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The Value of Flexibility in a Time of Uncertainty

By

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Acknowledgments

This thesis not only represents the efforts that have been made to complete this research project, but it also represents the efforts made during my entire academic career. I am not referring to my own efforts but rather, I am referring to the efforts made by all of my professors, lecturers, and keynote speakers that have contributed to the development, and to the expansion of knowledge in the field of maritime studies. It has been a privilege to learn from these exceptional people who have inspired me, and pushed me to develop my knowledge, and skills. It is my hope that by presenting this research paper I can also make a small contribution of my own to the field of maritime studies.

Specifically, I would like to thank my supervisor Dr Michelle Acciaro who understood the direction that I was attempting to pursue, and guided me just enough so that I could reach my goals with this research project. Having one of the leading experts on the subject of my thesis as my supervisor has given me a lot of additional motivation.

I want to thank my dearest Tiara for supporting me while I was writing this thesis.

And mostly, I would like to thank my parents for the sacrifices they have made, their constant support, and the freedom they have allowed me that has enabled me to follow the path that I am on today.

Abstract

The maritime industry is facing a testing time ahead of it due to a plethora of new environmental regulations that are being introduced within a relatively short time period. This will oblige shipping companies to make the most of every animate and inanimate asset available to them. The most notable environmental regulations being introduced include concerns about ballast water, energy efficiency, and emissions. Each of these topics are deserving of research and investigation in order to assist shipping companies to develop methods of evaluating compliance to these new environmental regulations. In addition, these environmental regulations are being introduced in a time where the maritime industry finds itself in a trough within the shipping cycles, making the task of facing a multitude of new regulations even more challenging.

This research paper has focused on the issue of compliance with emissions, more precisely, the issue that shipping companies face when complying with MARPOL Annex VI Regulation 14, which has introduced more stringent limits regarding the emissions of sulphur from vessels. This is because compliance with MARPOL Annex VI Regulation 14 is likely to be the most expensive regulation for shipping companies to comply with, and because MARPOL Annex VI Regulation 14 is likely to transform the maritime industry as we know it.

This research presents the various options a shipping company has in order to comply with MARPOL Annex VI Regulation 14, and continues by thoroughly examining how dual fuel propulsion systems can provide a shipping company with a means of compliance.

A valuation model has been developed in this research paper that allows the incorporation of uncertainties, and that can be easily adapted, and used by shipping companies to evaluate investments towards dual fuel propulsion systems. The incorporation of uncertainties was facilitated by the use of a binomial pricing model in order to conduct a real options analysis valuation of the option to switch. The incorporation of uncertainties in this model was paramount, due to the many uncertainties a shipping company must take into account when making investments towards a dual fuel propulsion system.

The model demonstrates that the decisive factor driving the adoption of a dual fuel propulsion systems in general is fuel price differentials. The model also demonstrates that depending on the characteristics, and operational parameters of the vessel in question, other uncertainties such as the availability of LNG bunkering facilities, and the enforcement date of the global sulphur cap can have a sizable impact on how much a shipping company should invest in a dual fuel propulsion system.

The author believes that the uptake of dual fuel propulsion systems is likely to not only allow shipping companies to comply with the upcoming regulations and minimise their fuel costs, but will also facilitate the development of the new paradigm of low emissions shipping.

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List of Abbreviations

CO2	Carbon Dioxide
DNV	Det Norske Veritas
DWT	Dead Weight Tonnes
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EGCS	Exhaust Gas Cleaning Systems
EIA	International Energy Agency
EPA	Environmental Protection Agency
EU	European Union
GHG	Green House Gasses
HFO	Heavy Fuel Oil
IMO	International Maritime Organisation
KW	Kilo Watt
LNG	Liquefied Natural Gas
LSFO	Low Sulphur Fuel Oil
MARPOL	International Convention for the Prevention of Pollution from Ships
MBTU	Million British Thermal Units per hour
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
NOx	Nitrogen Oxide
NPV	Net Present Value
ODS	Ozone Depleting Substances
OPEX	Operating Expenses
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SEEMP	Ship Energy Efficiency Management Plan

UNCTAD	United Nations Conference on Trade and Development's
VOC	Volatile Organic Compounds

Chapter 1: Introduction

1.1 Background

Contemporary society is becoming acutely aware of the environmental issues and their impact on the world. Global warming is one of the most pressing of these issues and society in general, policy makers, environmentalists, scientific researchers, and scholars have turned their attention to mitigating emissions as a result of awareness. The maritime industry however, had been overlooked in the early stages of this global awareness, and as a result not many significant strides to reduce emissions from propulsion systems installed on vessels had been made (Smith 2013). It is worth noting that although vessels' propulsion systems had not made many significant contributions in emission reductions, the maritime industry only contributed by 2.2% to global CO2 emissions in 2012, and according to the International Maritime Organisation (IMO) the maritime industry is responsible for only 10% of the transport sector's CO2 emissions. This undoubtedly makes shipping the most environmentally efficient means of transporting goods (IMO 2014). If one considers that 80% of global trade is transported by sea, and that the global population is increasing by 57 million people per day (ABB 2012), it is therefore understandable that UNCTAD (2012) has predicted a possible increase of maritime emissions by 200-300% due to the growth of the global economy, and in turn the growth of the demand for maritime transport if emissions are not properly regulated.

As efficient as the maritime industry might be, and as little as it might contribute to global emissions in comparison to other industries, this does not mean that the maritime industry produces negligible quantities of emissions. In fact, the Third IMO GHG study (2014) found that the maritime industry produced 938 million tons of CO2 in 2012, and that the maritime industry also produces approximately 20.9 million tonnes of Nitrous oxides (NOx), and 11.3 million tonnes of Sulphur oxides (SOx) annually. With the aforementioned potential increase in emissions of 200-300% there is considerable incentive to properly regulate maritime emissions. In an effort to move the maritime industry into the era of emission conscious operations, the IMO, which has regulated pollution in the maritime industry through the International Convention for the Prevention of Pollution from Ships (MARPOL) since 1973, adopted new regulations regarding emissions. These new regulations regarding emissions that the IMO adopted came in the form of an additional Annex, to the MARPOL regulations. This was MARPOL Annex VI which was adopted in 1997, and which restricted the emissions of SOx, NOx, Ozone Depleting Substances (ODS), and Volatile Organic Compounds (VOC). MARPOL ANNEX VI entered into force in 2005, and since 2005 there have been some major revisions to ANNEX VI which have made a notable impact on the future of maritime emissions, and on the maritime industry in general. The revisions with the greatest impact are considered to be the following:

The first major revision was the Marine Environmental Protection Committee's (MEPC) Resolution 203(62) which entered into force in 2013 is the addition of chapter 4 to Annex VI. This revision sets forth mandatory efficiency measures regarding a vessel's technical design (Energy Efficiency Design Index (EEDI)), as well as operational guidelines (Ship Energy Efficiency Management Plan (SEEMP)). The second major revision is MEPC's Resolution 58 which entered into force in 2010, and includes a revised mandatory gradual decrease of allowed emissions of SOx, NOx, and particulate matter inside Emission Control Areas (ECA), and globally. Both of the aforementioned revisions to MARPOL Annex VI are currently playing major roles in bringing the maritime industry into what one might consider as the new paradigm of "green shipping". Both these regulations provide a measurable improvement in global emissions reduction, but they prove to be challenging for the shipping companies to implement. One of the biggest challenges comes with the introduction of the revised MARPOL Annex VI Regulation 14, which requires a sizable decrease in the sulphur content in the fuels being used inside of ECAs to 0.10% from 1.00% as of 1.1.2015, and a global sulphur limit (cap) to 0.50% from 3.50% as soon as 1.1.2020 and as late as 11.2025. (IMO 2014)

EEDI and SEEMP allow for a gradual progression in order to allow the shipping companies to gain expertise and implement new technology incrementally in order to gain efficiency. This ultimately leads to a reduction in Operating Expenses (OPEX), and thus provides the shipping companies with a positive return on investments made to gain these efficiencies. On the other hand, the new and more stringent sulphur regulations do not provide for any potential reduction of OPEX. On the contrary MARPOL Annex VI Regulation 14 leaves shipping companies with very few tangible options that require either sizable Capital Expenses (CapEx), and or higher fuel costs. Compliance to MARPOL Annex VI Regulation 14 will be the focal point of this research paper.

A brief overview of the three main options for compliance with MARPOL Annex VI Regulation 14 within ECAs, include the following:

1. A shipping company can switch from burning residual fuels to burning distillate fuels which are more heavily refined fuels that contain less sulphur than residual fuels or blends that were commonly used. Prices for distillate fuels are approximately 50% higher than residual fuels. Fuel costs make up anywhere from 35-65% of a vessel's OPEX (Technoveritas).

2. A shipping company can invest in abatement technology also known as scrubbers or Exhaust Gas Cleaning Systems (EGCS), which clean the vessels exhaust fumes. This will allow the vessel to continue to burn the cheaper residual fuels, but this will require a large CapEx, and potentially additional OPEX.

3. A shipping company can invest in the installation of a propulsion system that operates on alternative fuels which are virtually sulphur free. Currently the alternative fuel of choice in the maritime industry is LNG. The price of LNG compared to traditional maritime fuels per Million British Thermal Unit equivalent (mmbtu), compared with distillate fuels is considerably lower which makes this solution a particularly interesting method of compliance. Notwithstanding, this method of compliance requires a large CapEx relating to the installation of the propulsion system. One of the main drawbacks of this method of compliance is the lack of LNG bunkering availability, which is currently limiting the uptake of what many consider as the future fuel of the maritime industry.

As difficult as it may be to comply with the sulphur regulations within the ECA zones, the upcoming global sulphur cap will be even harder to comply with because shipping companies will be forced to use one of the three methods of compliance mentioned above on a permanent basis. It must be taken into account that the shipping fleet is extremely diversified, and as such there is no single method of compliance that is best suited for all vessels. The author agrees with the consensus of the experts in this field of research, that state that these methods of compliance to MARPOL Annex VI must be considered on a case by case basis.

In the opinion of the author the LNG propulsion method is the most effective method of compliance, and shows the most potential for the future. This is the argument put forth and consequently supported in this research paper. Currently the maritime industry finds itself in a stalemate often referred to as a “chicken and egg dilemma”; the ports are reluctant to invest in LNG bunkering, and the ship owners are reluctant to invest in LNG propulsion systems. Although many ports may be reluctant to invest in LNG bunkering infrastructure, there are a few key ports that are pushing forward with these investments such as the Port of Rotterdam and the Port of Singapore that have or are developing LNG bunkering facilities. There are also a few proactive shipping companies such as UASC and TOTE that have recognized the value of LNG as a future fuel, and are investing in dual fuel, or dual fuel ready newbuilds (vessels that can burn both traditional marine fuels and LNG).

Dual fuel propulsion is not a new technology, but in the recent years the maritime industry has been making strides to efficiently adopt this technology to vessels. The reason for this is that it is likely to provide the operational flexibility needed to operate a vessel in the most stringent ECAs by burning LNG, while eliminating the risk of running out of fuel due to the lack of LNG bunkering facilities by maintaining the ability to operate on traditional maritime fuels. Dual fuel technology might be able to solve the stalemate created by inflexible solutions to the adoption of LNG as a maritime fuel, while at the same time creating value for shipping companies due to the technology’s inherent flexibility.

1.2 Justification and Brief Methodology (intro to ROA)

The more stringent regulations found in MARPOL Annex VI, and especially the sulphur regulations (Regulation 14) have brought about a general state of uncertainty in the maritime industry, as shipping companies consider the benefits and drawbacks of the various methods of complying with these regulations. In order to assist the shipping companies, and to develop understanding throughout the maritime industry, various exacting studies have been conducted by organisations, classification societies, research groups, port authorities, and academics. The larger studies such as DNV 2020 study, and the IMO GHG studies have wide scopes, and have an industry wide approach. This helps to convey a general understanding of the challenges shipping companies face while contemplating compliance to new regulations in the ever-changing landscape of the maritime industry. The studies with smaller scopes are conducted by academics and usually target a single method of compliance, or compare two or more different methods of compliance like the Green Ship of the Future study (Møllenbach *et al* 2012).

The author's goal was to present a research paper on a topic that seems to be missing when searching through the existing literature a topic that could help to provide transition from the current status quo of the industry's compliance to MARPOL Annex VI, which is mainly characterized by the use of distillate fuels, and move it gradually into the era of alternative fuels such as LNG.

The author therefore decided to conduct research on dual fuel technology, a technology that not only could provide shipping companies with a means to comply with MARPOL Annex VI, but could also facilitate the aforementioned transition of the maritime industry into the era of LNG. This research could prove to be significant because it provides a model for future use and application to this emerging field.

In order to ascertain whether or not an investment in a dual fuel propulsion system could be a viable solution for a shipping company, the value of such an investment would have to be estimated. Essentially the additional value that a dual fuel vessel provides comes in the form of flexibility, as the vessel can burn LNG, distillate fuels, and residual fuels (MAN 2014). The vessel therefore can switch fuel allowing the shipping company to minimize its costs according to its location and to the market price of the various fuels.

In order to quantify the value of flexibility, the potential savings from operating with a dual fuel vessel have to be compared to other methods of compliance to MARPOL Annex VI. This can be done by considering the potential savings as cash flows, in order to estimate the Net Present Value (NPV) of an investment in a dual fuel propulsion system. This would normally be estimated using traditional Discounted Cash Flow valuations (DCF), but these methods do not capture the additional value of flexibility that a dual fuel vessel provides, or the managerial flexibility required to operate a vessel in what is considered to be a readily changing environment. Therefore, a Real Options Analysis (ROA) valuation was determined to be the most fitting model, because it can incorporate the additional value that managerial flexibility offers with regard to the uncertainty, and it is able to account for the value of the option to switch fuels (flexibility) that a dual fuel vessel provides. ROA valuation will be thoroughly presented in chapter three.

1.3 Objectives

The main research question of this thesis is the following:

What is the value of flexibility that a dual fuel propulsion system provides its operator?

Although the research during this project evolved organically, a few sub questions had to be answered in order to make sure the research was conducted thoroughly, and that the main question was answered diligently. The sub questions to the main research are the following:

1. What types of vessels will allow for a good evaluation, and how will their operation on a dual fuel propulsion system offer cost reductions?
2. How do fuel prices affect the investment into a dual fuel vessel, and how should they be measured?
3. What is the effect of operating a dual fuel vessel regarding vessel productivity and profit? How does the propensity of a dual fuelled vessel to be chartered differ to that of a traditionally fuelled vessel?

The aim of this research paper is to create a theoretical foundation, and a basic model that a shipping company can consult and or adapt to their specific needs in order to evaluate an investment regarding dual fuel vessels. By answering the main research question, this research paper will discover the many intricacies, and uncertainties that would drive such a decision, as well as providing a model that allows for the valuation of such a decision by accounting for uncertainties, and the many variables, and their volatilities.

The first question is designed in order to generate a thought process regarding the types of vessels which should be used in this research, and what kind of operational parameters need to be given to these vessels. This is a crucial consideration that has to be made in order to portray realistic scenarios. Certain assumptions regarding the operational parameters must be made in order to enable probabilities of external uncertainties to be factored into the research, so that conclusive results can be derived. By answering the first sub question, the hypotheses, and main scenarios for the model are formed.

The second question introduces the main cost item that needs to be considered while operating a vessel i.e., the fuel cost. The fuel cost depends on the Fuel Consumption (FC) of the vessel, and the price of the fuel. The value of the option to switch to LNG that a dual fuel propulsion system provides stems directly from the reduction of fuel costs, therefore the second question is necessary to give insight into how future fuel prices and their differentials should be taken into consideration. By answering the second sub question, the role and effect of fuel price differentials can be understood, and the sub-scenarios for the model are formed.

The first two sub questions allow for construction of scenarios, sub-scenarios, and in turn the creation of the ROA valuation model that allows the main research question to be answered. There is good reason however, to believe that a dual fuel vessel constantly operated in the optimal mode will also be more attractive on the market, thus creating a larger demand for its services. This could create various scenarios such as a potential for a higher yearly productivity or a premium rate, which could also affect the value of an investment into a dual fuel propulsion system making this third sub question relevant but not a main part of the model.

1.4 Limitations

The limitations in this research paper are mainly related to the limited data available regarding methods of compliance with MARPOL Annex VI, namely traditional fuel switching, abatement technology, and dual fuel/LNG propulsion systems. This is because the issue of compliance with the revised MARPOL Annex VI is a fairly recent topic, and most of the methods of compliance are still in their developmental stages e.g., assumptions regarding the availability of distillate fuels, the pace of LNG bunkering development, and if abatement wash water will be accepted by port states, and if so at what ports, and at what cost (Noteboom 2010, Loyds Register 2012.b).

Other limitations that have had an effect on this research paper include the time frame. This research topic requires that a significant amount of research is conducted, whilst simultaneously requiring a thorough comprehension of ROA. As previously stated the shipping fleet is diverse, and is made up of many different types, and sizes of vessels. The author would have liked to include a wider variety of vessels, but due to the time restrictions this was not possible, therefore, the scope of the research is smaller than it could have been. It would have also been interesting to quantify the potential savings that dual fuel vessels could provide when taking EEDI and NOx regulations into consideration.

Other limitations include the incorporation of FC at berth, the well to wake efficiencies of each method of compliance, the estimation of the value of lost cargo space by the installation of LNG fuel tanks and whether the loss can be justified by reductions in fuel costs, and the evaluation of future fuel price forecasts.

Finally the lack of access to professional web sources like IHS Fairplay, and historical AIS vessel movement reports may have also limited the approach of this research paper, but did not have a significant effect on the final results.

1.5 Brief Methodology

This research paper will use a ROA valuation to quantify the value of the flexibility provided by a dual fuel propulsion system, and to determine how much of an investment a shipping company should make into a dual fuel propulsion system in order to comply with MARPOL Annex VI Regulation 14. The dual fuel method of compliance is only compared to the method of compliance to switch from residual fuel to distillate fuel, because the method to switch from residual fuels to distillates is currently the method of choice for ship owners (DNV 2012). Additionally, comparison only to the method of switching from residual fuels to distillate fuels will provide for a model that minimises assumptions compared to a model that incorporates all three methods of compliance. Although it is of interest to compare the costs related to the EGCS method of compliance it will not be included in order to simplify the model, and to minimise assumptions (The replicability of this model allows it to be adjusted for this research in the future). In another attempt to further simplify the model, the installation of the dual fuel propulsion system is assumed to be installed on newbuilds in construction that will be delivered at the beginning of 2020. By doing this, variables related to retrofitting existing vessels with dual fuel propulsion systems are also eliminated.

The ROA valuation of the option to switch will be used as dual fuel vessels allow their operators the flexibility to change the type of fuel they use at will. Dual fuel vessels fit in perfectly to ROA valuation models with the option to switch, as these models are based on managerial flexibility to change input or output parameters and modes of operation. (Brach 2003)

It was decided that two types of vessels, with different operational parameters would be used for comparison in order to present an unbiased, and meaningful study. To construct the vessels' operational parameters, several logical assumptions based on the available data had to be made. As previously stated, the environment that vessels operate in, is dynamic and vessel operators face various forms of external uncertainties when considering price differentials, upcoming regulations, LNG bunkering availability, availability of distillate fuel, shipping cycles, and the competitive environment. Therefore two hypotheses were formed regarding the vessels, and two main scenarios were constructed for each vessel based on assumptions regarding their operational parameters. Fuel price differentials are then introduced and allow for the inclusion of sub-scenarios based of fuel price differentials.

Both single step and two-step binomial asset trees are then constructed based on the binomial asset tree approach as per Brach (2003). This is done in order to establish the foundation needed to build the potential future cash flows of both vessels given their FC, and the scenarios, and sub-scenarios. By creating binomial decision trees, the author was able to present a frame work that portrays the probabilities related to uncertainties the operators of both vessels face while remaining easily understandable. Single step and two-step binomial pricing models, adapted from the binomial pricing model as per Brach (2003) are then used to conduct the ROA valuations on the option to switch to LNG a dual fuel propulsion system offers its operator. The binomial pricing model allows for easy manipulation of variables and the probabilities of uncertainties materialising, while also allowing additional variables and uncertainties to be included making this a useful model for future evaluation of investment decisions regarding dual fuel propulsion systems.

