of the ammonia option increased from \$0.98 to \$4.27 million. The sensitivity analysis for the embedded option showed that the future ammonia investment increased the value of the LNG investment in all scenarios except one. In a situation with a carbon tax of \$10 and a mean NH3-LNG spread of \$40, the option to invest in ammonia was worthless. Further, we found that the combined option value increased with a higher arrival rate of the ammonia technology. This has important implications for the shipping industry, where emissions are assumed to be phased out over a longer time period. By actively pursuing flexible emission-reducing technology and accounting for the possible strategies in the real options valuation, the total investment can have a significant value. Conversely, failing to identify possible strategies can significantly undervalue the investment and lead to sub-optimal investment decisions. As faster arrival of new technology increases the option value, we suggest shipowners and policymakers invest in further R&D and pilot projects on the use of ammonia in shipping.

An interesting avenue for further research would be to apply our model for other technology alternatives, e.g. liquefied petroleum gas and biodiesel. As we found that the embedded option added significant value to the investment problem, further research could include more flexibility in the model. This can be done by adding more embedded options, such as the switch to bio-LNG once that becomes commercially available. In addition, we can relax the assumption that the investments must be done in a particular sequence as it in some cases will make sense to invest directly in zero-emission technologies.

Appendices

A Calculation of GBM parameters

The drift parameter is calculated by

$$\hat{\mu} = \bar{X} + \frac{\hat{\sigma}^2}{2} \tag{A.1}$$

Where the mean is given by

$$\bar{X} = \frac{1}{n}\left(\log \frac{X_t}{X_{t-1}}\right) \tag{A.2}$$

The sample variance is given by

$$\hat{\sigma} = \sqrt{\frac{1}{n-1}\sum_{t=1}^{n}\left(\log \frac{X_t}{X_{t-1}} - \bar{X}\right)^2} \tag{A.3}$$

B Derivation of the now-or-never investment decision (Equation 9)

Particular solution must satisfy:

$$\frac{1}{2}\sigma^2 V_0''(P) + \mu(P_s - m)V_0'(P) + \rho V_0(P) + P + \alpha C = 0 \tag{B.1}$$

We guess on a particular solution on the form $V_p(P) = aP + b$. Inserted in Equation B.1, this yields:

$$\mu(P - m)a + \rho V_0(aP + b) + P + \alpha C = 0 \tag{B.2}$$

All of the parts containing P must equal zero for this to hold for all values of P.

$$P(1 - \mu ma - \rho a) = 0 \tag{B.3}$$

$$a = \frac{1}{\mu + \rho} \tag{B.4}$$

The resulting part of B.2 must also be zero, to hold for the situation where P = 0. Substituting the result of Equation B.4 in Equation B.2:

$$\Rightarrow \mu ma + \rho b + \alpha C = 0 \tag{B.5}$$

$$\Rightarrow \mu m(\frac{1}{\mu+\rho}) + \rho b + \alpha C = 0 \tag{B.6}$$

$$b = \frac{\mu m}{(\mu+\rho)\rho} + \frac{\alpha C}{\rho} \tag{B.7}$$

We have derived a solution on the form $aP + b$. The solution becomes:

$$\frac{P}{\mu+\rho} + \frac{\mu m}{(\mu+\rho)\rho} + \frac{\alpha C}{\rho} \tag{B.8}$$

$$= \frac{\rho P + \mu m + \alpha C \mu + \alpha C \rho}{(\mu+\rho)\rho} \tag{B.9}$$

$$= \frac{m + \alpha C}{\rho} + \frac{P - m}{\rho + \mu} \tag{B.10}$$

C Derivation of the finite now-or-never investment decision

To solve for the optimal threshold in the finite lifetime option, we need the value of the now-or-never decision, F(P). We derive this in the following section.

