Powering newly constructed vessels to comply with ECA regulations under fuel market prices uncertainty: Diesel or dual fuel engine?

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Abstract

Over the last decade, marine engine engineering has evolved considerably, to the point where engine technology can be considered mature and reliable using LNG as fuel without affecting safety at sea. This paper analyses the choice between different engines jointly and considers the alternatives of installing or not installing a sulphur scrubber when building a new vessel. We consider the possibility of installing a dual or a diesel engine. The dual engine is more flexible because it can consume liquefied natural gas (LNG) as other marine fuels but the initial investment is more expensive. On the other hand, the use of scrubbers enables the use of marine fuels with high sulphur content in Emission Control Areas (ECAs), these marine fuels are usually cheaper also we consider Selective Catalytic Reduction technology (SCR) in all cases to minimize NO_x.

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The paper calibrates a stochastic model for LNG and determines four marine fuel correlated prices. The work also considers a possible regulatory change from a non ECA to an ECA in the future. When we aggregate the installation costs to the present value of the expected combustible cost under uncertainty we can select the cheapest alternative. In our base case with a probability of 75% of the Mediterranean Sea becoming an ECA area in 2025 and also a probability that all the European Atlantic coast becomes an ECA area by 2030, we obtain a minimum of expected present value of investment and fuels cost of 25.62 million US$ with a Dual engine with scrubber configuration.

Our work shows that, in the cases considered, the use of a dual engine is the best alternative minimizing the total of investment and fuel costs. Finally, we analyze the distribution of fuel cost and its associated risks.

1. Introduction

The demand for shipping services depends on several factors such as the world economic situation, trade policy, environmental regulations or oil and other commodities´ prices. Maritime transport shows a growing trend over recent decades, in Fig. 1., we can observe the evolution of the world´s seaborne trade volumes reaching 10,287 million metric tons in 2016 (UNCTAD, 2017). This trend is expected to continue in the future causing significant negative environmental implications and health impacts (Cullinane and Bergqvist, 2014). In fact, it has been estimated an increase of 2.8% in 2017 and a compound annual growth rate of 3.2% between 2017 and 2022 (UNCTAD, 2017). In Fig. 2. we observe the evolution of the merchant fleet and find the trend is similar to that of the world seaborne trade. This fact can be easily understood as the shipping industry is responsible for the carriage of around 90% of world trade (ICS 2018).

This scenario augurs the need to build new vessels, not only because many of them have reached the end of their useful life but also because of the need to import and export more goods. In fact seaborne trade is expected to grow at 2.4% per annum (Mickeviciene 2011).

According to various international policies there is a clear aim calling for a faster transition towards sustainable energy production and use (United Nations 2015; UN Environment 2017). Maritime transport burning traditional fuel has an effect on human health and climate change and also on ecosystems due to acid deposition and eutrophication (Schrooten et al. 2009; Kapsenberg 2017; Depledge et al 2017).

To minimize this effect, the International Maritime Organization (IMO) has implemented a number of conventions such as the International Convention on Prevention and Pollution by Ships (MARPOL) (IMO 2011) and the Energy Efficiency Design Index (EEDI) (IMO 2012a) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) (IMO 2012b) for all ships. In this regard, new vessels should be designed taking into account the Best Available Technologies (BAT) and present and future environmental regulations. In October 2016 the IMO implemented a new SOx regulation[1] and a new NOx regulation[2] determining the so-called Emission Control Areas (ECAs) to mitigate health and environmental effects. There are two main areas of emissions and fuel quality requirements defined: one is the ECA-s and the other is the global. ECA-s include the Baltic Sea, the North Sea, the North American ECA, US Caribbean,

[1] See MARPOL Annex VI Fuel Sulphur limits. Sulphur Oxides (SO_x) – Regulation 14

[2] See MARPOL Annex VI NO_x Emission limits. Nitrogen Oxides (NO_x) – Regulation 13

Puerto Rico, US Virgin Islands. Further designated areas are under discussion, such as Australia, Mexico or the Mediterranean Sea. In an ECA the Sulphur cap is set at 0.1 per cent m/m and the permitted NOx emission is 8 g/kWh.