Finally a sensitivity analysis is conducted in order to compare the savings in fuel costs that a dual fuel propulsion system provides for each vessel depending on fuel price differentials. These savings are then graphed in order to illustrate how the assumptions regarding the uncertainties, and how the fuel price differentials will affect the value, and the Critical Cost (K) of investing in a dual fuel propulsion system for each vessel.

Instead of the binomial pricing method, a dynamic programing model such as the Bellman Equation can be applied once the scenarios and sub-scenarios are complete. Due to the many external uncertainties, and the lack of ability to calculate probabilities related to these external uncertainties in this model, the research paper uses the more basic binomial pricing method. The use of the Bellman Equation could allow for a more precise result, which can be extremely useful to a shipping company interested in making a very precise calculation given that it has more information available to it, and can better calculate the probabilities of external uncertainties.

1.6 Structure

A literature review will follow this chapter in order to provide the background information the reader requires for the understanding of the subject and the uncertainties shipping companies are facing when considering investments into dual fuel propulsion systems. The literature review will be followed by the methodology chapter that will introduce ROA, and will review the most relative research papers that have contributed to this research paper. The methodological approach used for this paper will then be justified, and will be explicitly presented. The sub research questions will be answered and combined in order allow for the creation of the binomial pricing ROA valuation models. Once the models are created, chapter four will present the data analysis and findings based on the both single step and two-step binomial pricing ROA valuation models for each vessel, and a sensitivity analysis will be conducted. Finally the findings will be summarised, and a conclusion will be made regarding the research conducted.

Chapter 2: Literature Review

2.1 Introduction

The topic of compliance with MARPOL Annex VI requires extensive research to be conducted by consulting various sources of information such as academic journals, books, market reports, news articles, technical papers, databases, and studies by governmental bodies and organisations. As previously stated, many of these aforementioned sources of information contain important information regarding compliance with MARPOL Annex VI, which is essential for understanding the potential benefit of investments towards dual fuel propulsion. However, there is little information regarding the benefit and true potential of dual fuel vessels.

In order to present the information which has been gathered in a logical method, the thematic structure will be used because it is a good manner of presenting, and evaluating the outcomes of research that contain a large scope of information. (Pope *et al* 2007)

The literature review will begin by introducing the revised MARPOL Annex VI regulations, and their potential effect on shipping companies, and the maritime industry as a whole. The literature review will then proceed to describe the issues regarding traditional fuels currently available in the maritime industry. Then the three aforementioned methods of compliance will be introduced, and their benefits, drawbacks, and intricacies will be discussed. As a hybrid method of compliance, dual fuel propulsion systems will then be thoroughly reviewed, including technical aspects, operational aspects, and the CapEx related to these systems. Additional financial considerations of operating a dual fuel vessel apart from fuel related costs will be introduced, and will include operational, and voyage related costs. Finally, additional potential benefits of investing in a dual fuel propulsion system are acknowledged. These include increased vessel productivity, and revenue due to flexibility and increased attractiveness for charterers.

By exploring all of these aspects, the literature review will eventually provide an understanding of the issues, and particularities that need to be taken into consideration while building the model and conducting this research.

2.1.1 Regulations

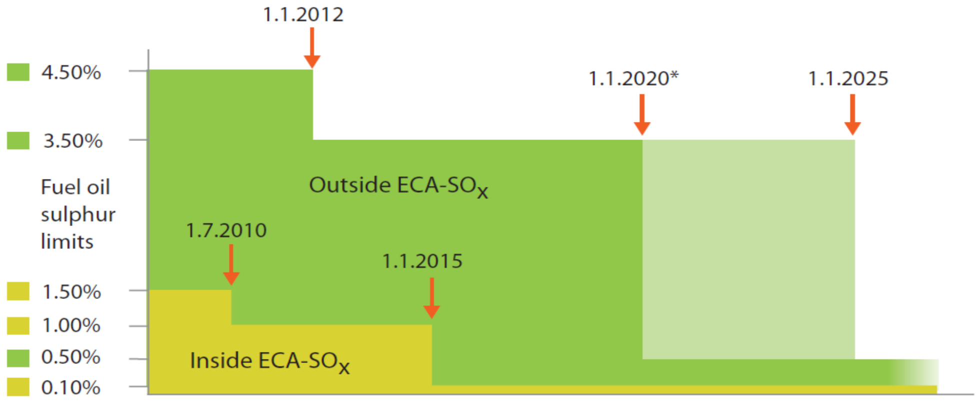
As briefly mentioned in the introduction, in 1997 the IMO adopted Annex VI in order to regulate maritime emissions, and entered into force in 2005. Since the original regulations there have been a two major amendments to Annex VI that have laid down the pathway for change within the maritime industry. These two amendments come in the form of MPEC Resolution 203(62), and MPEC Resolution 58.

MPEC Resolution 203(62) introduces Chapter 4, and along with it new efficiency measures which include: The Energy Efficiency Design Index (EEDI) which is mandatory for all new vessels whose building contract is placed after 1.1.2013 and/or is delivered after 1.1.2015, and the Ship Energy Efficiency Management Plan (SEEMP) which is mandatory for all vessels in service. These new efficiency measures are very important and interesting, but will not be the main focus of this research paper, even though dual fuel propulsion systems could also allow compliance to these measures.

MPEC Resolution 58 which entered into force in 2010 is the focus of this research paper, specifically Regulation 14 which introduced the more stringent sulphur regulations. Regulation 13 which introduced more stringent NOx regulations is also worth considering because a dual fuel propulsion system can make use of LNG in ECAs and will allow vessels to comply with the newest and most stringent NOx cap (Tier III) set by Regulation 13, but will not be the main focus of this research paper.

Compliance with MARPOL Annex VI Regulation 14 regarding sulphur is the focal point of this research paper. MARPOL Annex VI Regulation 14 requires vessels that want to operate inside ECAs to reduce the sulphur content of their fuel from 1.00% to 0.10% as of 1.1.2015. In addition Regulation 14 also requires the reduction of sulphur content in fuels on a global level from 3.50% to 0.50%. This global sulphur cap is likely to come into force as early as 1.1.2020, however, its enforcement might be pushed back to 1.1.2025 depending on a Fuel Availability review that is being conducted by the IMO. This review is concerned with the required availability of distillate fuels that will be needed to fuel the maritime fleet by the time the global sulphur cap is enforced. The fuel availability study is due to be made public in 2018, and it is something the maritime industry is keeping close track of. Figure 1 below, portrays the sizable drop in the allowed sulphur contents.

Figure 1: MARPOL Annex VI Regulation 14. Sulphur Cap Enforcement Dates. Source: Lloyd's Register (2012.a)



*Depending on the outcome of a review of fuel oil availability, to be completed 2018, the 2020 date could be deferred to 2025

Even though the enforcement of the global cap might be pushed back until 2025, the European Union (EU) has decided to go ahead and implement the 0.5% sulphur regulations as of 2020 (DNV 2014). Another consideration is that existing ECA regions may soon be spreading. Currently ECAs exist in the Baltic Sea, the North Sea, the coasts of North America and the United States Caribbean Sea area. Potential ECAs include the Sea of Marmara, Hong Kong, and some Regions in China, notable some of the coast along Guangdong, and the Pearl River Delta. (Merk and Li 2013)

As previously mentioned in the introduction, there are only a few ways for a shipping company to comply with the more stringent sulphur caps set forth in MARPOL Annex VI Regulation 14, and they will all come at a cost premium. It is costly and difficult for shipping companies to comply with the ECA cap of 2015, and complying with the global cap will be an even greater challenge and expense.

A likely effect of the introduction of these more stringent sulphur regulations is an increase in the cost of transportation, as more expensive fuels and large CapEx will have to be made by shipping companies. One could assume that this premium will be paid by the shipping companies, but actually a large percentage of this will be passed on to the consumer. Noteboom (2010) predicted an increase in freight rates of 7% to 20% within ECAs after the enforcement of the 2015 ECA sulphur cap due to the use of more expensive fuels. This can be verified, but as this is not within the scope of the research; a logical presumption is made that increased fuel costs of operating on distillates will make shipping services more expensive. A side effect that an increase in the cost of shipping services could cause, is a shift in modality to land based transportation in ECAs. According to UNCTAD (2012) such a shift in modality might actually result in an increase of emissions in certain regions. (Noteboom 2010; Rozmarynowska and Oldakowski 2012; UNCTAD 2012).

This increase in OPEX due to MAPOL Annex VI Regulation 14 that is virtually unavoidable comes at a time when the shipping industry finds itself in a recession. This does not make things easy for shipping companies already operating at a loss, or barely scraping by. The timing is unfortunate, but the need for these measures is justifiable.

As summarised by Acciaro (2014), sulphur emissions have negative effects on human health, the environment, and affect the global climate. According to Eyring *et al* (2010) approximately 70% of maritime emissions are produced no more than 400 km from coastlines causing serious air quality problems to coastal areas. Although these problems are concentrated in coastal areas, they are not isolated within coastal areas because the effects of sulphur emissions are dispersed, and cause a variety of externalities to a wide geographical area.

The combustion of traditional maritime fuels releases sulphur dioxide and nitrogen oxides, which form Particulate Matter (PM) and Ozone due to atmospheric, and chemical mechanisms (Vutukuru and Dabdub 2008). Emissions by vessels result in large quantities of PM with particles that have a diameter of less than 2.5μm (fine particulate matter) to be released, which is proven to cause cardiopulmonary diseases, and eventually to premature mortality (Volker *et al* 2010). Winebrake *et al* (2009) completed a study that presents the potential reduction of premature mortality that the potential uptake of low sulphur fuels can provide.

Sulphur dioxide emissions, in conjunction with nitrogen oxides cause acidification of rain water that leads to the deterioration of building materials. This means that historical land marks, and recently built structures are negatively impacted (Tzannatos 2009). Acidification also has a well-documented detrimental effect relevant to the modification of the ecosystem by altering the natural pH levels of freshwater sources and thus harming fauna and flora.

Sulphate Aerosol is also a by-product of sulphur emissions which is found to make a climatic impact in a different way. Sulphate aerosols absorb solar radiation while creating an "*albedo"* effect within clouds (forming smaller droplets) which allows them to reflect more solar radiation back to space. Therefore the release of sulphate aerosols have been linked to a potential climatic cooling effect (Jones *et al* 2001). Although it would appear that sulphate aerosols might have a beneficial effect on global climate change, they are simultaneously produced with carbon dioxide, whose long term negative externality outweighs any midterm positive externality created. (Acciaro 2014; Laurier *et al* 2009)

Based on a study by Maffi *et al* (2007) externalities of sulphur and PM emissions in the Mediterranean during 2005 alone, were estimated at €6.65 billion and €1.95 billion. The U.S Environmental Protection Agency (EPA) estimates that annually $110 billion dollars can be saved on healthcare due to the adoption of the more stringent MARPOL sulphur regulations of 2015. (Heisman and Tomkins 2011)

2.2 Methods of Compliance

In order for a vessel to comply with the more stringent sulphur regulations introduced by MARPOL Annex VI Regulation 14 there are three main options available that have been introduced in the background section of the introduction. The first option is to switch from burning residual fuels to burning distillate fuels, the second option is to continue burning residual fuels, and invest in abatement technology/scrubbers/EGCS, and the third option is to invest in an alternative fuel propulsion system.

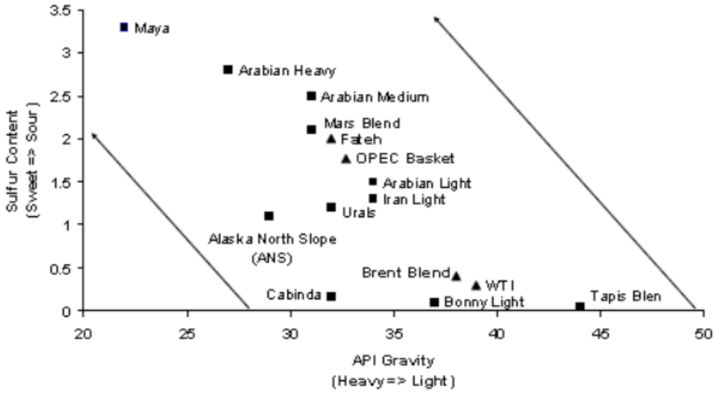
In the following sections the factors behind the decisions a shipping company has to make when choosing between these options will be discussed, and each method of compliance will be explained in detail.

2.2.1 Traditional Fuels and Compliance by Switching to Distillates

The refining processes used to make fuels will be described briefly in order to provide an understanding of the differences in composition between residual and distillate fuels, why a shift in fuel type is necessary, and how the price differentials between these two fuels can be explained.

All traditional marine fuels are produced from crude oil, but in order to make fuels from crude oil it must be refined. The refining process depends on the *'quality'* of the crude oil used, and on the type of fuel that is being made. There are many different '*qualities'* of crude oil, but only two determinants govern the '*quality'* of the crude oil extracted. These determinants are the crude oil's density (light, medium, heavy), and how much sulphur the crude oil contains (sweet, sour). The heavier grades of the oil require more involved refining methods, and the sour oils require more involved processing to remove the high levels of sulphur (RTP *et al* 2008). A representation of the different types of crude oil and their specifications can be found in figure 2 below.

Figure 2: Quality by Crude Type. Source: RTP *et al* (2008)



Different types of refineries exist to refine the different *'qualities'* of crude oil needed for the production of fuels. For this research paper the different types of refineries will be categorised into three relevant types.

Hydroskimming refineries use sweet crude to produce distillates, and gasoline. Cracking refineries build in complexity from the more basic hydroskimming refineries by additionally incorporating vacuum distillation, alkylation units, and catalytic cracking processes in order to be able to use heavy, and sour crude for the production of distillates, and gasoline. Coking refineries are the most complex type of refinery, and incorporate all of the processes of a cracking refinery while additionally incorporating hydrogen processing, hydrocrackers, and delayed coking units in order to be able to use the heaviest crude for the production of distillates and gasoline (RTP *et al* 2008). The types of refineries, and the percentage of fuel types they produce are summarised in table 1 below.

Table 1: Typical Production of Refinery Types. Adapted from: RTP *et al* (2008)

Typical Production of Refinery Types			
Type of Refinery	Hydroskimming	Cracking	Coking
Propane/Butane	4%	8%	7%
Gasoline	30%	45%	58%
Distilate Fuel	34%	27%	28%
Residual Fuel	32%	26%	15%

The main purpose of these refineries is the production of '*light'* and '*clean'* fuel types such as gasoline and distillates. Residual fuels used in vessels are by-products of the refining process of these '*light'* and '*clean'* fuels; they are thick sludge like substances that have to be heated in order to be used in a vessels propulsion system. Residual fuels also contain most of the remaining pollutants (especially sulphur) that were removed from the '*light'* and '*clean'* fuel types (Man 2013). As by-products of the refining processes of distillates, and gasoline residual fuels are considerably cheaper. According to the figures found in the Clarksons database, residual fuels are approximately 50% cheaper than distillate fuels, this is corroborated by Renolds

(2011) and UNCTAD (2012). This price differential between residual, and distillate fuels explains why it is common practice within the maritime industry to use residual fuels as bunkers (ship fuel), especially when no regulations regarding emissions from vessels are being enforced. According to Lloyds Register (2012.a) in 2010 76% of all bunkers used were residual fuels. The introduction and enforcement of MARPOL Annex VI, and the revision of Annex VI Regulation 14 means that vessels can no longer burn cheap high sulphur residual fuels in SECA regions, or in any area once the global sulphur cap is enforced.

The most common residual bunker is Heavy Fuel Oil (HFO), and the most common distillate bunker is Marine Gas Oil (MGO). There are also many variations of bunker types and blends of fuels such as Marine Diesel Oil (MDO) (distillate), and Low Sulphur Heavy Fuel Oil (LSFO) (residual), and Intermediate Fuel Oil (IFO), a blend of 75% HFO and 25% MGO used to comply with the previous 1% sulphur cap in SECAs (Williams *et al* 2013). For this research paper only HFO and MGO will be taken into consideration when reference is made to traditional marine fuels since these are the most common residual and distillate fuels used as bunkers. See table 2 below.

Table 2: Traditional Marine Fuels. Source: Author

Residual	Distilate
HFO (380 cst)	MGO

The option of complying with the more stringent sulphur caps found in MARPOL Annex VI Regulation 14 by means of switching from burning residual fuels to burning distillate fuels is currently the method most commonly used by shipping companies as it does not require any additional large CapEx to be made for machinery. This is the simplest option available, but there are complicated switching procedures while a vessel is in operation that can put the vessel at risk. When entering/exiting SECAs the vessels crew must take measures against thermal shock due to a drop of the engines operating temperatures, pump failures due to different densities of bunkers, engine shut down due to fuel mixture incompatibilities, excessive engine wear or damage due to varying lubricity of the fuels, and failure to comply with sulphur regulations due to contamination of MGO by remaining HFO in fuel tanks (DNV 2014). Once the global sulphur cap is enforced, vessels are likely to continue to use different fuel qualities inside and outside of SECAs but for this research paper it is assumed that MGO will be used in all regions.

Although this method does not require large additional CapEx (investment into training of crew and personnel is likely), the fuel price differential between HFO and MGO is approximately 50%. This is a substantial difference when taking into account the large quantities of fuel a vessel consumes. Over an extended period of time the additional expenses of burning MGO will become significant. These additional expenses are highly dependent on the operational characteristics of each vessel e.g., Specific Fuel Oil Consumption (SFOC), days at sea, and days spent in SECAs. Currently a vessel that does not, or rarely spends time in SECAs will not incur much additional OPEX by choosing to comply by switching to MGO when in SECAs. However once the global sulphur cap is enforced, all vessels will have to comply in all areas, meaning that vessels with a substantial annual FC are likely to pay millions in additional OPEX. The effect that the enforcement of the global sulphur cap will have on the prices of MGO should also be considered as studies predict that the cost of low sulphur distillates such as MGO will increase as demand for these fuels also increases after the global sulphur cap is enforced. (Mazraati 2011; DNV 2008)

This increase in demand for MGO (distillates) due to the global sulphur cap is one of the focal points that the IMO, and the refining industry are taking into consideration. This sudden increase in demand for distillates by the maritime industry might leave the petroleum industry unable to meet this demand, and might lead to a shortage of marine distillate fuels. The IMO availability study due to be released in 2018, examines the potential of the refining industry to respond to the demand for marine distillates by the shipping industry. This will be the decisive factor behind the decision on whether to implement the global sulphur cap in 2020 or in 2025. In order to meet the demands for distillates by the shipping industry, refining companies would have to make large investments into more complex refineries such as the aforementioned coking type of refinery as the crude oil extracted is gradually becoming increasingly sour and heavy (SWECO 2012). Such investments cost $0.5-$1 billion per refinery, and will take three to four years to come online (Purvin and Gertz 2009). An article written by Brown (Reid 2013) for Lloyds List presents expert opinions which estimate that European refineries would have to invest $50 billion in order to meet this demand. Another concern is that the more involved refining processes needed for the production of distillate bunkers will lead to an increase in CO2 emissions by refineries. It is estimated that the CO2 emitted by European refineries will increase by 3% when the global sulphur cap is enforced. (Avis and Birch 2009)

For vessels currently in service, that spend little to no time in SECAs the option to use traditional marine fuels for compliance is the preferred option. This option however, is less obvious for vessels that spend the majority of their time in SECAs, or for newbuilds whose operational patterns are yet to be established, and that will definitely be in operation once the EU and global sulphur caps are enforced.

2.2.2 Compliance by Means of Abatement Technology

The second option a shipping company has in order to comply with the more stringent MARPOL Annex VI Regulation 14 is to continue to burn HFO, and to invest in abatement technology/ EGCS, or more commonly known as scrubbers, to remove the sulphur content from the exhaust gas. While treating the exhaust gas for sulphur, scrubber systems also reduce the emission of particulate matter into the air (DNV 2012). Scrubber systems come in two forms; wet scrubbers, and dry scrubbers (the use of dry scrubbers will not be examined). Wet scrubbers are more common than dry scrubbers, and exist in three variations. These are the following: The open loop system, the closed loop system, and the hybrid system.

The open loop system which uses the alkalinity in sea water to cause a chemical reaction with the exhaust gas, thus removing the sulphur in the exhaust gas. The particulate matter is filtered out of the wash water (used sea water), and it is then discharged into the sea. Open loop scrubbers are the simplest, cheapest, and most cost effective EGCS systems, but because of the potential regulations against the discharge of wash water in certain areas this can limit their application. The effectiveness of open loop EGCSs to remove sulphur content can also be limited by operating in areas where the sea water is warm, or where the sea water has low levels of alkalinity (Reynolds 2011).