$$\begin{aligned} V(P) &= \mathbb{E}\left[\int_0^T (P + \alpha C)dt\right] \\ &= \int_0^T \mathbb{E}[P_t]e^{-\rho t} + \int_0^T \alpha C e^{-\rho t} \\ &= \int_0^T (m + e^{-\mu t}(P_0 - m))e^{-\rho t}dt + \int_0^T \alpha C e^{-\rho t}dt \\ &= \int_0^T (m + \alpha C)e^{-\rho t}dt + \int_0^T (P_0 - m)e^{-(\mu+\rho)t}dt \end{aligned}$$

Calculating the integrals, we get the value for the now-or-never decision:

$$V(P) = \frac{m + \alpha C}{\rho}(1 - e^{-\rho t}) + \frac{P_0 - m}{\mu + \rho}(1 - e^{-(\rho+\mu)t}) \tag{C.1}$$

Here, we have used that

$$\mathbb{E}_0[P_t] = m + (P_0 - m)e^{-\mu t}$$

D Derivation of the option threshold

Recall the equation for V(P) and the relationship for the constants A and B:

$$\frac{1}{2}\sigma^2 V''(P) + \mu(P-m)V'(P) + \rho V(P) + P + \alpha C = 0 \tag{D.1}$$

$$B = -\frac{\sqrt{\mu}}{\sigma}\frac{\Gamma(\frac{1}{2})\Gamma(\frac{1}{2}(1+\frac{\rho}{\mu}))}{\Gamma(\frac{3}{2})\Gamma(\frac{\rho}{2\mu})}A \tag{D.2}$$

To simplify the derivations and improve readability, we introduce some notation. For the long gamma expression, we write:

$$\Gamma = \frac{\sqrt{\mu}}{\sigma}\frac{\Gamma(\frac{1}{2})\Gamma(\frac{1}{2}(1+\frac{\rho}{\mu}))}{\Gamma(\frac{3}{2})\Gamma(\frac{\rho}{2\mu})} \tag{D.3}$$

The derivation of the option threshold in the analytical solution is done by using the value matching and smooth-pasting conditions. The value matching condition is given by

$$V(P) = F(P) - K \tag{D.4}$$

Applying the expression for V(P) and F(P) (must be added) into Equation D.4, we get

$$\begin{aligned} AH\left(\frac{\rho}{2\mu}, \frac{1}{2}, \frac{\mu}{\sigma^2}(m-p)^2\right) - \Gamma A(m-p)H\left(\frac{1}{2}(1+\frac{\rho}{\mu}), \frac{3}{2}, \frac{\mu}{\sigma^2}(m-p)^2\right) \\ = \frac{\alpha C - m}{\rho}(e^{\rho T}-1) - \frac{P-m}{\mu+\rho}(e^{\rho T}-1) - K \end{aligned} \tag{D.5}$$

Considering the smooth-pasting condition, we first find the derivatives of the Kummer function. The derivative is given in Slater (1960) and we also apply the chain rule. The derivative of the Kummer function is

$$\frac{d}{dp}H(a,b,z(p)) = \frac{a}{b}H(a+1,b+1,z)\frac{dz(P)}{dP} \tag{D.6}$$

Where the derivative of z with respect to P is

$$\frac{dz(P)}{dP} = -\frac{2\mu}{\sigma^2}(m-P) \tag{D.7}$$

Before moving on, we again introduce some simplifying notation to avoid the long expressions that occur by the differention of the Kummer function: $a = \frac{\rho}{2\mu}$, $b = \frac{1}{2}$, $d = \frac{1}{2}(1+\frac{\rho}{2\mu})$, $g = \frac{3}{2}$. Lastly, $z = (m-p)^2\frac{\mu}{\sigma^2}$. Consider the smooth-pasting condition:

$$V'(P) = F'(P) \tag{D.8}$$

$$\begin{aligned} V'(P) = A\frac{a}{b}H(a,b,z)\frac{dz}{dP} + \Gamma A\frac{d}{g}H(d+1,g+1,z)\frac{dz}{dP} \\ +\Gamma AH(d,g,z) + \Gamma Ap\frac{d}{g}H(d+1,g+1,z)\frac{dz}{dP} \end{aligned} \tag{D.9}$$