The use of Liquefied Natural Gas (LNG) can be an option to mitigate these adverse effects. In this context Schinas and Butler (2016) propose a methodology to evaluate the required incentives to promote LNG as marine fuel. The life-cycle emission of natural gas compared with petroleum based marine fuels has been studied by Thomson et al. (2015), Bengtsson et al. (2011) and Brynolf et al. (2014). To make LNG-fueled vessel expansion possible it is necessary to increase LNG bunkering facilities. The US Energy Information Administration (EIA) has recently reported a significant increase. European ports are also expanding their LNG bunkering capacities. According to Calderon et al. (2016) there are at present 22 terminals in operation, 6 terminals under construction and 24 planned. Gu et al. (2016) develop a stochastic model involving tactical and operational decisions in maritime bunker management.

Many articles have been written regarding sulphur and nitrogen emissions in the marine sector as Molina-Serrano et al. (2018) and Zetterdahl et al. (2016).

Other studies are primarily focused on the analysis of the difference between sulphur emissions due to burning HFO, MGO or ULSFO. Abadie et al. (2017) examine how the existing fleet can be adapted to the new emission regulation. This work is focused on Diesel engines so the options considered are the use of low-sulphur marine diesels or installing a scrubber. The result of this study indicates that the longer a vessel sails in the ECA zone and the longer the time a ship spends at sea, makes investing in scrubbers an attractive option in order to maintain longevity in the ship´s life. In the case of newly designed boats, the range of possibilities is much wider. This is because dual engine technology is mature enough for ship-owners and ship builders to consider it as a new option. The use of dual engines permits significant reduction of SOx, NOx and CO_2 (Burel et al. 2013). These authors also calculate a reduction of 35% in operational costs and 25% in CO_2 emission reduction.

Livanos et al. (2014) compare a dual fuel engine with a conventional diesel engine, equipped or not with waste heat recovery systems, and calculate the system´s efficiency. These authors assume fixed and constant marine fuel prices. Deniz and Zincir (2016) propose alternative fuel use on marine diesel engines, these fuels are methanol, ethanol, liquefied natural gas and hydrogen. The findings of this work is that LNG is the most suitable alternative fuel.

Fagerholt et al. (2015) propose an optimization model and conclude that ship operators choose to sail longer routes to avoid ECA-s or even reduce speed in ECA-s to avoid burning more expensive fuel. The estimation of fuel consumption and speed is also analyzed by Bialystocki and Konovessis (2016) under different wind conditions and temperatures. In this context, estimating energy consumption and shipping emissions

Moreno-Gutiérrez et al. (2015) assume there are nine different methods and compare their use.