The closed loop system uses a mixture of sodium hydroxide and freshwater stored on board to cause a chemical reaction with the gas which removes the sulphur in the exhaust gas. The water is then recirculated into storage tanks on board, and reused so that no wash water is discharged into the sea. Closed loop EGCS systems allow a vessel to operate in all regions, regardless of regulations, and sea water alkalinity or temperature. However this operational freedom comes with additional expenses including: more expensive systems, costly chemicals, and wash water disposal at port (not all ports are equipped to receive, or are willing to receive) (Reynolds 2011; Noteboom 2010; Lloyds Register 2012.b).

The hybrid system is a combination of the open and closed loop systems, which allows either open or closed loop operation depending on the regulations of the area the vessel finds itself in (Reynolds 2011). Table 3 below shows an estimation of prices for an EGCS system.

Table 3: Prices for EGCS Systems Based on Engine Power. Source: Reynolds (2011)

Prices for EGCS			
Types	Open Loop	Closed Loop	Hybrid
EGCS Ratings (By Engine size)	USD	USD	USD
36MW	3100000	385000	3600000
16MW	2900000	3600000	3120000
12MW	2000000	2500000	2220000
10MW	1800000	2150000	1920000
3MW	1300000	1850000	1560000
1MW	1000000	1750000	1260000

Shipping companies can be reluctant to invest in EGCS systems because of the large initial CapEx, uncertainty regarding regulations, and a relatively unproven track record. According to calculations by Reynolds (2011) a shipping company should refrain from investing in an EGCS system if the operational profile of the vessel does not exceed a FC of 4000 tons per annum within SECAs. DNV (2012) predicts that less than 200 scrubbers will be installed per annum until the global sulphur cap is enforced. Once the global sulphur cap is enforced, the method of compliance by investing in scrubbers will have a rapid uptake.

2.2.3 Alternative Fuels and Compliance by Means of LNG Propulsion Systems

The third option that a shipping company has in order to comply with MARPOL Annex VI Regulation 14 is to invest in the installation of a propulsion system that operates on alternative fuels which are virtually sulphur free. The alternative fuels that are most likely to be used as marine fuel in the mid to long term are the following: Hydrogen, Biogas, Biodiesel, Di-Methyl (DME), Ethanol/Methanol, LPG and LNG (DNV 2012).

Marine engine manufacturers have been diligently working on the development of propulsion systems that have the ability to burn fuels other than traditional marine fuels, now that the enforcement of the global sulphur cap is approaching. MAN has just released (01/07/2015) its ME-LGI engine that has the ability to burn liquid gases such as methanol, DME, (bio-) ethanol, LPG, in addition to HFO. However the fuel that is most likely to lead the maritime industry into a new paradigm of low emission shipping is LNG. According to Bengston *et al* (2011) *"LNG will be the next coming substitute to fossil oil",* and it is believed that the uptake of LNG will serve as a bridging technology for fuels like hydrogen and biogas. The author shares this opinion, and this is the reason why research into the facilitation of dual fuel propulsion systems has been conducted.

LNG is the only alternative fuel that can be considered to be fully proven as a marine fuel. It has been successfully used by LNG carriers as a fuel for decades (LNG carriers take advantage of the boil off gases from their cargo), and although it is not yet common practice, LNG propulsion systems have been installed and used for quite some time on vessels other than LNG carriers. Possibly the oldest example of this is the MV Accolade II built for Adelaide Brighton Cement in Australia, where she is still operating successfully since 1981. (Sexton 2014)

One of the main drivers behind the adoption of LNG as a marine fuel is that it allows a reduction of sulphur emissions by virtually 100% allowing a vessel to comply with MARPOL Annex VI Regulation 14. Additional benefits to the use of LNG as a maritime fuel include the reduction of CO2, PM and Nitrogen Oxide (NOx) emissions by approximately 20%, 99%, and 90% respectively. This additionally enables a vessel to comply with the upcoming Tier III NOx regulations, and to contribute to a vessel's EEDI (ABB 2012; DNV 2012). These figures are corroborated by the case study of the MV Bit Viking. (Germanischer Lloyd 2012)

The other main driver behind the adoption of LNG as a marine fuel is the significant price differential between LNG and traditional marine distillate fuels. Historical prices of LNG, and oil based distillate fuels are indicative of these price differentials. However, historical LNG prices are only available for LNG at LNG import terminals and at gas hubs, but not for LNG as a fuel. The price of LNG varies from region to region because LNG prices are largely reliant upon regional supply and demand, as illustrated in figure 3 below.

Figure 3: Estimated Prices for LNG per mmbtu. January 2015. Source: Cunningham (2015)

Prices for LNG as a fuel would also have to account for Liquefaction costs, and for redistribution costs (DNV 2015). A study conducted by the Danish Maritime Authority (2012) demonstrates that LNG bunker prices will be highly dependent on regional LNG prices, and investments regarding logistics and infrastructure the port has made in order to facilitate LNG bunkering.

The investments ports would have to make into LNG bunkering infrastructure can be substantial, and are highly dependent on the method or methods of choice they plan on implementing. The methods that are available for LNG bunkering are Ship to Ship (STS), Truck to Ship (TTS), and Terminal to Ship via Pipeline (TPS). Based on a feasibility study that was conducted, the Danish Maritime Authority (2012) recommends that STS is suitable for bunkering receiving vessels with an LNG fuel tank capacity over 100m^3, TTS is suitable for receiving vessels with an LNG fuel tank capacity up to 200m^3, and TPS is most suitable for large transfers of LNG bunkers to regular customers. The LNG bunkering methods selected by ports depend on the volume of LNG bunkers the port is expecting to handle, and the port's operational and spatial constraints. STS, and combinations of STS with TPS are expected to be the most commonly used method/s adopted by ports as they provide fast loading rates and flexible operations when combined. (Danish Maritime Authority 2012)

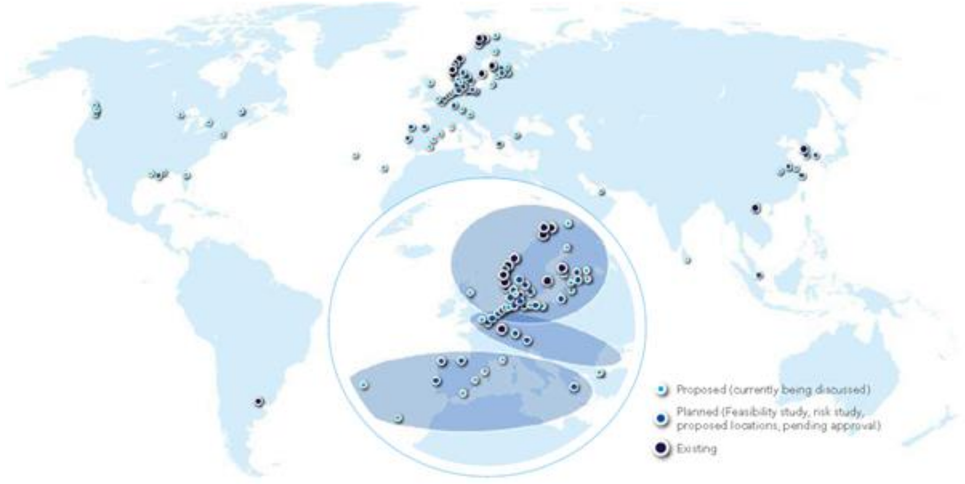
LNG is considered by the majority as the fuel of the future partially due to the large proven reserves of natural gas (IEA 2011). This is reflected by the booming global annual production capacity which is predicted to reach approximately 400mtpa by 2018. This reflects a 34% increase in annual production (Cunningham 2015; ABB 2012). Two substantial contributors to this increase in global production are the US shale gas *'Revolution'*, and the tripling of Australia's production capacity by 2018 (Cunningham 2015; IEA 2011). China could also play a major part in the growing production of natural gas as it has one of the largest shale gas reserves, but due to a potentially difficult extraction process as a result of rocky terrain it is predicted by Sandalow *et al* (2014) that there will be little growth in the short term.

This abundant supply of natural gas has led many experts to speculate that even when oil prices make a full recovery from their current slump, the supply of LNG will overshadow the demand, and LNG prices will not recover for a long time. This would indicate that price differentials between LNG and traditional marine fuels are likely to grow. (Cunningham 2015)

This sentiment is mirrored in much of the literature regarding the adoption of LNG as a marine fuel, as LNG prices are forecasted to remain relatively stable while prices of marine distillates are expected to rise due to the gradual increase of oil, and the increased demand that the global sulphur cap will create. The fuel price differentials are examined in greater detail in chapter 3 section 6.1.

Although LNG provides environmental, and financial incentives there are some challenges for a shipping company that wants to adopt LNG as a method to comply with MARPOL Annex VI. The most prominent challenge that the uptake of LNG propulsion systems face is the lack of LNG bunkering facilities at ports. This is largely due to the aforementioned “chicken and egg” stalemate the maritime industry is facing: shipping companies are reluctant to invest in LNG propulsion systems due to the lack of availability of LNG bunkering, and ports are reluctant to invest in LNG bunkering infrastructure due to the uncertainty of demand for LNG. LNG bunkering infrastructure is materialising within ECAs, and is gradually materialising in future ECAs due to the current and future demand for LNG bunkers within these regions. (DNV 2015; Stulgis *et al* 2014). This can be seen in figure 4 below.

Figure 4: Proposed, Planned, and Existing LNG Bunkering Facilities. Source: DNV (2015)



Governmental bodies need to become invested in the process in order to encourage a more rapid development of LNG bunkering infrastructure. Examples of this are the EU transport council’s directive 2014/94/EU that has allocated €21 billion in order to make LNG bunkering available in all 139 EU ports by 2025, and the Port of Singapore announcing $2 million funding per bunkering vessel for the successful applicants of proposals made in order to secure an LNG bunkering supplier licence. The Port of Singapore launched its first request for these proposals on the 28/07/2015 (Stulgis *et al* 2014; MPA 2015). Once LNG bunkering has become common practice in the large maritime centres, operational, regulatory and safety practices for LNG bunkering will have become fully established. This will allow smaller ports to follow the guidelines set by these industry leading ports, thus facilitating the global adoption of LNG bunkering (DNV 2012). This is a necessary step because of the intricate logistical challenges ports face when considering the development of LNG logistical networks, and LNG bunkering procedures due to the inherent nature of LNG.

LNG is natural gas that has been converted to a liquid form by cooling it to -163°C. This is done in order to reduce the volume of natural gas, so that it takes up 1/600th of the space in order to facilitate storage and transport (ABB 2012). The exact composition of the natural gas depends on the location of the extraction, but it mainly consists of methane, with traces of propane, and ethane. The quality of LNG depends on its methane content. (Bengtsson *et al* 2011)

Although LNG takes up 1/600th of the space of natural gas, it only has approximately 60% of energy content per volume in British Thermal Units (BTU) compared to traditional marine fuels. This means that for a vessel to retain its range, LNG tanks will take up two and a half to four times the volumetric size of traditional fuel tanks in order to accommodate for the volume of the LNG, and the additional space required by their specialised design (ABB 2012; Hellen 2009). This additional space required by LNG propulsion systems can be considered to be one of the challenges that LNG propulsion systems face as shipping companies may be unwilling to compromise cargo capacity. This is especially relevant for deep sea vessels that require large amounts of fuel, and need long ranges. The space that the LNG tanks will take on board depends on the type of tanks selected. There are three main tank types that are currently being used and they include type A, type B, and type C tanks. The type of tanks that are most commonly used are type C tanks, because they allow for a greater pressure build up and retention of boil off gas. This way very little gas is wasted, however because of their cylindrical shape these tanks take up the most volume. Tank types A and B are built into the hull and thus offer the highest fuel stowage density, and take up the least amount of space. (DNV 2015; HEC 2013)

Another challenge that the uptake of LNG propulsion systems faces is the high additional CapEx required in comparison to a traditional propulsion system. According to Verbeek *et al* (2011) a shipping company will have to pay approximately double the amount for LNG fuel tanks and an LNG burning engine compared to a traditional marine fuel tanks and engine. The biggest share of this investment premium can be attributed to the cost of the LNG fuel tanks. (Go LNG 2015)

DNV estimates that the LNG method of compliance can save a shipping company $12 million compared to the traditional fuel method of compliance, and $4 million compared to the scrubber method of compliance over a 20 year period (ABB 2012). And according to Lloyds's Register (2014) LNG Bunkering Infrastructure Survey, price differential is the main factor that will attract the use, and uptake of LNG.

2.3 Dual Fuel Propulsion Systems

The three methods of compliance with MARPOL Annex VI mentioned above all have their benefits and drawbacks, and will all have a role to play in the future. The method of switching to distillates is perceived as a short term solution, the method to use scrubbers is perceived as a medium term solution, while the option to use LNG is perceived as a long term solution (DNV *et al)*. The choice of method is highly dependent on the age of the vessel in question, which raises the question; what method of compliance should shipping companies that own new vessels, or are placing orders on newbuilds choose. A vessel's life span is approximately 20-25 years, and the global sulphur cap will be enforced in five to ten years meaning that shipping companies that own new vessels, or that plan on investing in newbuilds have a difficult decision to make. This decision depends on many factors, but there is one alternative option shipping companies have that will allow them to combine the method to switch to distillate marine fuels, with the method to burn LNG. This is the option to invest in a dual fuel propulsion system. This effectively creates a flexible strategy for future compliance with MARPOL Annex VI that bridges the short term method to switch to distillate fuels, and the long term method to burn LNG. The incorporation of operational flexibility provided by the ability of a vessel to switch fuel type is fast becoming a trend in the maritime industry. (ABB 2012)

2.3.1 Dual Fuel Technology Available

Dual fuel propulsion systems have been in use for a long time. One of the earliest examples is that of the propulsion system designed for the previously mentioned MV Accolade II built in 1981. Since 1981 dual fuel propulsion has come a long way, and companies such as Rolls Royce, Wartsila, and MAN have led the innovation of the engines required for these types of propulsion systems. Each company has a slightly different and credible approach, but due to the abundancy of available information made public by MAN, the MAN ME-GI gas burning dual fuel engines will be considered as the standard for modern dual fuel engines in this research paper.

MAN has been experimenting with dual fuel technology since 1987, and at the end of 2012 the company launched its first ME-GI dual fuel engines (MAN 2014; DNV 2015). MAN's ME-GI engines have successfully tackled most, if not all of the issues related to the use of LNG which include: methane slip, methane number specification, and the ability to run in mixed fuel mode.

Methane slip due to localised gas fuel pocket formation, and valve overlap has been eliminated because the ME-GI engine is designed to operate according to the diesel cycle principle instead of the Otto cycle principal. This is an important advancement because this is a common issue for dual fuel engines, and the escape of a small quantity of methane into the atmosphere causes a sizable increase in GHG emissions (MAN 2014). The methane number specification relates to the quality of LNG. As previously mentioned LNG will differ in methane content (quality), and most of the LNG produced has low methane content. Different engines will have different methane number specifications which will only allow them to burn a certain grade of LNG and above. MAN's ME-GI engines are able to burn all qualities of LNG further increasing the flexibility of the vessel. Finally MAN's ME-GI engines allow for operation on a mixed fuel mode, which can allow the vessel operator to extend the range of the vessel (due to potential limited LNG range) while minimising fuel costs. (MAN 2014)

The CapEx cost of a dual fuel propulsion system for a vessel, will be greater than a traditional propulsion system for the same reasons that investment into an LNG only propulsion system is greater. However because of the dual fuel propulsion system's ability to burn traditional fuels, and to operate on mixed fuel modes the vessel's range is greater. This means that the LNG tanks required for a given range could be 48% smaller than those of an LNG only propulsion system. This is an important consideration as LNG tanks are the most expensive component of an LNG burning propulsion system, and the actual premium on the engines is negligible. Therefore a dual fuel propulsion system is cheaper than an LNG only propulsion system. (Go LNG 2015)

The additional CapEx of installing a dual fuel propulsion system compared to a traditional propulsion system can be substantial, however the savings it can provide in fuel costs can more than make up for this initial investment if the operational profile of the vessel in question allows for this, and if fuel price differentials are favourable. This sentiment is reflected by all surveys, studies, and relevant academic journals.

2.3.2 Financial Incentives of Dual Fuel Propulsion Systems

There are multiple financial incentives of investments into dual fuel propulsion systems. These include the more obvious savings on OPEX that dual fuel propulsion systems can provide, but also include some important considerations regarding the added value that is derived from operational flexibility, the potential to attract charters from clients that are conscious of their triple bottom line (as defined by Elkington 1999), and the second hand value of the vessel which depends on all of the above mentioned factors.

The savings in OPEX that a dual fuel propulsion system provides are directly related to the fuel costs which as previously mentioned can make up 35%-65% of a vessel's OPEX. However, a dual fuel propulsion system can affect a vessels OPEX by more than simply reducing fuel costs. A vessel's OPEX depends on Operating Costs (OC), Voyage Costs (VC), and periodic maintenance (considered negligible in this research). By consulting Stopford's (2009) break down of OC, and VC a complete picture of how the OPEX of a vessel can be affected by a dual fuel propulsion system. This is presented below with equations (1) and (2).

$$OC = M + ST + MN + I + AD \qquad (1)$$

$M = manning\ cost$

$ST = stores$

$MN = routine\ maintenance\ and\ repair$

$I = insurance$

$AD = administration$

Where OCs are concerned the factors that might be affected by operating a dual fuel propulsion system include: manning costs are likely to be affected as more highly trained personnel will be required to work in the engine room and to conduct bunkering procedures, routine maintenance and repairs are reported to be lower by Adelaide Brighton Cement due to *"less wear and tear on the machinery"* (Sexton), insurance is likely to be higher due to the more expensive machinery (and possible higher risk due to the innate characteristics of LNG), and administration costs could or could not change depending on the shipping company in question.

$$VC = FC + PD + TP + CD \qquad (2)$$

$FC = fuel\ consumption$

$PD = port\ dues$

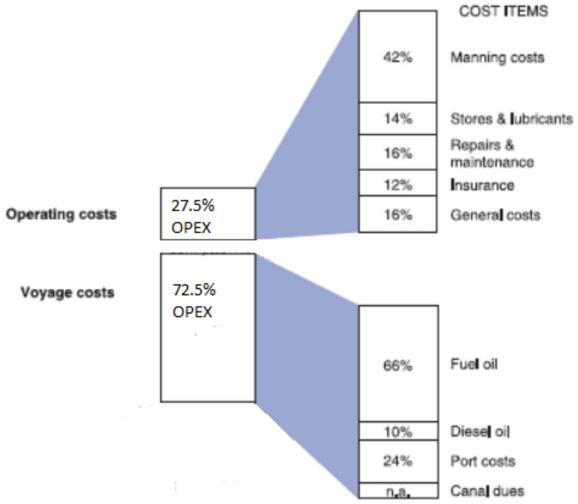
$TP = tugs\ and\ pilotage$

$CD = canal\ dues$

Where VCs are concerned the obvious factor that is affected by the operation of a dual fuel propulsion system is the fuel consumption. The only other factor that could be affected is the port dues, since the introduction of initiatives to reduce pollution at ports. An example of this is the Port of Singapore's Green Port Programme which offers reduced port dues of up to 25% to vessels burning clean fuels. (MPA 2015.a)

The additional considerations regarding the effect that a dual fuel propulsion system can have on a vessel's OC, VC, and eventually OPEX aside from reducing fuel costs are noteworthy, and a shipping company must take them into consideration. However, these variables have relatively small effects on a vessel's OPEX compared to fuel costs. An example of this is portrayed in figure 5 below.