Derivating F(P) given by Equation C.1, we get

$$F'(P) = \frac{1}{\mu+\rho}(1 - e^{-(\mu+\rho)T}) \tag{D.10}$$

Equating the two expressions, we get the smooth-pasting condition. By doing some algebra, we get an expression for A

$$A = \frac{1 - e^{-(\mu+\rho)T}}{\frac{a}{b}H(a+1,b+1,z)\frac{dz}{dP} + \Gamma((p-m)\frac{d}{g}H(d+1,g+1,z)\frac{dz}{dP} + H(d+1,g+1,z))} \tag{D.11}$$

Substituting the expression for A directly into Equation D.5, we can solve the the resulting expression numerically. An analytical solution is not obtainable due to the Kummer function. The solution for the optimal threshold P^* is solved by using a numerical solver in Python.

References

ACCIARO, M. (2014). Real option analysis for environmental compliance: Lng and emission control areas. *Transportation Research Part D*, 28, 41–50.

ADLAND, R., F. BJERKNES, AND C. HERJE (2017a). Spatial efficiency in the bulk freight market. *Maritime Policy Management*, 44, 413–425.

ADLAND, R., D. HANSSON, AND L. VON DER WENSE (2017b). Valuing cargo flexibility in oil transportation. *Maritime Policy Management*, 44, 803–814.

ARGUS (2020). Green shift to create 1 billion tonne 'green ammonia' market? *Technical report*.

BALCOMBE, P., J. BRIERLY, C. LEWIS, L. SKATVEDT, J. SPEIRS, A. HAWKES, AND I. STAFFELL (2019). How to decarbonise international shipping: Options for fuels, technologies, and policies. *Energy Conversion and Management*, 182, 72–88.

BESSEMBINDER, H., J. F. COUGHENOUR, P. J. SEGUIN, AND M. M. SMOLLER (1995). Mean reversion in equilibrium asset prices: Evidence from the futures term structure. *The Journal of Finance*, 50, 361–375.

BJERKSUND, P. AND S. EKERN (1995). *Contingent Claims Evaluation of Mean-Reverting Cash Flows in Shipping in L. Trigeorigs (ed.) Real Options in Capital Investment: Models, Strategies, and Applications*. Praeger Publishers.

BOOMSMA, T. K., N. MEADE, AND S. E. FLETEN (2012). Renewable energy investments under different support schemes: A real options approach. *European Journal of Operational Research*, 220, 225–237.

BRENNAN, M. AND E. SCHWARTZ (1985). Evaluating natural resource investments. *The Journal of Business*, 58, 135–157.

BRUNEKREFF, B. AND S. T. HOLGATE (2002). Air pollution and health. *The Lancet*, 360, 1233–1242.

COMPERNOLLE, T., P. M. KORT, AND J. J. J. THIJSSEN (2020). Optimal investment under carbon pricing: taxing or trading. *Working paper*.

CORTAZAR, G., M. GRAVET, AND J. URZUA (2008). The valuation of multidimensional american real options using the lsm simulation method. *Computers Operations Research*, 32, 2191–2213.

DECHEZLEPRÊTRE, A., D. NACHTIGALL, AND F. VENMANS (2018). The joint impact of the european union emissions trading system on carbon emissions and economic performance.

DIXIT, A. (1989). Entry and exit decisions under uncertainty. *Journal of Political Economy*, 97, 620–638.

Dixit, A. K. and R. S. Pindyck (1994). *Investment under uncertainty*. Princeton University Press, Princeton, New Jersey, United States of America.

Economist, T. (2020). Not-so-slow burn. *Technical report*.

Fuss, S., J. Szolgayova, M. Obersteiner, and M. Gusti (2008). Investment under market and climate policy uncertainty. *Applied Energy*, 85, 708–721.