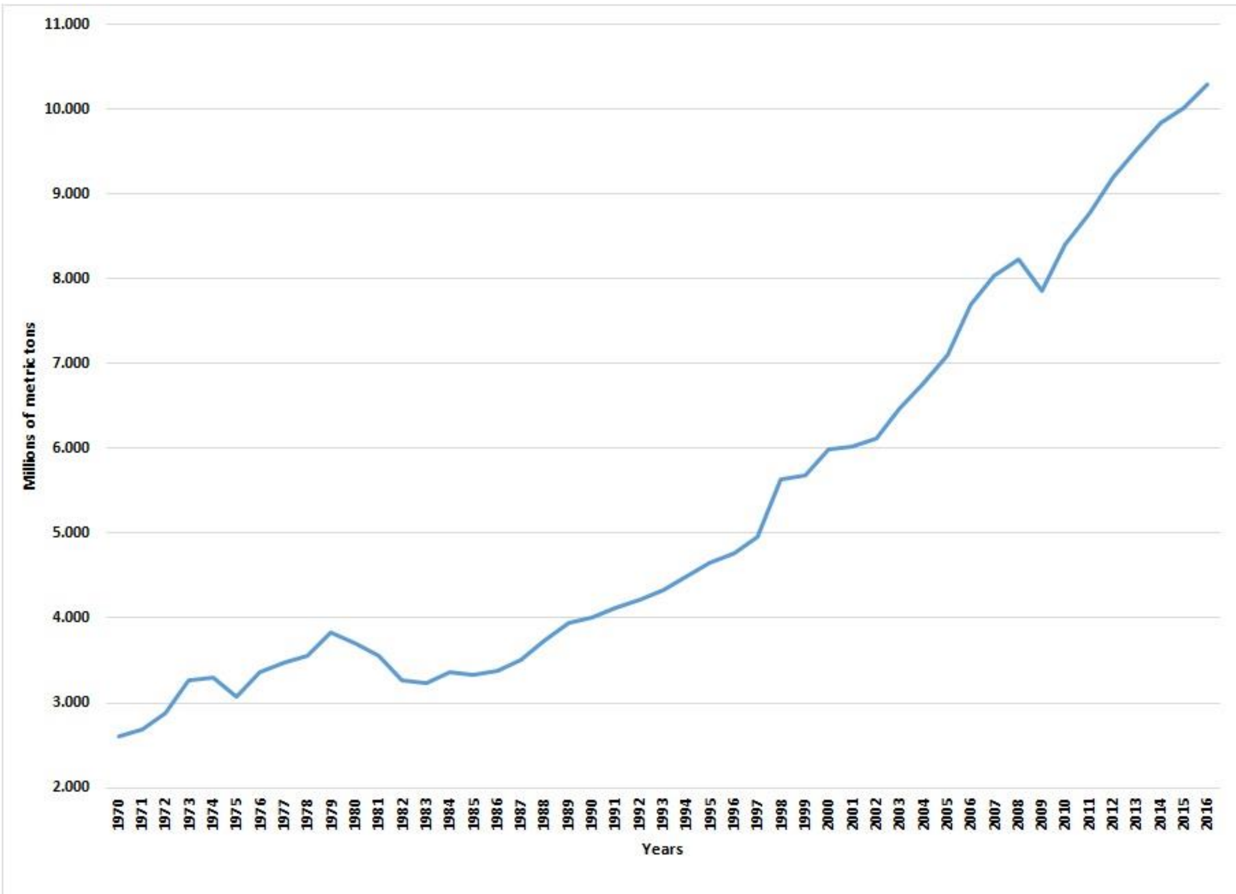

Fig. 1. International seaborne trade development (prepared by the authors with data from UNCTAD, 2017).

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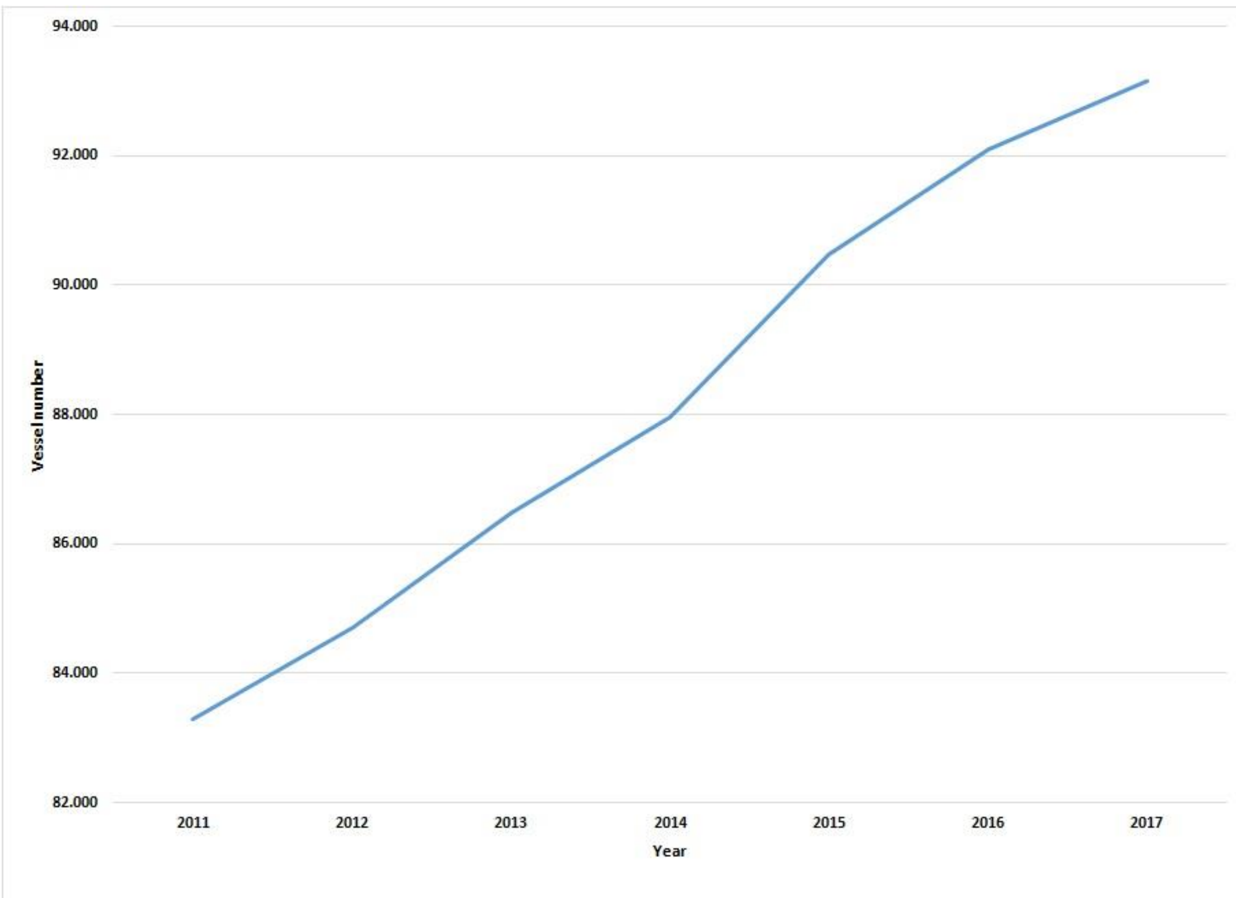