Figure 5: Vessel's OC, and VC adapted from Stopford's General Cost Classification of a ten year old Capesize Bulker. Source: Stopford (2009)



In addition to the savings related to OPEX, the added value that operational flexibility, and the potential to attract charters from clients that are conscious of their triple bottom line that a dual fuel propulsion system can create, should be taken into consideration. The operational flexibility provided by a dual fuel propulsion system allows a vessel to operate in all areas including ECAs, and areas that have little or no LNG bunker availability. This effectively broadens the operational profile of the vessel, and allows it compete for a wider range of charters. This operational flexibility also allows the vessel to move to and from areas in order to capitulate on the highest charter rates that develop regionally or on certain trade routes due to market trends while burning the cheapest bunkers available (DNV 2012). The argument that a vessel operating on a dual fuel propulsion system will be able to minimise fuel costs has been presented throughout this research paper, and is likely to increase the propensity of the vessel to be chartered. This is especially relevant for vessels competing for long term bareboat charters, and time charters because the charterers in these types of charter parties are responsible for the fuel costs, and are more likely to charter a vessel with low fuel costs (DNV 2012). According to DNV's owners survey 35% of owners in the survey report that the charterers pay for 100% of the fuel costs, while 65% of the owners in the survey report that charterers pay more than 50% of the fuel costs. It could also make sense that a charterer is willing to pay higher charter rates as long as they would be minimising costs in the long run. The more environmentally friendly dual fuel vessels are also bound to attract charters from companies that are conscious of their triple bottom line, and looking to reduce their carbon footprints. Examples of companies working in collaboration with shipping companies to reduce their carbon footprints are given by Stulgis *et al* (2014) and include Wal-Mart and IKEA.

The additional value created by the wider range of potential charters, and the increased attractiveness to charterers who pay their own fuel bills will undoubtedly positively affect a vessel's annual loaded days at sea which will affect the vessel's productivity (P). This can be presented mathematically by referring to equation (3) as per Stopford (2009) presented below.

$$P = 24 * S * LD * DWU \tag{3}$$

$S = average\ operating\ speed\ per\ hour$

$LD = loaded\ days\ at\ sea\ per\ annum$

$DWU = dead\ weight\ utilization$

An increase in annual productivity will affect the vessel’s potential to earn revenue (R), along with any potential for a premium freight rate that might be negotiated. This can also be presented mathematically by referring to equation (4) as per Stopford (2009) presented below.

$$R = \frac{P * FR}{DWT} \tag{4}$$

$P = productivity$

$FR = freight\ rate$

$DWT = deadweight$

The added value of an investment towards a dual fuel propulsion system as discussed above will allow a vessel to increase its revenue, and potentially create additional cash flows thus increasing the NPV of the vessel. Therefore, the potential for increased productivity, and lower FC that is derived from investing in a dual fuel propulsion system can positively affect the second hand value of the vessel. (DNV 2012; Stopford 2009)

As presented throughout this research paper, and other studies, surveys, and academic journals, the most significant incentive for investments to be made towards a dual fuel propulsion system is the reduction of fuel costs. Therefore the assessment of the value created by a dual fuel propulsion system in this research will be based on the reduction of fuel costs, and will be presented in the following chapter.

Chapter 3: Methodology

3.1 Introduction to Real Options Analysis

The question posed in this research paper is: **What is the value of flexibility that a dual fuel propulsion system provides its operator?** To begin to answer this question, it is necessary to define what value is, and how this value is quantified. Value is defined by the Oxford, and Webster's dictionaries as the monetary worth of something, but also the worth, and utility of something compared to the price paid for it. Therefore the value of the option to switch to LNG that a dual fuel propulsion system provides its operator, is the current monetary worth of the system based, on all the profitability it is capable of generating for its operator in the future.

Traditional methods of valuation including the Cost Approach, the Market Approach, and the Income Approach, all use Discounted Cash Flow (DCF) valuation. DCF is universally accepted because it is easy to use; it clearly gauges decision factors, it incorporates risk factors, the time value of money, and it provides the decision makers with a clear outcome (Mun 2012). Although DCF provides an easy and clear method of valuation it includes critical assumptions, and overlooks certain realities associated with making investments in projects. Some of these assumptions made by DCF valuation are: that a fixed discount rate can take all risks into consideration, that a project will be passively managed, that predicted cash flows are easily determined by previous cash flows, and that every element that has a decisive effect on a project and its value will be quantified through the Net Present Value (NPV).

In reality: risk is not a constant, and thus a fixed discount rate for the duration of a project is unrealistic. Projects are managed either constantly or managerial decisions are made at discrete time periods and cash flows are almost always stochastic, based on the existence of internal and external uncertainties therefore, it is almost impossible that every element that has a decisive effect on a project or its value can be quantified. (Mun 2012)

These assumptions or simplifications DCF valuations make, have led industry leaders, academics, and managers to the conclusion that DCF valuation methods are not sufficient to properly evaluate the investment of a project. This is due to the fact that DCF valuations are not designed to incorporate uncertainties a project might face, and the managerial decisions that could be taken to adjust to these uncertainties in order to achieve to the optimal outcome of a project.

This however does not mean that DCF valuation is of no value. On the contrary, it provides the building blocks of what Trigeorgis (1993) calls an "*expanded NPV rule*" which takes into account both the operational value of flexibility, and traditional DCF valuations. Therefore Real Options Analysis (ROA) is introduced not as a totally new valuation method, but as a much needed extension of project valuation. Brach (2003) refers to this as "*the next level of financial and strategic analysis*".

The concept behind ROA is having the option to do or not to do something; one can interpret this as managerial flexibility. Brach (2003) describes flexibility as freedom of choice, and refers to a manager's decision to act or to forgo an option available to him, with regard to financial call, and put options.

This freedom of choice, or "*flexibility*" is required in order for the optimal outcome of a project to be realised. A project manager has to be able to proactively act, or react to an uncertainty. This uncertainty can be both external and internal, and come in many forms including a change in legislation, entry of a new technology, and an upswing in the market, *et.al.* A manager's ability to react to uncertainties, whether they are internal or external allows for either the creation of additional value, or the minimisation of loss, which a traditional DCF valuation cannot capture this. ROA allows for consideration of these options, and when a manager always chooses the value maximising option, this represents *optimal behaviour,* this is known as the Bellman equation of dynamic programing. (Kulatilaka 1993)

Another advantage of ROA is that it allows for the inclusion of a variable discount rate based on an estimation regarding risk. This can be achieved by using the binomial pricing model which takes the best case scenario, and the worst case scenario, allowing for an estimation of the expected value. Subsequently, the scenarios, and the expected value are used to estimate the risk neutral probability, which adjusts the discount rate at discrete time intervals along a binomial decision tree (Brach 2003).

An alternative method to incorporate a variable rate of return based on probable risk, would be to use the Cox, Ingersoll, and Ross (CIR) process. Instead of using the risk adjusted discount rates, the certainty equivalent of cash flows can be used. This method uses the risk free discount rate, but adjusts the expected cash flow for risk at discrete time intervals (Kulatilak 1993). This risk adjustment should only be used where drift rates of stochastic variable inputs can be calculated easily.

Because ROA is based on the inclusion of flexibility, quantifying an option only makes sense if the ability to exercise the option exists, which means that the option has to be tangible. The ability to exercise the option depends on financial and organisational factors and the aptitude to continually apply *optimal behaviour* is also a pre requisite in order for ROA to be meaningful. It may be difficult for an organisation to adapt ROA because it incorporates a modular strategy that requires the entire organisation to be willing and able to implement the changes required in order to achieve *optimal behaviour* when necessary*.*

Optimal behaviour for real options is achieved either when the decision is made to exercise the call option when the exercise price (K), which is all expenditures required to create the asset is less than (S), or the present value of future cash flows from the asset. ($S - K = C$) gives the value of the call option (C). The option will be considered to be in the money as long as the value of the call option is greater than 0 (Brach 2003).

As per Mun (2012), ROA is a combination of management science, econometric modelling, economic analysis, statistics, decision sciences, and financial theory. Therefore ROA is the ideal method to evaluate the research question, as the environment a vessel operates in is full of external uncertainties that need to be accounted for such as markets, and regulations that are constantly changing and evolving. This requires flexible management that should apply *optimal behaviour*. In addition, a dual fuel vessel inherently provides the management of a shipping company managerial flexibility.

3.2 Relative Applications of Real Options Analysis

ROA valuation can be used in various ways in order to provide solutions to different types of research questions, making this a flexible method of valuating flexibility. Brach (2003) refers to six basic managerial options which include: The Option to Defer, The Option to Abandon, The Option to Switch, The Option to Expand/Contract, The Option to Grow, and The Option to Stage. This means that ROA can be applied to a large variety of business applications/projects, and that ROA can be useful to quantify various options of a specific business applications/projects. In addition the same option in ROA can be formulated by using a variety of different methods/models that a researchers deem as most fitting to their particular case.

In order to familiarise himself with the various forms of ROA, and to be able to formulate the method/model that is most suitable to answer the research question at hand, the author has consulted a number of research papers. The most relevant to the formulation of the model for this research will be presented below.

"A real option to invest in low-sulphur maritime transport", by Acciaro (2014) is an ROA valuation of the option to defer that a shipping company has when considering the adoption of retrofitting LNG propulsion systems, or Exhaust Gas Cleaning Systems (EGCS) to their vessels in light of the more stringent MARPOL Annex VI sulphur regulations. The research conducted by Acciaro (2014) has thematic, and structural similarities to this research paper since both research papers study means of compliance with MARPOL Annex VI Regulation 14. Acciaro (2014) creates hypotheses by selecting two vessels and their particularities, and develops four equally probable fuel price scenarios. Acciaro (2014) then runs an ROA model with the option to defer. The research conducted by Acciaro (2014) has provided insight to creating a structure for the model in this research paper.

"The Option to Change the Flag of a Vessel", by Kavussanos and Tsekreos (2011) is an ROA valuation of the option that a shipping company has to change/switch to/from flags of convenience to/from a national flag. This is an important consideration in the maritime industry as flags of convenience provide for reduced operating costs due to lower taxation, but also increased operational risk due to relaxed safety requirements. Kavussanos and Tsekreos (2011) refer to this as the risk-return trade-off, and have devised their research in such a way as to enable both shipping companies, and governments with a means to understand what variables are the most critical when decisions regarding flagging a vessel are made. The research conducted by Kavussanos and Tsekreos (2011) is brings up important considerations for this research paper since the model to switch is used. These considerations include the introduction of switching at fixed levels ($bi<0<bh$) and how the higher the correlation between profitability under a national flag (πn), and profitability under a flag of convenience (πc) diminishes the value of the option to switch is, and how this correlation increases bh and decreases bi which results in less of a willingness to switch.

"The Value of Flexibility: The Case of a Dual-Fuel Industrial Steam Boiler", by Kulatilaka (1993) is an ROA valuation of the option to switch fuel types that a dual fuel burning steam boiler provides its operator. Kulatilaka (1993) investigates whether the

additional investment in the more expensive steam boiler provides a sufficient increase in cash flows in comparison to the traditional cheaper single fuel steam boiler for such an investment to be considered *in the money*. The research conducted by Kulatilaka (1993) has provided important insights to this research paper including the introduction of the Bellman equation of dynamic programing. Kulatilaka (1993) presents a clear method to normalise the price of different fuels, introduces CIR to the equation instead of using discount rates and he uses probabilities to calculate the expected value of the future period, and uses Ordinary Least Squares (OLS) regression to quantify the volatility of input variables (in this case fuel prices). By using these methods Kulatilaka (1993) is able to quantify the value of flexibility in a precise manner, and demonstrates that the probability of a switch in the mode of operation is most likely to occur when the normalised price of the two fuels are indifferent, and that at this time the option to switch is the most valuable. This is not the case in this research project, because unlike the stationary dual fuel steam boiler in Kulatilaka's (1993) research, where LNG is considered to be constantly available and the option to switch is induced by fuel price differentials, the option to switch for a dual fuel propulsion system installed on a vessel is induced when operation on LNG is made possible due to the availability of LNG. This is because LNG is considered to be consistently cheaper than MGO, but is not always available as a marine fuel. This means that the larger the difference of the normalised price of fuels is, the more valuable the flexibility provided by a dual fuel propulsion system becomes.

"The time dimension and value of flexibility in resource allocation: The case of the maritime industry", by Axarloglou *et al* (2012) is an ROA valuation of flexibility that operating a vessel in the tramp market provides in contrast to Time Chartering (TC) a vessel. Axarloglou *et al* (2012) explain how the difference in Voyage Charter (VC) rates and TC rates can be explained by the risk premium (φ) which includes Unemployment Risk Premium (URP), Trip Specific Additional Costs (TSAC), and how due to the different duration of the contracts, and how the φ fluctuates over time depending on the state of the market (shipping cycles). Axarloglou *et al* (2012) proceed to describe operating a vessel in the tramp market as buying a series of call options, which would be foregone if the vessel was time chartered. Axarloglou *et al* (2012) use OLS regression to correlate the different variables that affect costs, and conclude that the *"time dimension"* (the business cycle, the volatility, the stage of the industry, and the growth prospects of the industry) have a significant effect on the value of flexibility that operating a vessel in the tramp market provides. The *"time dimension"* is also an important consideration for this research paper as the investment towards a dual fuel propulsion system will provide fluctuating cash flows depending on fuel price differentials, and other uncertainties over the lifespan of a vessel.

"Ship Investment under Uncertainty: Valuing a Real Option on the Maximum of Several Strategies" by Bendall and Stent (2007), is an ROA valuation of the implementation of a flexible strategy compared to inflexible strategies regarding high speed container vessels operating a hub and spoke system in Singapore. According to Bendall and Stent (2007) three strategies are compared, and valuate best/worst/most likely scenarios are formed based on stochastic variables. A simulation of 15,000 vessels is performed, and volatilities and correlations of variables are estimated. When both DCF and ROA valuations are made, the results obtained

by the DCF valuation predict the flexible strategy as sub-optimal since it is not able to account for managerial flexibility. However the results obtained using ROA valuation demonstrate that with the inclusion of managerial flexibility the flexible strategy is the most valuable strategy to follow.

“Market switching in shipping— A real option model applied to the valuation of combination carriers” by Sodal *et al* (2007), is an ROA valuation of the option to switch between dry bulk and wet bulk markets. The operation of combination carrier allows for Sodal *et al* (2007) to investigate whether the additional cost of purchasing a more expensive combination carrier, over a liquid bulk carrier is a worthwhile investment. They choose to use a liquid bulk carrier as the base case because it is closer in comparison to a combination carrier than a dry bulk carrier. Sodal *et al* (2007) use a mean reverting Ornstein-Uhlenbeck (O-U) process because it can provide a good estimate of the freight rate spread, while the value of flexibility is expressed in Kummer functions. The results show that the variables that have the greatest effect on the value of flexibility of combination carriers are the volatility and correlation of freight rates and their long run mean differential. If switching costs are low they can be negligible.

3.3 Proposed Structure of Real Options Analysis

After consulting the available research it is apparent that the only valuation method suitable to quantify the value of flexibility provided for by a dual fuel propulsion system is ROA valuation.

Actually the research question is ideal for ROA valuation due to the inherent flexibility that a dual fuel propulsion system provides its operator with. ROA valuation allows for the stochastic variables, their correlation and volatility (such as fuel prices), the *time dimension*, and the probability of uncertainties (such as a potential increase in ECAs and the enforcement date of the global sulphur cap, the availability of LNG bunkering) to be taken into consideration when building such a model.

In order to quantify the value of flexibility provided for by a dual fuel vessel, the author begins by developing hypotheses regarding the operational characteristics of two different vessels in order to present unbiased results. The author then presents potential future outcomes by creating scenarios. These scenarios are created by taking the uptake of LNG bunkering, and the upcoming sulphur regulations into consideration. Then sub-scenarios are introduced based on the evaluation of potential maximum, and minimum fuel prices.

Separate asset trees are then used to plot out the scenarios, and sub-scenarios for both of the dual fuel versions of the vessels in order to properly estimate the probability of the scenarios, and sub-scenarios which might materialise depending on assumptions made when taking the appropriate variables, and uncertainties into consideration.

This allows for multiple cash flow timelines for each vessel to be estimated based on the hypotheses, the scenarios, and the sub-scenarios. This results in a range of annual fuel cost differentials. The present value of these cash flows (savings) are then used in an ROA valuation in the form of a binomial pricing model derived from the binomial pricing model presented by Brach (2003) which will allow for the quantification of the value of the option to switch to and from LNG that a dual fuel propulsion system generates for each vessel.

Because of the many uncertainties related to this research question, a more basic binomial approach that incorporates assumptions, and scenarios is used. However the options to use, or include equations, such as those found in the Bellman dynamic programing model could allow for a more precise approach. This could be useful to a shipping company looking to make a very precise calculation providing that it has more data and information available to it, and therefore needs to make fewer assumptions.

3.4 First research question: Justification of Hypotheses and Scenarios

What types of vessels will allow for a good evaluation, and how will their operation on a dual fuel propulsion system offer cost reductions?

In order to begin to answer the first research question, and to enable this research paper to properly portray the flexibility that a dual fuel vessel can provide a shipping company in lieu of the aforementioned uncertainties, it was important to carefully consider the types of vessels that will allow for the construction of an interesting model that fits the research question.

Diligent research was conducted by using Clarksons Sin online database, and The Baltic Exchange. Other resources were also consulted in order present realistic hypotheses regarding the “typical” vessel types, and their operational characteristics. It should be noted that an attempt was made to only include recent newbuilds as they are designed and operated with the latest fuel saving technologies and techniques.

3.4.1 Hypotheses of the Two Vessels and Scenarios

Hypothesis 1 and scenarios

The first vessel that has been selected for evaluation is the MV Fengning, a Handysize bulk carrier. It is assumed that this vessel will operate exclusively within the EU economic zone waters in the Mediterranean. This hypothesis has been created in order to demonstrate the value of the option to switch for vessels operating in the tramp market within the EU economic waters in the Mediterranean, an area where sulphur regulations will be enforced in 2020 but availability of LNG bunkering is still uncertain. In this hypothesis two scenarios are provided. The first scenario assumes that there will be a quick uptake of LNG bunkering and that there will be 30% LNG bunkering availability by 2020, there will be 50% availability by 2025, and by 2035 there will be 100% availability. The second scenario assumes that there will be a slow uptake of LNG bunkering and that there will be 10% LNG bunkering availability by

2020, there will be 30% availability by 2025, and by 2035 there will be 60% availability (These assumptions are based on estimations made by the author). This means that if fuel price differentials favour LNG the operator will be able to operate on LNG at the particular percentage of LNG availability during that time period given the scenario. It is also assumed that the vessel will spend 250 days at sea. The vessel specifications are found below in table 4.

Hypothesis 2 and scenarios

The second vessel that has been selected for evaluation is MV Amazon Victory, a Long Range Panamax product tanker (LR1). It is assumed that this vessel will be operating exclusively on routes from the Persian Gulf, to Northern European ports. Route T94 as per Clarksons Sources & Methods (2015), is a “typical” route for an LR1 Panamax product tanker. Two scenarios exist for this hypothesis, the first is that the global sulphur cap will be enforced in 2020, and the second is that the global sulphur cap will be enforced in 2025. This hypothesis was created in order to examine the value of the option to switch to LNG that a dual fuel propulsion system provides for vessels that operate crossing areas where the date of enforcement of more stringent sulphur regulations is both certain (EU economic zone), and uncertain (Arabian Gulf, Arabian Sea, Red Sea, and non EU economic zones in the Mediterranean). Calculations are based on the average speed of vessels on this route, and the average sea margin for this voyage as given by Clarksons (2015). Based on these assumptions and the typical operating pattern for this type of vessel on this route, it is estimated that the vessel will make seven voyages, spending 306.39 days at sea, and 35 days at berth/waiting. The remaining 24 days are considered to be off hire or to be used for maintenance. For this hypothesis it is assumed that by 2020 the vessel will be able to bunker LNG at Rotterdam as there is an LNG bunkering station in existence which will allow the vessel to make the ballast leg of the voyage on LNG when the price differentials are favourable for the use of LNG. It is assumed that by 2025 LNG bunkering will also be available in the Persian Gulf, allowing the vessel to use LNG on all legs of the voyage when the fuel price differentials are favourable for the use of LNG. The vessel specifications are found below in table 4. Both vessels are real vessels found in Clarksons database.

Table 4: Vessel Specifications. Source: Clarksons (2015) and Author’s calculations

	Unit	Vessel 1: MV Fengning	Vessel 2: MV Amazon Victory
Category		Handysize Bulker	LR1 Product Tanker
DWT	Tons	39,250t	72,142t
Built	Year	2015	2014
GT	Tons	24,785t	44,776t
Engine		Wartsila 5RT-flex50-B 124rpm	MAN 6S60MC-C7.2 105 rpm
SMCR	kW	8,409kW	13,560kW
NCR	kW	4,507kW at 53% SMCR*	10,784kW at 79% SMCR*
SFOC	g/kWh	166.4g/kW	170g/kW
FC at Speed	Tons/Day at kts	18t at 14kts	44t at 13.5kts*
Avg peer FC	Tons/Day	21.05t	41.5t
Days at Sea	Days per year	250	306.39

*Calculated by using equation ($FC = SFOC * kW * 24/10^6$), and the data on the vessels available in Clarksons Database.