Gamba, A. (2003). Real options valuation: A monte carlo approach. *WBS Finance Group Research Paper*, 14.

GL, D. (2019). Energy transition outlook 2019: Maritime forecast to 2050. *Technical report*.

Haehl, C. and S. Spinler (2020). Technology choice under emission regulation uncertainty in international container shipping. *European Journal of Operational Research*, 284, 383–396.

Hahn, W. J. and J. S. Dyer (2008). Discrete time modeling of mean-reverting stochastic processes for real option valuation. *European Journal of Operational Research*, 184, 534–548.

Insight, D. G. A. F. (2020). https://afi.dnvgl.com/statistics?repid=4.

Kitzing, L., N. Juul, M. Drud, and T. K. Boomsma (2017). A real options approach to analyse wind energy investments under different support schemes. *Applied Energy*, 188, 83–96.

Laughton, D. G. and H. D. Jacoby (1993). Reversion, timing options, and long-term decision-making. *Financial Management*, 22, 225–240.

Lindstad, H. E., C. F. Rehn, and G. S. Eskeland (2017). Sulphur abatement globally in maritime shipping. *Transportation Research Part D*, 57, 303–313.

Longstaff, F. A. and E. S. Schwartz (2001). Valuing american option by simulation: A simple least-squares approach. *The Review of Financial Studies*, 14, 133–147.

MAN (2019). Engineeering the future two-stroke green-ammonia engine. *Technical report*.

McDonald, R. L. and D. Siegel (1986). The value of waiting to invest. *Quarterly Journal of Economics*, 101, 707–727.

McKinsey, E. I. B. (2019). Global gas lng outlook to 2035. *Technical report*.

Moreno, M. and J. F. Navas (2003). On the robustness of least-squares monte carlo (lsm) for pricing american derivatives. *Review of Derivatives Research*, 107–128.

Mossin, J. (1968). An optimal policy for lay-up decisions. *The Swedish Journal of Economics*, 70, 170–177.

Network, C. S. I. (2020). https://sin.clarksons.net.

Parliament, E. and the Council (2015). Decision (eu) 2015/1814 of the european parliament and of the council of 6 october 2015 concerning the establishment and operation of a market stability reserve for the union greenhouse gas emission trading scheme and amending directive 2003/87/ec. *Official Journal of the European Union*, 58, L264/1–L264/5.

Parry, I., D. Heine, K. Kizzier, and T. Smith (2018). Imf working paper: Carbon taxation for international maritime fuels: Assessing the options.

Psaraftis, H. N. and C. A. Kontovas (2009). Co2 emission statistics for the world commercial fleet. *WMU Journal of Maritime Affairs*, 8, 1–25.

Rehn, C. F., A. Haugsdal, and S. O. Erikstad (2016). Flexible strategies for maritime sulphur emission regulation compliance. *Conference paper: PRADS2016 4–8 September, Copenhagen, Denmark*.

Schwartz, E. S. (1997). The stochastic behaviour of commodity prices: Implications for valuation and hedging. *The Journal of Finance*, 52, 923–973.

SEA-LNG (2020). Lng as a marine fuel – the investment opportunity, https://sea-lng.org/our-work/, last accessed: 16.6.2020.

Slater, L. J. (1960). *Confluent Hypergeometric Functions*. Cambridge University Press.

Sødal, S., S. Koekebakker, and R. Adland (2008). Market switching in shipping - a real option model applied to valuation of combination carriers. *Review of Financial Economics*, 17, 183–203.

Sødal, S., S. Koekebakker, and R. Adland (2009). Value based trading of real assets in shipping under stochastic freight rates. *Applied Economics*, 41, 2793–2807.

Trigeorgis, L. (1993). The nature of option interactions and the valuation of investments with multiple real options. *The Journal of Financial and Quantitative Analysis*, 28, 1–20.

UNCTAD (2019). Review of maritime transport 2019. *Technical report*.

NTNU

Norwegian University of
Science and Technology