Fig. 2. Worldwide merchant fleet (number of vessels) (prepared by the authors with data from UNCTAD).

This paper analyzes the effect of Sulphur and NOx limits regulation in the investment decision when building a new vessel together with the possibility of new extended ECAs. We use a stochastic model for spot and future prices calibrated with market quotes. We consider two possible engines (dual and diesel)

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in conjunction with the possibility of a scrubber installation and under the uncertainty that some part of the sea route becomes an ECA area in the future.

The paper is organized as follows: Section 2 briefly describes the health and environmental regulation affecting the shipping sector. Section 3 presents the base case, the stochastic model and its calibration with market data. Section 4 shows the marine engine´s technical and economical specifications. Section 5 presents the resulting calculation and Section 6 concludes. The paper is supplemented with two Appendix, the Appendix A describes the stochastic Brent and natural gas price models and the Appendix B includes a list of nomenclature and abbreviations.

2. Present and future IMO regulations

The third IMO GHG Study (IMO, 2014) estimated international shipping to produce 35.64 Gigatonnes CO_2 emissions in 2012, representing 3.1% of the world’s total emissions. In order to mitigate this contribution to global warming, in April 2018 IMO adopted an initial IMO Strategy on reduction of GHG emissions from ships (IMO, 2018). The goal is to reduce total annual GHG emissions by at least 50% by 2050 compared to 2008. The agreement brings shipping in line with the Paris Climate Agreement´s temperature goal.

For reducing NO_x and SO_x emissions the IMO has defined two different zones, ECA-s and non-ECA-s. In these ECAs, according to IMO Web site (2015a), the Sulphur cap is 0.10% m/m (mass/mass), while outside ECAs the cap will be 0.50% in 2020 (3.5% m/m before 2020). In the case of NOx emission, according to IMO

(2015b), Tier III limits to around 2 gr/Kwh at 2000 rpm engine speed in an ECA and to around 8 gr/kwh at 2000 rpm outside an ECA.

It is possible to create new ECA areas in the future; this generates uncertainty about future regulation that must be taken into account in the investment decision of a new vessel´s configuration. Panagakos et al. (2014) examine the effect of designating the Mediterranean Sea as an ECA area and Kontovas et al. (2016) examine the effects of modal shifts in the case of the Mediterranean becoming an ECA area. Further ECAs have been proposed, Australia, Japan, the Mediterranean Sea and Mexico (Andersson and Brynolf 2015). What is more, in June 2015 the IMO released a document - the Mediterranean Action Plan (MAP 2015) - aiming to strengthen cooperation between the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC) and the European Commission as well as the European Maritime Agency. It is with this in mind that we assume a 75% probability that the Mediterranean Sea will become an ECA area in 2025. Also, we assume the probability that all the European Atlantic coast becomes an ECA area by 2030.