Establishing the hypotheses regarding vessel specifications and operating patterns, allow for the estimation of voyage costs related to fuel, which in turn allow for annual fuel consumption to be calculated for both vessels and their dual fuel counterparts in the next sections.

3.4.2 Fuel Cost Calculation Models for the Vessels

In order to quantify the costs associated with each vessel, one must first take the low calorific value of each fuel into account which allows for an appropriate assessment of FC in each of a dual fuel vessel's the three operating modes: HFO, MGO, and LNG. The calorific values of the fuels listed in the feasibility study conducted by Perez *et al* (2014) are used. The FC of the vessels can be seen in table 5 and table 6 below.

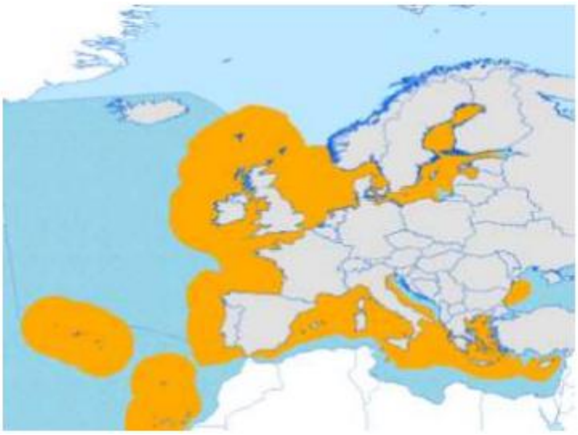
FC for the first hypothesis and scenarios for MV Fengning, are relatively straight forward, as the vessel will be operating exclusively in the Mediterranean EU economic zone and the sulphur regulations are being enforced in 2020. Depending on fuel price differentials, the appropriate fuel will be chosen for the operation of dual fuel version of MV Fengning.

Table 5: Fuel consumption for MV Fengning. Source: Author

Vessel 1: MV Fengning			
	HFO	MGO	LNG
Speed	14	14	14
Days at Sea	250	250	250
Days at Berth	80	80	50
Days in ECAs	0	330	330
FC at sea per day in tons	18	17.07	14.85
Annual FC at Sea in tons	4500	4268.69	3713.41

FC for the second hypothesis, and the 2020/25 global sulphur cap enforcement scenarios, is harder to calculate because the permanent route (T94) on which the MV Amazon Victory is operated, must be segmented into four different legs. This must be done in order to calculate how many tons of each type of fuel the MV Amazon Victory will burn while she crosses each of the four legs of the voyages. This is necessary to quantify the changes in fuel costs due to the upcoming sulphur regulations, and the effect they will have on the OPEX of MV Amazon Victory when she is operating in each of the four different legs of route T94. Figure 6 below depicts the EU economic zones that a sulphur cap will be enforced in by 2020.

Figure 6: EU SECA zones by 2020. Source: ECA and emissions: Mohn (2014)



Route T94 from the Persian Gulf to Rotterdam has been segmented into the following legs: Mina Al Ahmadi to Fouad, Fouad to Tanger, Tanger to Ushant, and from Ushant to the Shell Oil terminal in Rotterdam. Each of these legs represents either an existing SECA (Ushant-Rotterdam), the upcoming EU SECA in 2020 (Tanger-Ushant), or regions where the enforcement date of the global sulphur cap is still unknown (Mina Al Ahmadi-Fouad-Tanger). It has been assumed that while in the Mediterranean, on the leg from Fouad-Tanger MV Amazon Victory will remain in North African economic zones to minimise fuel costs by avoiding EU SECA zones. On the leg from Tanger-Ushant it is assumed that MV Amazon Victory will not deviate to go around the EU SECA zones in the Atlantic and will therefore have to switch to a low sulphur alternative.

The use of the Netpas program has facilitated precise breakdown of each leg of route T94. Netpas is a widely acknowledged voyage estimation tool, and is used by many respected shipping companies. MV Amazon Victory's average speed on her laden and ballast voyages are entered into Netpas, along with a 2 percent sea margin. The results provide the exact time in days it takes MV Amazon Victory to conclude each leg of the laden and ballast voyages. This allows for the time in days MV Amazon Victory spends in existing, and upcoming SECAs to be calculated, but also allows for the FC to be quantified for each type of fuel during each separate leg.

FC is calculated by accounting for the calorific values of the fuels, and by using a formula to calculate fuel consumption at different speeds. The FC at different speeds is then averaged to account for both laden and ballast voyage. The formula for calculating fuel consumption reductions according to speed (S), design speed (S^*), and design fuel consumption (FC^*) as presented by Stopford is useful as this allows for the fuel consumption of these vessels to be quantified at various speeds if necessary. The formula is written as follows:

$$FC = FC^* \left(\frac{S}{S^*}\right) \tag{5}$$

The results of the voyage estimations by using Netpas, combined with the calorific values of the fuels, and the calculations of FC for MV Amazon Victory, are presented in table 3 below. These results will allow for the annual fuel consumption of both a dual fuel version, and a traditionally fuelled version of the MV Amazon Victory to be estimated depending on future fuel price differentials.

Table 6: Fuel consumption for MV Amazon Victory. Source: Author

Vessel : MV Amazon Victory			
Days	Pre 2020	Post 2020 Med only SECA	Post 2020 Global SECA
Speed Lad/Ball	13.5/12.5	13.5/12.5	13.5/12.5
Days at Sea	306.39	306.39	306.39
Days at Berth	35	35	35
Days Mina-Fouad	151.83	151.83	151.83
Days Fouad-Tanger	88.76	88.76	88.76
Days Tanger-Ushant	43.54	43.54	43.54
Days Ushant-Rott	22.26	22.26	22.26
Days in ECAs	22.26	111.02	306.39
Annual FC			
Fuel type	FC HFO	FC MGO	FC LNG
FC in tons Mina-Fouad	6448.22	6116.77	5321.09
FC in tons Fouad-Tanger	3769.64	3575.87	3110.72
FC in tonsTanger-Ushant	1849.14	1754.09	1525.92
FC in tons Ushant-Rott	896.79	896.79	780.13

Although FC at berth is an important factor, it has been considered to be outside of the scope of this research paper because cold ironing is set to play a major role in the reduction of emissions of vessels at port, and will affect the FC of vessels at berth in the future.

3.5 Second research question: Justification of Fuel Price Differential Assessment and their effect on cash flows

How do fuel prices affect the investment into a dual fuelled vessel, and how should they be measured?

As previously stated the main factor in this ROA valuation with the option to switch is the potential savings on fuel cost that a dual fuel propulsion system provides a vessel operator. This is due to the ability it has over a traditional propulsion system to be able to respond to uncertainties such as the enforcement dates of the more stringent sulphur regulations, LNG availability, and the unpredictable price differentials of fuels.

A first attempt at scenario building was made by creating four scenarios that included regulatory uptake, LNG bunkering availability, and price differentials. These variables changed in a logical manner as they are all correlated to each other in various degrees. However this method was abandoned as it resulted because the option to switch, would be a permanent switch to or from a mode of operation.

Therefore, a different approach was developed, and the hypotheses of the vessels and their operating characteristics were created, and two scenarios for each vessel were chosen. In the case of MV Fengning the enforcement dates of the sulphur cap are known, and two scenarios are given for LNG bunkering availability. In the case of MV Amazon Victory, the availability of LNG bunkering is known, and scenarios of the enforcement dates of the global sulphur regulations are given. This leaves the uncertainty of the fuel price differential (sub-scenarios), which is covered in this section.

To introduce the sub-scenarios which are the uncertainty of fuel price differentials in this research paper, it was decided that a high, and low fuel price differential scenario was preferable. This, in combination with the hypotheses developed for the vessels, allows this research paper to better portray the continuous (depending on fuel price differentials and regulations) option to switch a vessel operator has when operating a dual fuel vessel.

3.5.1 Fuel Price Differentials

Instead of building scenarios by trying to predict the future price of fuel over the lifetime of the vessel, a maximum and minimum future fuel price differential between LNG and traditional fuels was used to build the model. This is because the value of the option to switch, provided by a dual fuel propulsion system is derived by the maximum, and minimum annual OPEX differential between the LNG and traditional modes of operation. This annual OPEX differential is a direct result of annual fuel price differentials. However, the assumptions regarding annual future fuel price differentials, must be derived from the potential volatilities, and the correlation of the prices of LNG, MGO, and HFO. Therefore, the estimation of the maximum and minimum expected fuel price differentials is conducted based on the analyses of historical data, projections by The Danish Maritime Authority (2012), the DNV 2020 Report (2012), and IEA (2011) reports.

An analysis was conducted regarding the prices, and price differentials between 380cst (HFO) and MGO at the major bunkering ports within the operating territories of the vessels used in this research paper in order to gain an insight into potential future outcomes. The fuel prices for HFO and MGO were compiled from 1995 to 2015 at the ports of Rotterdam, Gibraltar, and Fujiarah from the Clarksons database. The average annual price of each of these fuels was calculated, and a 95% correlation between the fuel price differentials of HFO and MGO was established by using the least squares method. The average annual growth rate of the price differential between the two fuels was calculated to be approximately 9% over a twenty year period. The standard deviation, and volatility were also calculated for HFO, and MGO over the past 10 years instead of 20 years in order to provide results that are more consistent with the current trends using the following formulas in excel:

Growth rate $= \frac{V(tn)}{V(to)} * \frac{1}{tn} - (to) - 1$ (6)

Standard Deviation$= LN(\frac{to}{t1})$ (7)

Volatility $= STDEV(to\colon tn) * (SQRT)10$ (8)

Historical LNG bunkering prices are not available since LNG bunkering is yet to be widely established. Therefore, average global LNG prices have been taken into consideration since LNG prices in the operational region (Europe/Middle East) of the vessels used in this research paper are priced at the global average. As previously established in chapter 2 section 2.3, LNG bunkering logistics must be added to these prices, and as mentioned by the Danish Maritime Authority (2012), these costs will vary depending on the throughput and design of the bunkering methods at various ports. All of the following estimations regarding differentials between LNG, and HFO/MGO take the calorific content of the fuels into consideration.

By breaking down the predicted LNG and MGO prices made by DNV (2020), and Danish Maritime Authority (2012), it appears that price of LNG is expected to constantly be 40% cheaper than MGO. This can be explained by the correlation coefficient of (0.88) found between LNG and MGO price differentials by The Danish Maritime Authority (2012). Therefore, the smallest foreseeable price differential between LNG and MGO is assumed to be 20% in order to account for any outlying prices. The lowest foreseeable price of $500/ton for MGO (DNV 2020), (a price that has not been seen since January 2007), leads the author to believe that the minimal price differential between LNG and MGO can be estimated at $100/ton.

The maximum price differential between LNG and MGO is assumed to be $800/ton. The annual fuel price increase for MGO over the past 20 years has been calculated at 7%, but due to the increasing SECA regions, there will be an increase in demand for low sulphur fuel which will, more than likely cause the price of MGO to rise above historical levels. The author agrees therefore, with the predictions made by DNV (2020) regarding the potential of MGO to reach the $2000/ton mark by 2035. Since LNG is expected to remain 40% cheaper than MGO, and given a $2000/ton high price for MGO, the maximum price differential between MGO and LNG is estimated to be $800/ton. This figure is corroborated by The Danish Maritime Authority (2012) where once converted from Euros to dollars, the maximum estimated price differential between LNG and MGO in their study is also $802/ton.

The minimum price differential between LNG and HFO can be considered to be $1/ton as any value above zero will induce a switch from HFO to LNG. It is taken for granted by the author that any price differential resulting in LNG to be more expensive than HFO will induce the use of HFO while in the appropriate area. The maximum price differential between LNG and HFO (where LNG is cheaper) has been estimated at $400/ton. In order to make this estimation the highest historical price of HFO $700/ton (March 2012) was taken as the ceiling price. This is because the increasing emissions regulations and gradual phasing out of HFO, will decrease the demand for HFO causing a decrease in price of HFO. Therefore the price of HFO is not expected to rise above $700/ton. The minimal price of $400/ton for LNG was determined by subtracting 20% from the above mentioned minimal price of MGO ($500), based on the high correlation of LNG and MGO prices. This price is also loosely corroborated by DNV (2020). The maximum and minimum price differentials used are summarised in table 7 below.

Table 7: Minimum and Maximum Fuel Price Differentials. Source: Author

	Minimum Differentials	Maximum Differentials
LNG-MGO	$100/ton	$800/ton
LNG-HFO	$1/ton	$400/ton

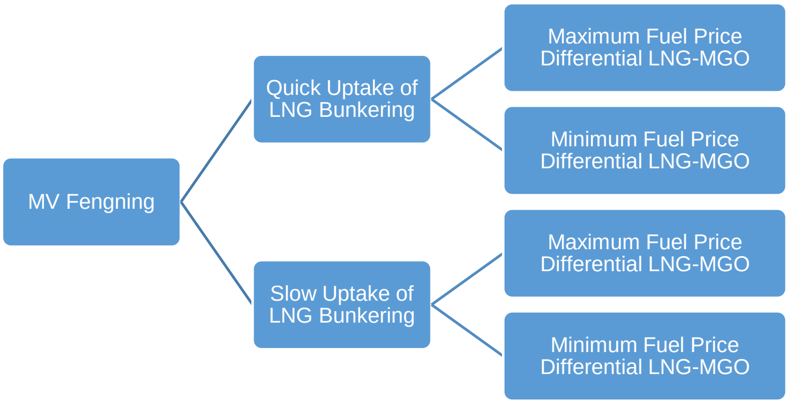
It must be noted that the above assumptions regarding fuel price differentials are by no means an attempt to forecast prices, but are logical assumptions regarding the maximum and minimum differentials fuel prices could fluctuate between. By using the fuel price differentials in table 7 the author is able to create the maximum and minimum cash flow scenarios, and sub-scenarios that are required in an ROA valuating the option to switch. This will be covered in the following sections.

3.5.2 Binomial Asset Trees and cash flows

Hypothesis 1: MV Fengning

Now that maximum and minimum price differentials have been established, the next logical step is to consider the probability of maximum and minimum price differentials materialising, and whether the high LNG bunkering uptake scenario or the low uptake scenario will materialise in the Mediterranean EU economic zone. A binomial asset tree was made in order to depict the hypothesis, the probabilities of the bunkering uptake scenario, the probabilities of the sub-scenarios of the fuel price differential and how they might materialise. See figure 7.

Figure 7: Binomial Asset Tree for MV Fengning. Source: Author



Assumptions regarding probabilities of a quick, or slow bunkering uptake (Scenarios 1 and 2) materialising are made, while simultaneously making assumptions regarding the probability of maximum or minimum fuel differentials (Sub-scenarios 1 and 2) materialising.

For this research paper it was assumed that the probability of quick/slow is 50/50% and that the probability of maximum/minimum LNG/MGO price differentials were also 50/50% meaning that each sub scenario has a 25% chance of materialising. These probabilities can be easily changed to match with the users predictions.

The visual element an asset tree contributes is the facilitation, the organisation, and creation of a cash flow (in our case savings) that changes over the course of the vessels 25 year lifespan.

By taking the hypothesis of MV Fengning's FC, days at sea/year, the assumptions regarding the two given fuel uptake scenarios, and the sub-scenarios regarding potential maximum and minimum LNG-MGO price differentials as per the asset tree, tables 8-11 below were created. These tables show the results of the calculations for the annual savings, savings per period, and total savings that a dual fuel propulsion system provides under each scenario, and sub scenario by being able to burn LNG instead of MGO when possible.

Table 8: MV Fengning Scenario 1: Quick LNG Bunkering Uptake. Sub Scenario 1: Maximum LNG-MGO Differential. Source: Author

MV Fengning. Scenario 1: Quick LNG Bunkering Uptake. Sub Scenario 1: Maximum LNG-MGO Differential			
Best case: Maximum Differential			
LNG uptake	2020-2025 30% LNG	2025-2035 50% LNG	2035-2045 100% LNG
Differential $/ton	$ 800.00	$ 800.00	$ 800.00
Annual FC/tons	4,268.69	4,268.69	4,268.69
30%, 50%, 100% FC LNG/tons	1,280.61	2,134.35	4,268.69
70%, 50%, 0% FC MGO/tons	2,988.08	2,134.35	-
$ Saved per Year	$ 1,024,485.98	$ 1,707,476.64	$ 3,414,953.27
$ Saved Per Period	$ 5,122,429.91	$ 17,074,766.36	$ 34,149,532.71
$ Saved in Total	$ 56,346,728.97		

Table 9: MV Fengning Scenario 1: Quick LNG Bunkering Uptake. Sub Scenario 2: Minimum LNG-MGO Differential. Source: Author

MV Fengning. Scenario 1: Quick LNG Bunkering Uptake. Sub Scenario 2: Minimum LNG-MGO Differential			
Worst Case: Minimum Differential			
LNG uptake	2020-2025 30% LNG	2025-2035 50% LNG	2035-2045 100% LNG
Differential $/ton	$ 100.00	$ 100.00	$ 100.00
Annual FC/tons	4,268.69	4,268.69	4,268.69
30%, 50%, 100% FC LNG/tons	1,280.61	2,134.35	4,268.69
70%, 50%, 0% FC MGO/tons	2,988.08	2,134.35	-
$ Saved per Year	$ 128,060.75	$ 213,434.58	$ 426,869.16
$ Saved Per Period	$ 640,303.74	$ 2,134,345.79	$ 4,268,691.59
$ Saved in Total	$ 7,043,341.12		

Table 10: MV Fengning Scenario 2: Slow LNG Bunkering Uptake. Sub Scenario 1: Maximum LNG-MGO Differential. Source: Author

MV Fengning. Scenario 2: Slow LNG Bunkering Uptake. Sub Scenario 1: Maximum LNG-MGO Differential			
Best case: Maximum Differential			
LNG uptake	2020-2025 10% LNG	2025-2035 30% LNG	2035-2045 60% LNG
Differential $/ton	$ 800.00	$ 800.00	$ 800.00
Annual FC/tons	4,268.69	4,268.69	4,268.69
10%, 30%, 60% FC LNG/tons	426.87	1,280.61	2,561.21
90%, 70%, 40% FC MGO/tons	3,841.82	2,988.08	1,707.48
$ Saved per Year	$ 341,495.33	$ 1,024,485.98	$ 2,048,971.96
$ Saved Per Period	$ 1,707,476.64	$ 10,244,859.81	$ 20,489,719.63
$ Saved in Total	$ 32,442,056.07		

Table 11: MV Fengning Scenario 2: Slow LNG Bunkering Uptake. Sub Scenario 2: Minimum LNG-MGO Differential. Source: Author

MV Fengning. Scenario 2: Slow LNG Bunkering Uptake. Sub Scenario 2: Minimum LNG-MGO Differential			
Worst Case: Minimum Differential			
LNG uptake	2020-2025 10% LNG	2025-2035 30% LNG	2035-2045 60% LNG
Differential $/ton	$ 100.00	$ 100.00	$ 100.00
Annual FC/tons	4,268.69	4,268.69	4,268.69
10%, 30%, 60% FC LNG/tons	426.87	1,280.61	2,561.21
90%, 70%, 40% FC MGO/tons	3,841.82	2,988.08	1,707.48
$ Saved per Year	$ 42,686.92	$ 128,060.75	$ 256,121.50
$ Saved Per Period	$ 213,434.58	$ 1,280,607.48	$ 2,561,214.95
$ Saved in Total	$ 4,055,257.01		

Tables 8-11 show how the price differentials between LNG and MGO play a much larger role than how quickly LNG bunkering is adopted.

The annual savings per time period (2020-2025, 2025-2035, 2035-2045) depending on the scenarios and sub-scenarios listed in tables 8-11, allow for the calculations of the maximum and minimum Present Values (PV) of the cash flows provided by the savings over the 25 year lifespan of MV Fengning. These can be seen in table 12 below.

Table 12: PV of Cash flows for Dual Fuel MV Fengning. Source: Author

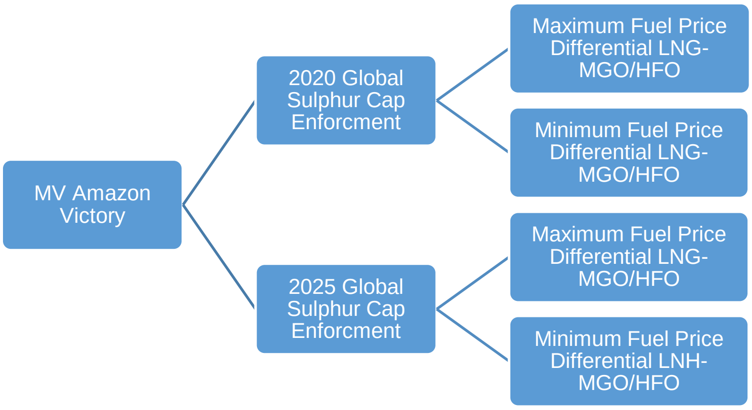
	PV of Future Cash Flows for Dual Fuelled MV Fengning			
Year	**Scenario 1: Sub Scenario 1**	**Scenario 1: Sub Scenario 2**	**Scenario 2: Sub Scenario 1**	**Scenario 2: Sub Scenario 2**
2020	$ 1,024,485.98	$ 128,060.75	$ 341,495.33	$ 42,686.92
2021	$ 1,024,485.98	$ 128,060.75	$ 341,495.33	$ 42,686.92
2022	$ 1,024,485.98	$ 128,060.75	$ 341,495.33	$ 42,686.92
2023	$ 1,024,485.98	$ 128,060.75	$ 341,495.33	$ 42,686.92
2024	$ 1,024,485.98	$ 128,060.75	$ 341,495.33	$ 42,686.92
2025	$ 1,707,476.64	$ 213,434.58	$ 1,024,485.98	$ 128,060.75
2026	$ 1,707,476.64	$ 213,434.58	$ 1,024,485.98	$ 128,060.75
2027	$ 1,707,476.64	$ 213,434.58	$ 1,024,485.98	$ 128,060.75
2028	$ 1,707,476.64	$ 213,434.58	$ 1,024,485.98	$ 128,060.75
2029	$ 1,707,476.64	$ 213,434.58	$ 1,024,485.98	$ 128,060.75
2030	$ 1,707,476.64	$ 213,434.58	$ 1,024,485.98	$ 128,060.75
2031	$ 1,707,476.64	$ 213,434.58	$ 1,024,485.98	$ 128,060.75
2032	$ 1,707,476.64	$ 213,434.58	$ 1,024,485.98	$ 128,060.75
2033	$ 1,707,476.64	$ 213,434.58	$ 1,024,485.98	$ 128,060.75
2034	$ 1,707,476.64	$ 213,434.58	$ 1,024,485.98	$ 128,060.75
2035	$ 3,414,953.27	$ 426,869.16	$ 2,048,971.96	$ 256,121.50
2036	$ 3,414,953.27	$ 426,869.16	$ 2,048,971.96	$ 256,121.50
2037	$ 3,414,953.27	$ 426,869.16	$ 2,048,971.96	$ 256,121.50
2038	$ 3,414,953.27	$ 426,869.16	$ 2,048,971.96	$ 256,121.50
2039	$ 3,414,953.27	$ 426,869.16	$ 2,048,971.96	$ 256,121.50
2040	$ 3,414,953.27	$ 426,869.16	$ 2,048,971.96	$ 256,121.50
2041	$ 3,414,953.27	$ 426,869.16	$ 2,048,971.96	$ 256,121.50
2042	$ 3,414,953.27	$ 426,869.16	$ 2,048,971.96	$ 256,121.50
2043	$ 3,414,953.27	$ 426,869.16	$ 2,048,971.96	$ 256,121.50
2044	$ 3,414,953.27	$ 426,869.16	$ 2,048,971.96	$ 256,121.50
P.V	**$ 21,444,495.10**	**$ 2,680,561.89**	**$ 11,746,538.45**	**$ 1,468,317.31**

The maximum and minimum PV’s of the cash flows are necessary in the ROA valuation used to quantify the value of flexibility that the option to switch provides the fuel version of MV Fengning.

Hypothesis 2: MV Amazon Victory

As in Hypothesis 1 a binomial asset tree was made in order to depict the scenarios, and the sub-scenarios for MV Amazon Victory. Instead of considering the uptake of LNG bunkering the scenarios for MV Amazon Victory are made to take into account whether the global sulphur regulations will be enforced in 2020 or in 2025 (scenarios 1 and 2). The sub-scenarios considering the maximum and minimum fuel price differentials remain the same as in hypothesis 1.See figure 8 below.

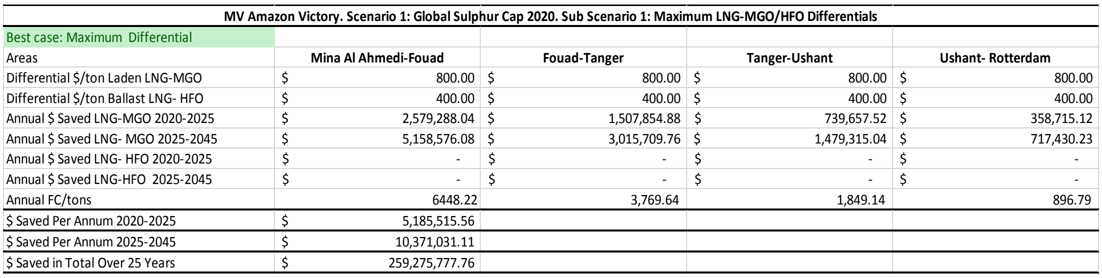
Figure 8: Binomial Asset Tree for MV Amazon Victory. Source: Author



For this research paper it was assumed that the probability of the enforcement of the global sulphur cap to come in 2020/2025 to be 40/60% and that the probability of maximum/minimum LNG/MGO price differentials were also 50/50% meaning that the sub-scenarios for 2020 enforcement each have a 20% chance of materialising, while each of the sub-scenarios for 2025 enforcement have a 30% chance of materialising. The probabilities in the model can be easily changed to match the user’s predictions. This example is used in this way to demonstrate the potential of the multi-step binomial pricing model to be used in a cumulative manner.

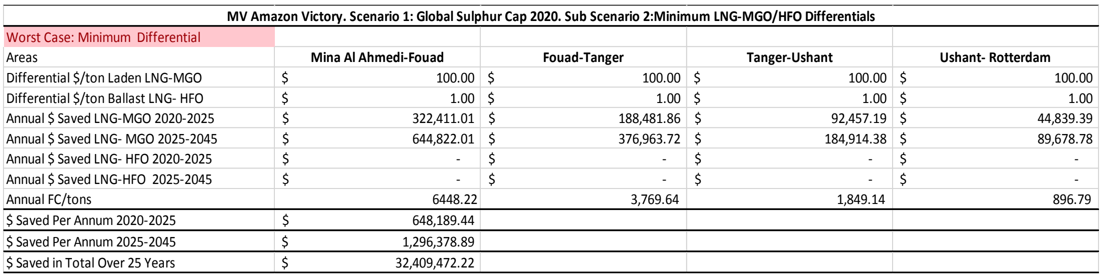
By taking the Hypothesis of MV Amazon Victory’s FC averaged for both laden and ballast voyages, the days at sea spent in each of the four areas along her journey, the scenarios of the pending decision regarding the enforcement of the global sulphur cap, and the sub-scenarios regarding potential maximum and minimum LNG-MGO/HFO price differentials as per the asset tree, tables 13-16 below were created. These tables show the results of the calculations for the annual savings, savings per period, and total savings a dual fuel propulsion system provides under each scenario, and sub scenario.

Table 13: MV Amazon Victory Scenario 1: Global Sulphur Cap 2020. Sub Scenario 1: Maximum LNG-MGO/HFO Differential. Source: Author



MV Amazon Victory. Scenario 1: Global Sulphur Cap 2020. Sub Scenario 1: Maximum LNG-MGO/HFO Differentials				
Best case: Maximum Differential				
Areas	Mina Al Ahmedi-Fouad	Fouad-Tanger	Tanger-Ushant	Ushant- Rotterdam
Differential $/ton Laden LNG-MGO	$ 800.00	$ 800.00	$ 800.00	$ 800.00
Differential $/ton Ballast LNG- HFO	$ 400.00	$ 400.00	$ 400.00	$ 400.00
Annual $ Saved LNG-MGO 2020-2025	$ 2,579,288.04	$ 1,507,854.88	$ 739,657.52	$ 358,715.12
Annual $ Saved LNG- MGO 2025-2045	$ 5,158,576.08	$ 3,015,709.76	$ 1,479,315.04	$ 717,430.23
Annual $ Saved LNG- HFO 2020-2025	$ -	$ -	$ -	$ -
Annual $ Saved LNG-HFO 2025-2045	$ -	$ -	$ -	$ -
Annual FC/tons	6448.22	3,769.64	1,849.14	896.79
$ Saved Per Annum 2020-2025	$ 5,185,515.56			
$ Saved Per Annum 2025-2045	$ 10,371,031.11			
$ Saved in Total Over 25 Years	$ 259,275,777.76			

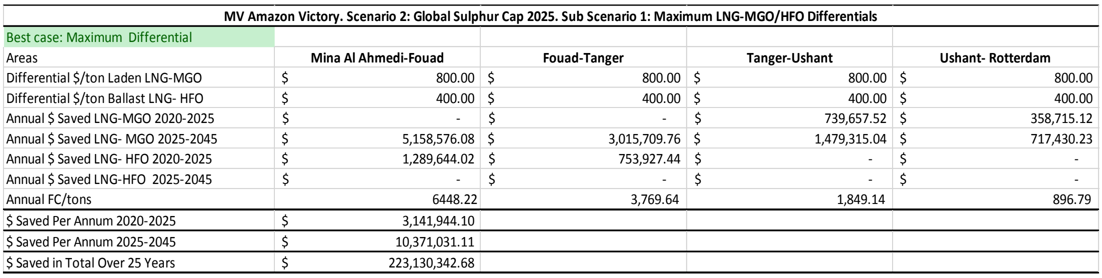
Table 14: MV Amazon Victory Scenario 1: Global Sulphur Cap 2020. Sub Scenario 2: Minimum LNG-MGO/HFO Differential. Source: Author



MV Amazon Victory. Scenario 1: Global Sulphur Cap 2020. Sub Scenario 2:Minimum LNG-MGO/HFO Differentials				
Worst Case: Minimum Differential				
Areas	Mina Al Ahmedi-Fouad	Fouad-Tanger	Tanger-Ushant	Ushant- Rotterdam
Differential $/ton Laden LNG-MGO	$ 100.00	$ 100.00	$ 100.00	$ 100.00
Differential $/ton Ballast LNG- HFO	$ 1.00	$ 1.00	$ 1.00	$ 1.00
Annual $ Saved LNG-MGO 2020-2025	$ 322,411.01	$ 188,481.86	$ 92,457.19	$ 44,839.39
Annual $ Saved LNG- MGO 2025-2045	$ 644,822.01	$ 376,963.72	$ 184,914.38	$ 89,678.78
Annual $ Saved LNG- HFO 2020-2025	$ -	$ -	$ -	$ -
Annual $ Saved LNG-HFO 2025-2045	$ -	$ -	$ -	$ -
Annual FC/tons	6448.22	3,769.64	1,849.14	896.79
$ Saved Per Annum 2020-2025	$ 648,189.44			
$ Saved Per Annum 2025-2045	$ 1,296,378.89			
$ Saved in Total Over 25 Years	$ 32,409,472.22			

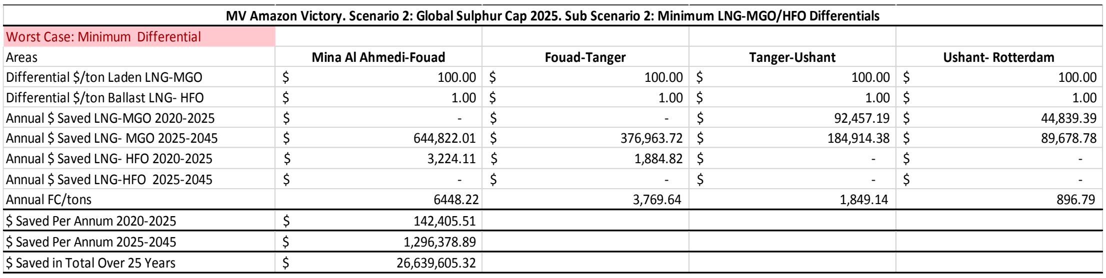
One can see in table 13 and 14 that if the global sulphur cap were to be enforced in 2020, there would be no need to factor in the price differential between LNG and HFO as a vessel would not be able to burn HFO in any of the four areas that need to be crossed in order to make the voyage to/from the Persian Gulf/Rotterdam without the use of scrubbers (Scrubbers are not in the scope of this research). It is also evident by looking at the table that the savings that the LNG propulsion system would provide are reduced by 50% between 2020 and 2025 compared to post 2025 because it is assumed that LNG bunkering will not be available in the Persian Gulf until 2025.

Table 15: MV Amazon Victory Scenario 2: Global Sulphur Cap 2025. Sub Scenario 2: Maximum LNG-MGO/HFO Differential. Source: Author



MV Amazon Victory. Scenario 2: Global Sulphur Cap 2025. Sub Scenario 1: Maximum LNG-MGO/HFO Differentials				
Best case: Maximum Differential				
Areas	Mina Al Ahmedi-Fouad	Fouad-Tanger	Tanger-Ushant	Ushant- Rotterdam
Differential $/ton Laden LNG-MGO	$ 800.00	$ 800.00	$ 800.00	$ 800.00
Differential $/ton Ballast LNG- HFO	$ 400.00	$ 400.00	$ 400.00	$ 400.00
Annual $ Saved LNG-MGO 2020-2025	$ -	$ -	$ 739,657.52	$ 358,715.12
Annual $ Saved LNG- MGO 2025-2045	$ 5,158,576.08	$ 3,015,709.76	$ 1,479,315.04	$ 717,430.23
Annual $ Saved LNG- HFO 2020-2025	$ 1,289,644.02	$ 753,927.44	$ -	$ -
Annual $ Saved LNG-HFO 2025-2045	$ -	$ -	$ -	$ -
Annual FC/tons	6448.22	3,769.64	1,849.14	896.79
$ Saved Per Annum 2020-2025	$ 3,141,944.10			
$ Saved Per Annum 2025-2045	$ 10,371,031.11			
$ Saved in Total Over 25 Years	$ 223,130,342.68			

Table 16: MV Amazon Victory Scenario 2: Global Sulphur Cap 2025. Sub Scenario 2: Minimum LNG-MGO/HFO Differential. Source: Author

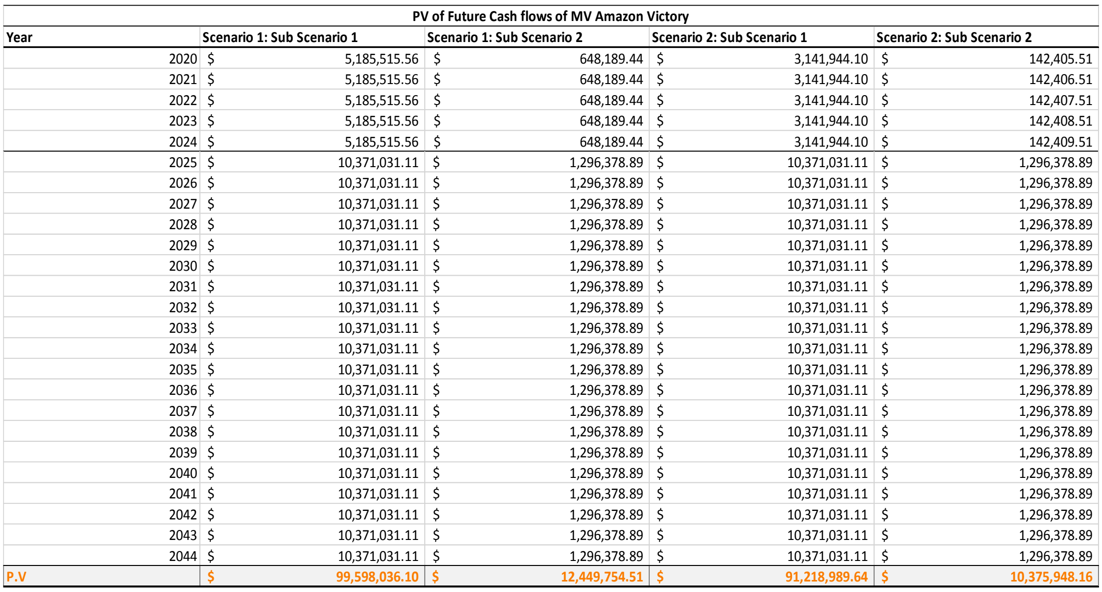


MV Amazon Victory. Scenario 2: Global Sulphur Cap 2025. Sub Scenario 2: Minimum LNG-MGO/HFO Differentials				
Worst Case: Minimum Differential				
Areas	**Mina Al Ahmedi-Fouad**	**Fouad-Tanger**	**Tanger-Ushant**	**Ushant- Rotterdam**
Differential $/ton Laden LNG-MGO	$ 100.00	$ 100.00	$ 100.00	$ 100.00
Differential $/ton Ballast LNG- HFO	$ 1.00	$ 1.00	$ 1.00	$ 1.00
Annual $ Saved LNG-MGO 2020-2025	$ -	$ -	$ 92,457.19	$ 44,839.39
Annual $ Saved LNG- MGO 2025-2045	$ 644,822.01	$ 376,963.72	$ 184,914.38	$ 89,678.78
Annual $ Saved LNG- HFO 2020-2025	$ 3,224.11	$ 1,884.82	$ -	$ -
Annual $ Saved LNG-HFO 2025-2045	$ -	$ -	$ -	$ -
Annual FC/tons	6448.22	3,769.64	1,849.14	896.79
$ Saved Per Annum 2020-2025	$ 142,405.51			
$ Saved Per Annum 2025-2045	$ 1,296,378.89			
$ Saved in Total Over 25 Years	$ 26,639,605.32			

Tables 15 and 16 demonstrate that if the global sulphur cap were to be enforced in 2025, the MV Amazon Victory's operator would be making a choice to burn LNG over HFO in the areas between Mina Al Ahmedi-Fouad-Tanger, on the ballast voyage before the global sulphur cap in 2025 (providing that the price differentials are favourable). After 2025, the choice will only be between LNG and MGO because the vessel will not be allowed to burn HFO on any legs of the voyage. The choice between LNG and MGO remains permanent on the legs between Tanger-Ushant as a sulphur cap will be in place as of 2020 in the EU economic zones, and is already in existence between Ushant to Rotterdam.

The annual savings per annum over the relevant parts of the voyages to and from Mina Al Ahmedi to Rotterdam, given the potential enforcement dates of the global sulphur cap, and the sub-scenarios of the maximum and minimum fuel price differentials in tables 13-16 allow for the calculations of the maximum and minimum PV's of the cash flows that can be provided by investing in a dual fuel propulsion system for the MV Amazon Victory over her 25 year lifespan. These can be seen in table 17 below.

Table 17: PV and Cash flows for Dual Fuel MV Amazon Victory 2020-2045. Source: Author

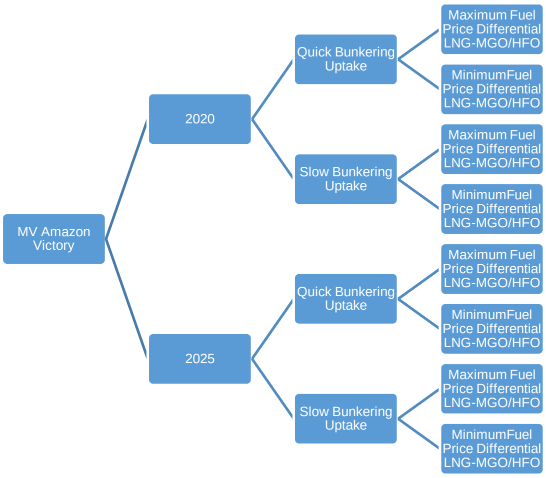


PV of Future Cash flows of MV Amazon Victory				
Year	**Scenario 1: Sub Scenario 1**	**Scenario 1: Sub Scenario 2**	**Scenario 2: Sub Scenario 1**	**Scenario 2: Sub Scenario 2**
2020	$ 5,185,515.56	$ 648,189.44	$ 3,141,944.10	$ 142,405.51
2021	$ 5,185,515.56	$ 648,189.44	$ 3,141,944.10	$ 142,406.51
2022	$ 5,185,515.56	$ 648,189.44	$ 3,141,944.10	$ 142,407.51
2023	$ 5,185,515.56	$ 648,189.44	$ 3,141,944.10	$ 142,408.51
2024	$ 5,185,515.56	$ 648,189.44	$ 3,141,944.10	$ 142,409.51
2025	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2026	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2027	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2028	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2029	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2030	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2031	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2032	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2033	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2034	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2035	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2036	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2037	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2038	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2039	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2040	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2041	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2042	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2043	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2044	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
P.V	**$ 99,598,036.10**	**$ 12,449,754.51**	**$ 91,218,989.64**	**$ 10,375,948.16**

The maximum and minimum PV's of the cash flows created by the option to switch to LNG by the operator of the MV Amazon Victory are necessary in order for the ROA valuation that is used to quantify the value of flexibility that the option to switch provides.

Consideration was given to creating a more complicated multi-step binomial asset tree for the second hypothesis in order to include the probability of LNG bunkering uptake in the Persian Gulf as depicted in figure 8 below. It was decided that the simple models constructed in this research paper provide greater clarity due to the fact that once one has understood the idea behind the model, it would be easy to add a greater dimension to it by including more uncertainties. See figure 9.

Figure 9: More Complicated Binomial Asset Tree for MV Amazon Victory. Source: Author



During the modelling process of the ROA many different probabilities were calculated, and different differentials were also easily changed. This means that the model can be easily modified in excel, and that it can be used interchangeably to calculate outcomes for specific cases.

The following sections of this research paper will use the hypotheses, scenarios, and sub-scenarios above to calculate the value of flexibility provided by dual fuel propulsion systems by using both single step and two-step binomial pricing models adapted from the binomial pricing model as presented by Brach (2003).

3.6 Conducting Real Options Analysis: The Option to Switch

Now that the PV of the future cash flows of all of the scenarios for both of the vessels have been estimated, the PV's of the cash flows can be applied to the single step and two-step binomial pricing models derived from the binomial pricing model as per Brach (2003) in order for the value of the option to switch that a dual fuel propulsion system provides for both vessels to become apparent.

The first step is to calculate the expected value (V) of the option. This is done by consulting the binomial asset tree, and based on the assumptions regarding the probability of each scenario, and then subsequent scenario materialising, a percentage is allocated to this probability (q). If calculated in a single step binomial pricing model the scenarios of maximum and minimum PV occurring would be represented as ($maxPV, minPV$), and the formula for V would be the following.

$$V = (q * maxPV + (1 - q) * minPV) \tag{9}$$

Since a two-step binomial pricing model has been introduced, when applicable the formula 9 for V is adapted as can be seen below in formula 10. The sum of all q's are still equal to 1. This allows for more than two scenarios to be simultaneously incorporated, which results in a more precise estimation of the expected value to be made depending on expectations of future outcomes.

$$V = (q * Ss1.1 + q * Ss1.2 + q * Ss2.1 + q * Ss2.2) \tag{10}$$

$Ss = sub\ scenario$

Once the expected value V is calculated, the second step is to calculate the Risk Neutral Probability (P). The risk neutral probability is dependent on the maximum and minimum PV's, and on the probabilities of certain cash flows materialising calculated in equation 10. This is done by including V into the equation. (P) is calculated by using formula 11 below where (rf) represents the risk free rate, usually associated with the interest rate for treasury bonds commonly valued at 7% .

$$P = \frac{(rf * V) - minPV}{maxPV - minPV} \tag{11}$$

The third step is to use the results from formula 11 in equation 12 below in order to calculate the value of the Call Option (C), which will enable the critical cost of investment (K) to be quantified. In equation 12 (rc^t) corresponds to the opportunity cost of money, and for business investments such as these the corporate cost of capital of 13.5% is commonly used.

$$C = \frac{P * maxPV + (1 - P) * minPV}{(1 + rf)^t} - K * rc^t \tag{12}$$

The final step is to set equation 12 equal to zero and then calculate the critical cost of investment (K). It is assumed in this research paper that (K), (the premium on a dual fuel propulsion system) will be paid six months before the vessel is in service, and that the dual fuel propulsion system will begin to create cash flows for the shipping company. A six month period has been assumed because it is likely that it will take a minimum of six months by the time the engine is installed and the vessel makes its first voyage. Therefore ($rc^{0.5}$) must be considered in order to quantify the value of the investment towards a dual fuel propulsion system that will be paid for six months prior to the date that it will begin to create cash flows for a shipping company.

This is done in excel by using the following calculation: $C/rc^{0.5}$ which is equal to the maximum amount that a shipping company should invest six months prior to a dual fuel propulsion system starting operations. This is based on the vessel type, its operational parameters, and the companies predictions regarding the probability of potential future cash flows to materialise based on assumptions made about uncertainties. In other words $C/rc^{0.5} = K$ is equal to the value of the option to switch six months before the investment begins making cash flows.

Chapter 4: Findings

The combinations of scenarios, and sub-scenarios, result in four potential cash flows for each vessel. As previously stated, the maximum and minimum PV's of these cash flows will be used in order to conduct the ROA valuation on the option to switch that a dual fuel propulsion system provides for both MV Fengning, and MV Amazon Victory. This will be done by calculating the critical cost of investment (K) which is the maximum investment that should be made in order to keep the option of investing in a dual fuel propulsion system *in the money*.

4.1 MV Fengning

The hypothesis made for MV Fengning incorporates two main scenarios, the quick uptake of LNG bunkering facilities in the EU economic zone within the Mediterranean, and the slow uptake of LNG bunkering facilities in the EU economic zone within the Mediterranean. The sub-scenarios relate to the maximum and minimum fuel price differentials. The valuation of the dual fuel propulsion system for each of the scenarios will first be conducted separately by using a single step binomial pricing model. This will provide a measure for comparison of the results provided by the two-step binomial pricing model that has been proposed.

4.1.1 Scenario 1. Quick Bunkering Uptake

A single step binomial pricing model has been used to conduct an ROA valuation of the quick bunkering uptake scenario, and a sensitivity analysis has been included in order to present a variety of potential outcomes that depend on the fuel price differentials. See table 18 below.

Table 18: MV Fengning Quick Bunkering Uptake. Source: Author

MV Fengning. Scenario1. Quick LNG Bunkering Uptake									
Probability of Maximum Fuel Price Differential	90%	80%	70%	60%	50%	40%	30%	20%	10%
Expected Value (V) =	$ 19,568,102	$ 17,691,708	$ 15,815,315	$ 13,938,922	$ 12,062,528	$ 10,186,135	$ 8,309,742	$ 6,433,349	$ 4,556,955
Risk Neutral Probability (P)=	97%	87%	76%	65%	55%	44%	33%	22%	12%
Call Option Value (C) =	$ 3,857,785	$ 3,487,861	$ 3,117,936	$ 2,748,011	$ 2,378,087	$ 2,008,162	$ 1,638,238	$ 1,268,313	$ 898,388
Critical Cost to Invest (K) =	$ 3,621,097	$ 3,273,868	$ 2,926,640	$ 2,579,411	$ 2,232,183	$ 1,884,954	$ 1,537,726	$ 1,190,497	$ 843,269

Table 18 above presents the critical cost to invest in a dual fuel propulsion system when scenario 1, the quick uptake of LNG bunkering facilities will materialise. The probability of maximum or minimum fuel price differentials materialising has been presented in 10% increments. Therefore if the shipping company that is investing, and will operate MV Fengning expects a high fuel uptake scenario, it could simply refer to table 18. The call option value is the maximum the company should invest in 2020 for a dual fuel propulsion system to begin operation in 2020, while (K) represents the maximum the company should invest in 6/2019 for a dual fuel propulsion system begin to operate in 2020.

4.1.2 Scenario 2

On the other hand if the shipping company that is investing in a dual fuel propulsion system for MV Fengning expects a slow uptake of LNG bunkering facilities as described by scenario 2, table 19 below should be consulted.

Table 19: MV Fengning. Slow Bunkering Uptake. Source: Author

MV Fengning. Scenario 2. Slow LNG Bunkering Uptake									
Probability of Maximum Fuel Price Differential	90%	80%	70%	60%	50%	40%	30%	20%	10%
Expected Value (V) =	$ 10,718,716	$ 9,690,894	$ 8,663,072	$ 7,635,250	$ 6,607,428	$ 5,579,606	$ 4,551,784	$ 3,523,962	$ 2,496,139
Risk Neutral Probability (P)=	97%	87%	76%	65%	55%	44%	33%	22%	12%
Call Option Value (C) =	$ 2,113,159	$ 1,910,527	$ 1,707,895	$ 1,505,264	$ 1,302,632	$ 1,100,000	$ 897,369	$ 694,737	$ 492,105
Critical Cost to Invest (K) =	$ 1,983,509	$ 1,793,310	$ 1,603,110	$ 1,412,911	$ 1,222,711	$ 1,032,512	$ 842,312	$ 652,113	$ 461,913

Table 19 above presents the critical cost to invest in a dual fuel propulsion system for MV Fengning when scenario 2, slow uptake of LNG bunkering facilities, will materialise. Just as in table 18, the probability of maximum or minimum fuel price differentials materialising has been presented in 10% increments, and the call option value (C) is the maximum the company should invest in 2020 for a dual fuel propulsion system to begin operation in 2020, while (K) represents the maximum the company should invest in 6/2019 for a dual fuel propulsion system begin to operate in 2020.

The critical cost (K) to invest in a dual fuel propulsion system varies by approximately 45% between a quick uptake, and a slow uptake in LNG bunkering facilities. There is a 77% difference between the critical costs to invest depending on the probability of maximum or minimum fuel price differentials materialising in both scenarios. It is more than likely however, that a shipping company will consider LNG bunkering uptake as an uncertainty that has to be taken into account while simultaneously accounting for fuel price differentials.

4.1.3 Comparison of Single Step Binomial and Two-Step Binomial Pricing Models

In order to take the uncertainties of LNG bunkering uptake and fuel price differentials into account simultaneously, the proposed two-step binomial pricing model is used, and the results can be seen in table 20 below. A 50/50 probability for LNG fuel bunkering uptake (scenario1 and 2) is assumed, and fuel price differentials are presented in 10% increments as in tables 18 and 19 above.

Table 20: Two-Step Binomial pricing model for MV Fengning. Source: Author

MV Fengning. Scenario 1 and 2 in a Two-Step Binomial Pricing Model									
Probability of Maximum Fuel Price Differential	90%	80%	70%	60%	50%	40%	30%	20%	10%
Expected Value (V) =	$ 15,143,409	$ 13,691,301	$ 12,239,194	$ 10,787,086	$ 9,334,978	$ 7,882,870	$ 6,430,763	$ 4,978,655	$ 3,526,547
Risk Neutral Probability (P)=	74%	66%	58%	50%	43%	35%	27%	19%	12%
Call Option Value (C) =	$ 2,985,472	$ 2,699,194	$ 2,412,916	$ 2,126,638	$ 1,840,359	$ 1,554,081	$ 1,267,803	$ 981,525	$ 695,247
Critical Cost to Invest (K) =	$ 2,802,303	$ 2,533,589	$ 2,264,875	$ 1,996,161	$ 1,727,447	$ 1,458,733	$ 1,190,019	$ 921,305	$ 652,591

This two-step binomial pricing approach allows for a more efficient method to quantify the value of an investment towards a dual fuel propulsion system for MV Fengning. This is because uncertainty of both LNG bunkering uptake, and fuel price differentials are taken into consideration simultaneously. The results demonstrate that there is a reduction of the risk neutral probability, because there is greater possibility of a lower outcome.

Depending on the predictions of fuel price differentials a company makes, table 20 presents the value of flexibility that a dual fuel propulsion system would provide MV Fengning. Assuming that price differentials between LNG and MGO average approximately 50% over the lifespan of MV Fengning, and the probability of a 50/50 quick/slow LNG bunkering availability will materialise in the EU economic zone within the Mediterranean, the value of flexibility provided by an investment towards a dual fuel propulsion system for MV Fengning in 2020 is **$2,126,637** for operations to begin in 2020, and for an investment made in 6/2019 **$1,727,446** for operations to begin in 2020. The difference is due to the opportunity cost of money for the six months the investment is not providing cash flows (savings). This means that in order for the investment to stay *in the money*, these are the maximum amounts that should be invested. Any investment above these amounts will lead to the value of the option becoming less than zero, and the option to invest in a dual fuel propulsion system should not be exercised.

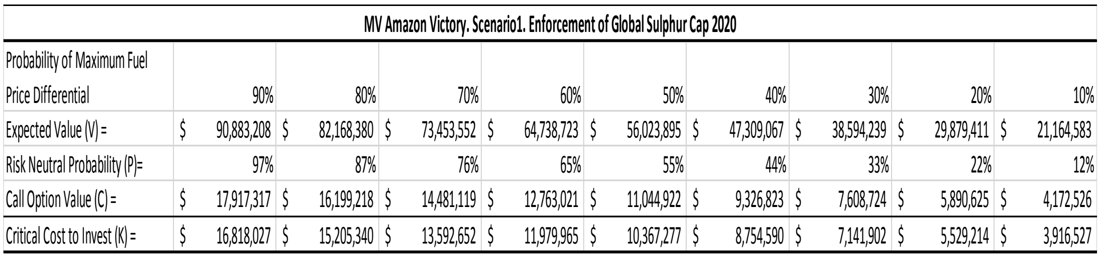
4.2 MV Amazon Victory

The hypothesis made for the MV Amazon Victory incorporates the two main scenarios, the enforcement of the global sulphur cap in 2020, and the enforcement of the global sulphur cap in 2025. Just as in the case of the MV Fengning, the sub-scenarios relate to the maximum and minimum fuel price differentials. A single step binomial pricing model is used for valuation of the dual fuel propulsion system for each of the scenarios. This is important for the hypothesis of MV Amazon Victory because the investment towards a dual fuel propulsion system will be made in 2019. By 2019 the results of the distillate fuel availability study will have been released, and there will be no need to make assumptions regarding the enforcement date of the global sulphur cap. This means that a two-step binomial pricing model is not necessary for a valuation of an investment towards a dual fuel propulsion system for MV Amazon Victory in the context of the proposed main scenarios. However, the two-step binomial pricing model will be included in section 4.2.3 in order to demonstrate how the model can be used by shipping companies that are considering investments into dual fuel propulsion systems for similar vessels whose construction will be completed prior to the release of the announcement of the enforcement date of the global sulphur cap.

4.2.1 Scenario 1

A single step binomial pricing model has been used to conduct an ROA valuation of the scenario which assumes that the global sulphur cap will be enforced in 2020. A sensitivity analysis has been included in order to present a variety of potential outcomes that depend on the fuel price differentials. See table 21 below.

Table 21: MV Amazon Victory. Enforcement of Global Sulphur Cap: 2020. Source: Author



MV Amazon Victory. Scenario1. Enforcement of Global Sulphur Cap 2020									
Probability of Maximum Fuel Price Differential	90%	80%	70%	60%	50%	40%	30%	20%	10%
Expected Value (V) =	$ 90,883,208	$ 82,168,380	$ 73,453,552	$ 64,738,723	$ 56,023,895	$ 47,309,067	$ 38,594,239	$ 29,879,411	$ 21,164,583
Risk Neutral Probability (P)=	97%	87%	76%	65%	55%	44%	33%	22%	12%
Call Option Value (C) =	$ 17,917,317	$ 16,199,218	$ 14,481,119	$ 12,763,021	$ 11,044,922	$ 9,326,823	$ 7,608,724	$ 5,890,625	$ 4,172,526
Critical Cost to Invest (K) =	$ 16,818,027	$ 15,205,340	$ 13,592,652	$ 11,979,965	$ 10,367,277	$ 8,754,590	$ 7,141,902	$ 5,529,214	$ 3,916,527

Table 21 above presents the critical cost to invest in a dual fuel propulsion system when scenario 1, the enforcement of the global sulphur regulations in 2020, will materialise. The probability of maximum or minimum fuel price differentials materialising has been presented in 10% increments. Therefore, once the decision is announced in 2018 regarding the enforcement of the global sulphur cap, and this decision is that the global sulphur cap will be enforced in 2020, the shipping company that is investing, and will operate MV Amazon Victory can refer to table 21. The call option value is the maximum the company should invest in 2020 for a dual fuel propulsion system to begin operation in 2020, while (K) represents the maximum the company should invest in 6/2019 for a dual fuel propulsion system begin to operate in 2020. If an average 50% fuel price differential was expected to materialise over the lifespan of the vessel, and the global sulphur cap is enforced in 2020, the shipping company investing in MV Amazon Victory should not invest over **$11,044,921** in 2020 for operations to begin in 2020, and in 6/2019 **$10,367,277** for operations to begin in 2020 in order for the option to stay *in the money*.

4.2.2 Scenario 2

Once the decision regarding the enforcement date of the global sulphur cap is announced, and this decision would be that the global sulphur cap will be enforced in 2025 the shipping company that is investing in a dual fuel propulsion system for MV Amazon Victory should consult table 22 below.

Table 22: MV Amazon Victory. Enforcement of Global Sulphur Cap: 2025. Source: Author

MV Amazon Victory. Scenario2. Enforcement of Global Sulphur Cap 2025									
Probability of Maximum Fuel Price Differential	90%	80%	70%	60%	50%	40%	30%	20%	10%
Expected Value (V) =	$ 83,134,685.50	$ 75,050,381.35	$ 66,966,077.20	$ 58,881,773.05	$ 50,797,468.90	$ 42,713,164.75	$ 34,628,860.61	$ 26,544,556.46	$ 18,460,252.31
Risk Neutral Probability (P)=	97%	86%	76%	65%	54%	44%	33%	22%	12%
Call Option Value (C) =	$ 16,389,722	$ 14,795,929	$ 13,202,136	$ 11,608,343	$ 10,014,549	$ 8,420,756	$ 6,826,963	$ 5,233,170	$ 3,639,376
Critical Cost to Invest (K) =	$ 15,384,156	$ 13,888,147	$ 12,392,139	$ 10,896,130	$ 9,400,122	$ 7,904,113	$ 6,408,105	$ 4,912,096	$ 3,416,088

Table 22 above presents the critical cost to invest in a dual fuel propulsion system for MV Amazon Victory when scenario 2, the enforcement of the global sulphur cap in 2025 will materialise. Just as in table 21, the probability of maximum or minimum fuel price differentials materialising has been presented in 10% increments, and the call option value (C) is the maximum the company should invest in 2020 for a dual fuel propulsion system to begin operation in 2020, while (K) represents the maximum the company should invest in 6/2019 for a dual fuel propulsion system begin to operate in 2020. If an average 50% fuel price differential is expected to materialise over the lifespan of the vessel and the global sulphur cap is enforced in 2025, the shipping company investing in MV Amazon Victory should not invest over **$10,014,549** in 2020 for operations to begin in 2020, and in 6/2019 **$9,400,122** for operations to begin in 2020.

The critical cost to invest in a dual fuel propulsion system varies by approximately 9-13% between the two main scenarios for the MV Amazon Victory, while there is a 77% difference between the critical costs to invest depending on the probability of maximum or minimum fuel price differentials materialising in both scenarios. This result demonstrates that the enforcement date of the global sulphur cap plays a relatively small role in comparison to fuel price differentials where savings provided by a dual fuel propulsion system for the MV Amazon Victory are concerned.

As previously stated, the enforcement date of the global sulphur cap will be announced in time for a shipping company investing (in 2019) in the propulsion system of the MV Amazon Victory to know if the regulations will be enforced in 2020 or in 2025. However a shipping company investing in a propulsion system before the enforcement date is released will have to consider this as an uncertainty, and as such this should to be taken into account while simultaneously accounting for fuel price differentials.

4.2.3 Two-Step Binomial Pricing Model for MV Amazon Victory

In order to take the uncertainty regarding the enforcement date of the global sulphur cap, and fuel price differentials into account simultaneously, the proposed two-step binomial pricing model is used. However, in order to present a valid model, a reconfigured table of cash flows and NPVs must be incorporated. This is because the delivery date of the vessel is assumed to be the beginning of 2016, which means that

MV Amazon Victory will be operating for four years prior to the enforcement of the sulphur cap within the EU economic zone, and at least four years prior to the enforcement of the global sulphur cap. During the four years prior to the EU economic zone sulphur cap the MV Amazon Victory will be switching between LNG and HFO on all the ballast legs of the voyage except for the Ushant-Rotterdam ballast leg where it will be switching between LNG and MGO. The reconfigured cash flows and NPVs can be seen in table 23 below.

Table 23: PV and Cash flows for Dual Fuel MV Amazon Victory 2016-2040. Source: Author

PV of Future Cash flows for MV Amazon Victory 2016-2040				
Year	**Scenario 1: Sub Scenario 1**	**Scenario 1: Sub Scenario 2**	**Scenario 2: Sub Scenario 1**	**Scenario 2: Sub Scenario 2**
2016	$ 2,772,115.34	$ 50,872.89	$ 2,772,115.34	$ 50,872.89
2017	$ 2,772,115.34	$ 50,872.89	$ 2,772,115.34	$ 50,872.89
2018	$ 2,772,115.34	$ 50,872.89	$ 2,772,115.34	$ 50,872.89
2019	$ 2,772,115.34	$ 50,872.89	$ 2,772,115.34	$ 50,872.89
2020	$ 5,185,515.56	$ 648,189.44	$ 3,141,944.10	$ 142,405.51
2021	$ 5,185,515.56	$ 648,189.44	$ 3,141,944.10	$ 142,405.51
2022	$ 5,185,515.56	$ 648,189.44	$ 3,141,944.10	$ 142,405.51
2023	$ 5,185,515.56	$ 648,189.44	$ 3,141,944.10	$ 142,405.51
2024	$ 5,185,515.56	$ 648,189.44	$ 3,141,944.10	$ 142,405.51
2025	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2026	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2027	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2028	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2029	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2030	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2031	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2032	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2033	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2034	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2035	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2036	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2037	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2038	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2039	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
2040	$ 10,371,031.11	$ 1,296,378.89	$ 10,371,031.11	$ 1,296,378.89
P.V	**$ 78,900,139.12**	**$ 8,861,117.08**	**$ 72,507,804.70**	**$ 7,279,014.31**

Based on the cash flows and NPVs in table 23 above, a two-step binomial pricing model is applied. It is assumed that the probability of the enforcement of the global sulphur cap to come in 2020/2025 will be 40/60% (scenario1 and 2), and fuel price differentials are presented in 10% increments as in tables 21 and 22 above. The results can be seen in table 24 below.

Table 24: Two-Step Binomial pricing model for MV Amazon Victory. Source: Author

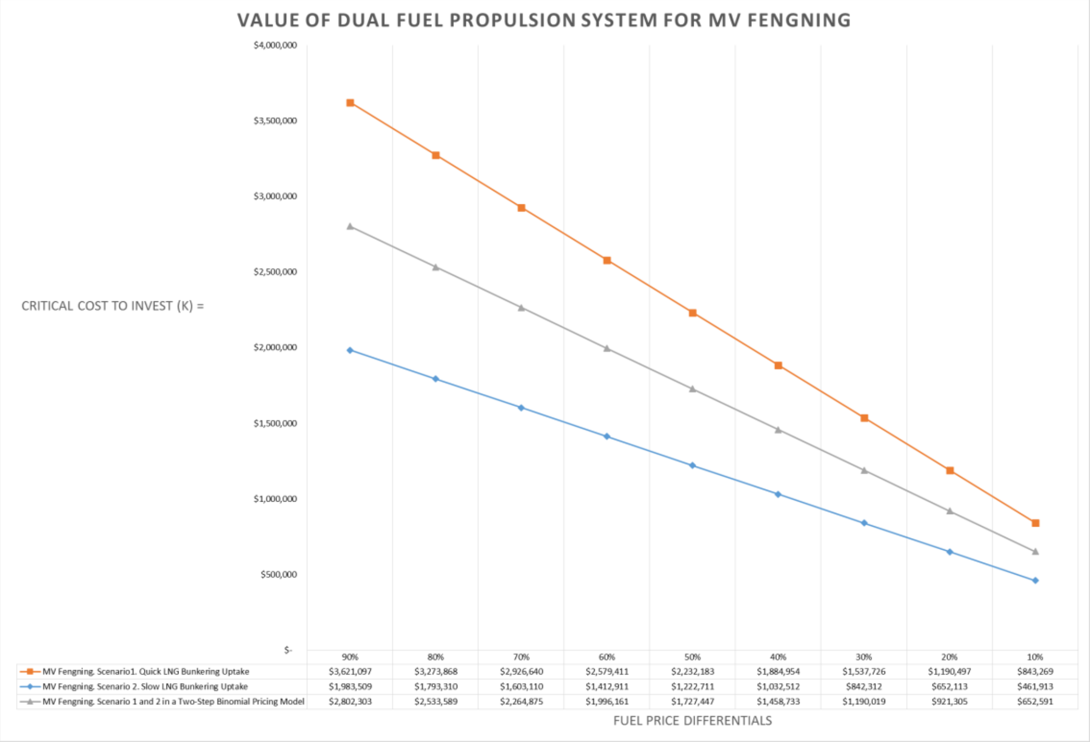
MV Amazon Victory. Scenario 1 and 2 in a Two Step Binomial Pricing Model 2016-2040									
Probability of Maximum Fuel Price Differential	90%	80%	70%	60%	50%	40%	30%	20%	10%
Expected Value (V) =	$ 68,541,859	$ 61,778,469	$ 55,015,078	$ 48,251,688	$ 41,488,297	$ 34,724,906	$ 27,961,516	$ 21,198,125	$ 14,434,734
Risk Neutral Probability (P)=	92%	82%	72%	62%	52%	42%	32%	22%	11%
Call Option Value (C) =	$ 13,512,796	$ 12,179,416	$ 10,846,037	$ 9,512,657	$ 8,179,278	$ 6,845,898	$ 5,512,518	$ 4,179,139	$ 2,845,759
Critical Cost to Invest (K) =	$ 12,683,739	$ 11,432,167	$ 10,180,594	$ 8,929,022	$ 7,677,450	$ 6,425,878	$ 5,174,306	$ 3,922,734	$ 2,671,162

The results in table 24 are indicative of the aforementioned assumptions. If the probability of the enforcement date of the global sulphur cap to come in 2020/2025 is 40/60%, and the assumption that the average fuel price differential of 50% will materialise over the lifespan of MV Amazon Victory the critical cost (K), the most a shipping company should invest in a dual fuel propulsion system today (6/2015) should be **$7,677,450** for operations beginning in 2016 (due to the six month opportunity cost of money), and **$8,179,278** for an investment made in the beginning of 2016.

4.3 Conclusion

The results of the six binomial pricing models that have been used to quantify the value of flexibility that is created by the option to switch to LNG that a dual fuel propulsion system for both MV Fengning, and MV Amazon Victory are summarised in figures 10 and 11 below.

Figure 10: Value of Flexibility Provided by a Dual Fuel Propulsion System for MV Fengning. Source: Author

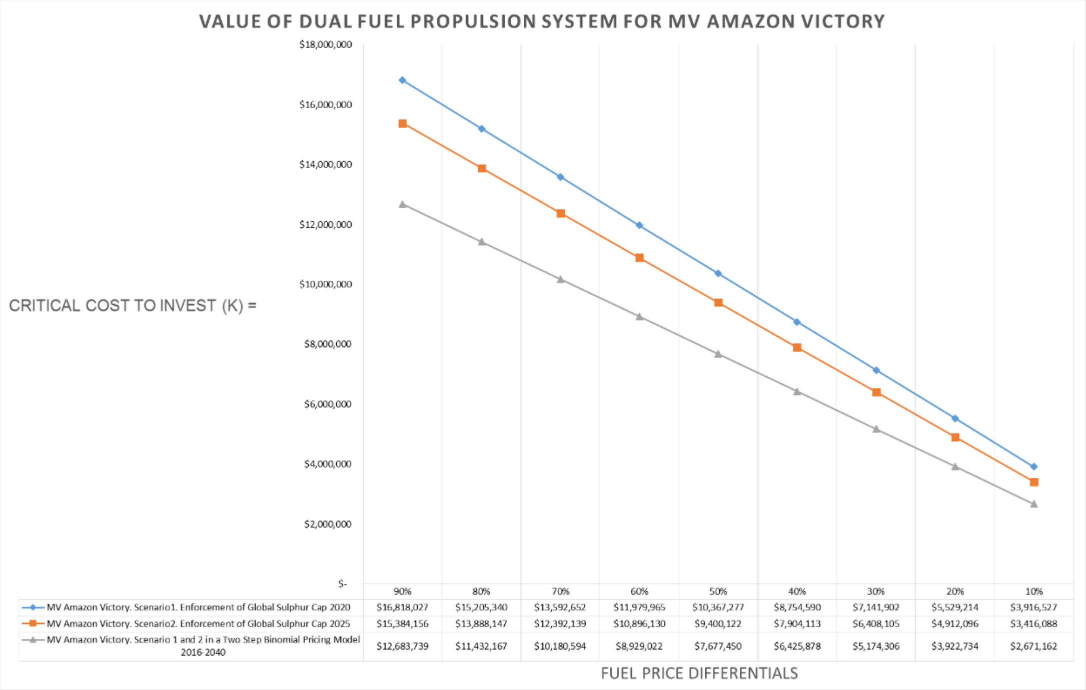


	90%	80%	70%	60%	50%	40%	30%	20%	10%
MV Fengning. Scenario1. Quick LNG Bunkering Uptake	$3,621,097	$3,273,868	$2,926,640	$2,579,411	$2,232,183	$1,884,954	$1,537,726	$1,190,497	$843,269
MV Fengning. Scenario 2. Slow LNG Bunkering Uptake	$1,983,509	$1,793,310	$1,603,110	$1,412,911	$1,222,711	$1,032,512	$842,312	$652,113	$461,913
MV Fengning. Scenario 1 and 2 in a Two-Step Binomial Pricing Model	$2,802,303	$2,533,589	$2,264,875	$1,996,161	$1,727,447	$1,458,733	$1,190,019	$921,305	$652,591

Figure 10 above illustrates the differences in the critical cost (K) to invest in a dual fuel propulsion system for MV Fengning in 6/2019, for operations beginning in 2020. Both of the single step binomial pricing models, and the two-step binomial pricing model used for MV Fengning are combined in figure 9. This enables a visual comparison of the single step binomial pricing models, and the two-step binomial model. The results indicate that the two-step binomial pricing model that has incorporated a 50/50% probability of the quick/slow bunkering uptakes materialising falls exactly in between the two single step binomial pricing models. This demonstrates that the proposed two-step binomial pricing model successfully allows for a valuation of the option to switch to LNG that is provided for by a dual fuel propulsion system, while simultaneously accounting for the probability of two uncertainties materialising by the use of a single model. This model can be easily modified by a shipping company to reflect its predictions regarding the probability of materialisation of uncertainties, while also allowing the incorporation of more uncertainties in a multi-step binomial pricing model if necessary.

Figure 11 below illustrates the differences in the critical cost (K) to invest in a dual fuel propulsion system for MV Amazon Victory. The single step binomial pricing models evaluate the critical costs (K) of scenarios 1 and 2 regarding investment in 6/2019 for operations beginning in 2020 and ending in 2045. The two-step binomial pricing model evaluates the critical costs (K) for investment in a dual fuel propulsion system for MV Amazon Victory on 6/2015 for operations beginning in 2016 and ending in 2040, with a probability of the enforcement of the global sulphur cap in 2020/25 to be 40/60%.

Figure 11: Value of Flexibility Provided by a Dual Fuel Propulsion System for MV Amazon Victory. Source: Author



	90%	80%	70%	60%	50%	40%	30%	20%	10%
MV Amazon Victory. Scenario1. Enforcement of Global Sulphur Cap 2020	$16,818,027	$15,205,340	$13,592,652	$11,979,965	$10,367,277	$8,754,590	$7,141,902	$5,529,214	$3,916,527
MV Amazon Victory. Scenario2. Enforcement of Global Sulphur Cap 2025	$15,384,156	$13,888,147	$12,392,139	$10,896,130	$9,400,122	$7,904,113	$6,408,105	$4,912,096	$3,416,088
MV Amazon Victory. Scenario 1 and 2 in a Two Step Binomial Pricing Model 2016-2040	$12,683,739	$11,432,167	$10,180,594	$8,929,022	$7,677,450	$6,425,878	$5,174,306	$3,922,734	$2,671,162

The two step-binomial pricing model is included in figure 11, in order to illustrate the differences in the critical cost (K) of investing in a dual fuel propulsion system before the enforcement date of the global sulphur cap is announced, and before the sulphur cap in the EU economic zone is enforced. The results show a sizable difference that can be attributed to the reduced cash flows of the first four years because the operator of MV Amazon Victory will have the option to switch to LNG from HFO in the EU economic zone before the enforcement of the sulphur cap in the EU economic zone. In addition the difference can also be attributed to a reduction of four years of operation where higher cash flows would be capitalised on due to the option the operator will have to switch to LNG from MGO on all legs of both the laden and ballast voyages.

For both vessels, the uncertainty that plays the most important role regarding how much a shipping company should invest in a dual fuel propulsion system, is the fuel price differentials. The bunkering uptake scenarios for MV Fengning also contribute a significant amount, while the scenarios of the global fuel cap for MV Amazon Victory contribute to a lesser amount. However, investment now towards a dual fuel propulsion system for MV Amazon Victory for operations beginning in 2016 compared to investment in 6/2019 for operations beginning in 2020, results in a significantly reduced critical cost (K) for the investment. This means that a shipping company should invest less towards a dual fuel propulsion system now, than they should in 6/2019.

When comparing the results in figure 10 for MV Fengning to the results in figure 11 for MV Amazon Victory, the critical cost (K) to invest is substantially larger for MV Amazon Victory. This is because MV Amazon Victory is a larger vessel, with a higher power output, and therefore she has a larger annual FC in comparison to MV Fengning. Furthermore MV Amazon Victory is assumed to spend 56 more days at sea than MV Fengning. It would be possible for one to jump to the conclusion, that it is much more profitable to install a dual fuel propulsion system on MV Amazon Victory than it would be to install on MV Fengning. Although this might be true, it is highly dependent on the additional costs required to install a dual fuelled propulsion system on the vessels in question. MV Amazon Victory not only requires a larger engine than MV Fengning, but as a vessel she requires a longer range, and she consumes more fuel, which means that she requires larger LNG tanks. As previously mentioned in Chapter 2 LNG tanks are the most expensive part of a LNG or dual fuel propulsion system, which means that a dual fuel propulsion system for MV Amazon Victory will be substantially more expensive that the dual fuel propulsion system required for MV Fengning.

Chapter 5: Conclusion

In this research paper, the value that is created by the option to switch to LNG that a dual fuel propulsion system provides (flexibility) a shipping company, is investigated. The challenge when evaluating investments towards dual fuel propulsion systems is accounting for the many uncertainties that a shipping company faces while considering such an investment.

Therefore, a model that will allow a shipping company to simultaneously account for the various uncertainties, while evaluating an investment towards a dual fuel propulsion system, has been presented. The binomial pricing model has been selected in order to conduct an ROA valuation on the option to switch to LNG that a dual fuel propulsion system provides. This is because the use of binomial models enables the user to easily and simultaneously account for a variety of uncertainties by assigning probabilities of materialisation to the uncertainties, and thus provides the basis for this research paper.

For the MV Fengning, assumptions have been made regarding the LNG uptake in the Mediterranean, and assumptions regarding the enforcement date of the global sulphur cap have been made for MV Amazon Victory. The author has made these assumptions in order to demonstrate how two of the most relevant uncertainties regarding the adoption of dual fuel propulsion systems can be included in a binomial pricing ROA valuation model, thus demonstrating the function, and simplicity of this model. If properly depicted in a graph as in chapter 4.3 the results can be easily understood by management, and based on the price premium a shipping company would have to pay for a dual fuel propulsion system, a decision regarding the investment towards a dual fuel propulsion system can easily be made.

Although this model has been used on newbuilds in order to minimise assumptions, this model can also be used by shipping companies that are considering a dual fuel retrofit for vessels that are in service, whether they have or have not been designed as LNG ready. The only difference for vessels in service is that the critical cost to invest (K) in a similar vessel type will likely be higher compared to a newbuild because additional modifications will need to be made, and the vessel will have to be laid up. For ship owners already operating vessels in service within areas where SECAs are not yet established, it would be recommended that they use this model of the ROA valuation of the option to switch, in combination with the ROA valuation of the option to defer presented by Acciaro (2013) in order to make such an investment at the right time since they can continue to operate on HFO without additional cost until the sulphur caps are enforced.

As simple as ROA valuation is to perform, and as clear as the results of the model are to comprehend, the accuracy of the findings of an ROA model are highly dependent on valid and accurate assumptions regarding variables and uncertainties. Arriving at these assumptions can often require complicated forecasting methods, and every care must be taken that these assumptions will properly reflect future outcomes. As per Brach (2003), *"ROA valuation is never better than the assumptions that go into the analysis"*. This is especially relevant where predictions regarding fuel price differentials are concerned. The findings in this research paper have shown, the probability of the materialisation of fuel price differentials can change the value of the investment by as much as 77%.

Another decisive factor is the premium of the dual fuel propulsion system, which is difficult for this author to make proper the assumptions due to the different characteristics of each vessel. This is why this research paper does not attempt to assess the cost of a dual fuel propulsion system, but rather introduces a model that a shipping company can use to estimate the maximum amount they should invest towards a dual fuel propulsion system based on vessel characteristics, operational parameters, and predictions of future outcomes.

It must be reiterated that although the reduction in fuel costs make up the most of the financial benefits related to compliance of the more stringent MARPOL Annex VI Regulation 14, there is potential for additional value to be created. Non fuel related reductions in OC, VC can drive down OPEX. There is also the potential for the vessel to increase its productivity by attracting more charters, and by being able to compete for a wider variety of charters while operating at the lowest possible cost. As mentioned in chapter 2, section 3.2, the aforementioned potential for a dual fuel propulsion system to create added value for its owner will undoubtedly increase the vessels second hand value, which will positively impact a shipping company's balance sheet.

An additional benefit that a dual fuel propulsion system provides over both the traditional marine fuel method of compliance (switching from HFO to MGO), and the method of using abatement technology in order to comply with MARPOL Annex VI, is that it also allows a vessel to comply with the NOx regulations coming into force in 2016. The additional value that a dual fuel propulsion system could create by enabling a vessel to comply with NOx regulations, compared to other methods of compliance with MARPOL Annex VI, would be an interesting topic for further research. This is because the need to install a Selective Catalytic Reduction system (SCR) for vessels using either the traditional marine fuel method of compliance, the abatement technology method, or even the dual fuel propulsion method when still burning MGO in SECAs, is bound to increase the CapEx. Additionally according to Reynolds (2011) there may be compatibility issues regarding abatement technology and SCRs. Another interesting topic for further research is the effect that a dual fuel propulsion system would have on a vessel's EEDI and SEEMP.

The author believes that dual fuel propulsion systems, although not suitable for every vessel, provide considerable advantages over other methods of compliance with MARPOL Annex VI. Dual fuel propulsion systems provide a mid to long term method of compliance with MARPOL Annex VI today. They are not restricted by the limited availability of LNG bunkering facilities which seriously hamper the uptake of LNG only propulsion systems, while also being cheaper.

The fact that dual fuel vessels are not constricted to areas where LNG bunkering facilities already exist, the uptake of dual fuel propulsion systems allows for a virtually risk free way for shipping companies to make the first step towards solving the "*chicken and egg*" stalemate that the maritime industry finds itself in regarding the adoption of LNG. The uptake of dual fuel propulsion systems will increase the demand for LNG at ports, which will enable ports to commit the large CapEx required to develop LNG bunkering facilities. This will in turn allow the shipping companies to benefit from lower fuel costs, the ports will benefit from reduced emissions, and the people living in coastal areas and environment will also benefit.

By introducing a model to evaluate the economic benefit, but also by thoroughly presenting the environmental, and social benefits that are attributable to the use of dual fuel propulsion systems, this research paper attempts to provide shipping companies with a means to evaluate how a dual fuel propulsion system can contribute to their triple bottom line. The author believes that a shipping company that incorporates sustainability into their corporate strategy will create a sustainable competitive advantage for itself. Therefore, the value of flexibility that a dual fuel propulsion system can provide in this time of regulatory, and developmental uncertainty, can be quantified by calculating fuel savings, but in reality, the value that can be created is far greater.

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