3. The Stochastic Model

3.1. The Base Model

Our model will be applied to the case described below, nevertheless by changing the parameters, it is possible for it to be used for other routing cases.

The geographical location of important ports is strategic in the historical flow of maritime trade. Thus, many of the routes that shipping companies take are already predefined on the basis of these ports. In fact, transport planning between ports can be achieved using the Bayesian Approach (De Gregorio-Vicente et al., 2017). The entrance of the Asian maritime trade to Europe is through the Mediterranean Sea, a significant port being Port Said in Egypt. At the other end of the Mediterranean Sea lies the port of Algeciras, an excellent connection either with America or Northen Europe. In Northern Europe, Bergen is a significant trading port. According to Eurostat (2017), these two European ports are among the 20 most important ports in Europe, and Port Said is among the fifty most important ports in the world according to the World Shipping Council (2018).

The engine choice for the new vessel is based on a predetermined route, and this is Port Said-Algeciras-Bergen (see Table 1). In fact, the route between these three ports presents a curiosity with regard to as for the new environmental regulation concerns. The Algeciras Port Said section is located in the Mediterranean Sea, actually non ECA, and is susceptible to becoming an ECA area. The stretch from Algeciras to Bergen is approximately half an ECA and the other half is not yet an ECA. The time distance in Table 1 is obtained assuming a theoretical vessel speed of 12.5 knots.

Table 1 Route details

Sea Route	Time	Nautical Miles	% ECA
Algeciras (Spain) - Port Said (Egypt)	6 days 03 hours	1,915	0%

Algeciras (Spain) - Bergen (Norway) DIRECT	5 days 20 hours	1,816	
. Non ECA		916	50.45%
. ECA		900	49.55%

For sailing pattern we use similar distribution to the employed in Abadie et al., 2017), based in (Green Ship of the Futures). We assume per year, 46.8 days for the ship to carry out maintenance repairs or off hire, 102.2 days waiting on charter orders and 216 days sailing. So, the annual navigation hours is assumed to be 5,184. For the modeling we divide the year in 36 steps of 365/36=10.14 days. That includes six navigation days and 4.14 days in port.

The reason for choosing this route is a double reason one, according to (Vanroye et al. 2014) this route is a Motorway of Sea (MOS), it is the axis of the corridor for trading goods from Asia to Northern Europe and also helps to illustrate what happens regarding fuel bunkering costs if environmental regulation changes, in particular if the Mediterranean sea becomes an ECA.

3.2. The Stochastic Marine Fuels Gap Prices

In some cases a commodity without long-maturity market futures quotes can be strongly correlated with others that have long-maturity market futures prices available. We show below that this is the case with crude oil products and marine fuels. In these cases it is possible to use futures quotes for the commodities without long-term projections to estimate other long-maturity futures prices. Cortazar et al. (2008) use the

Kalman filter approach for this type of estimation. For the stochastic process estimation of the marine fuel gaps, we use Rotterdam bunker prices from 10/19/2015 to 10/30/2017, a total of 531 trading days. In this paper, for marine fuels, we use the method proposed by Abadie et al. (2017), and we obtain Table 2.

Table 2 Price Gap Marine Fuel parameters.

	ULSFO	IFO180	IFO380	LSMGO
M^{*i}	40.405	-77.262	-107.486	59.373
k^{i}	40.515	13.840	16.918	47.507
σ^{i}	168.471	126.870	121.017	144.614
M_0^i	54.31	-91.69	-121.19	69.81

Table 2 shows the parameter of marine fuel gaps calculated following a similar procedure at Abadie et al. (2017).

3.3. The Stochastic Brent and Natural Gas Prices

For LNG we have landed prices for Spain and UK, the mean of these prices does not differ significantly in Natural Gas Prices for Europe. This can be seen in Figure 3. For this purpose in this paper, we use the UK

Natural Gas futures prices available on the Intercontinental Exchange (ICE, , United Kingdom), irrespective of their monthly maturity. Also we use Brent Crude Oil prices available on the Intercontinental Exchange (ICE).

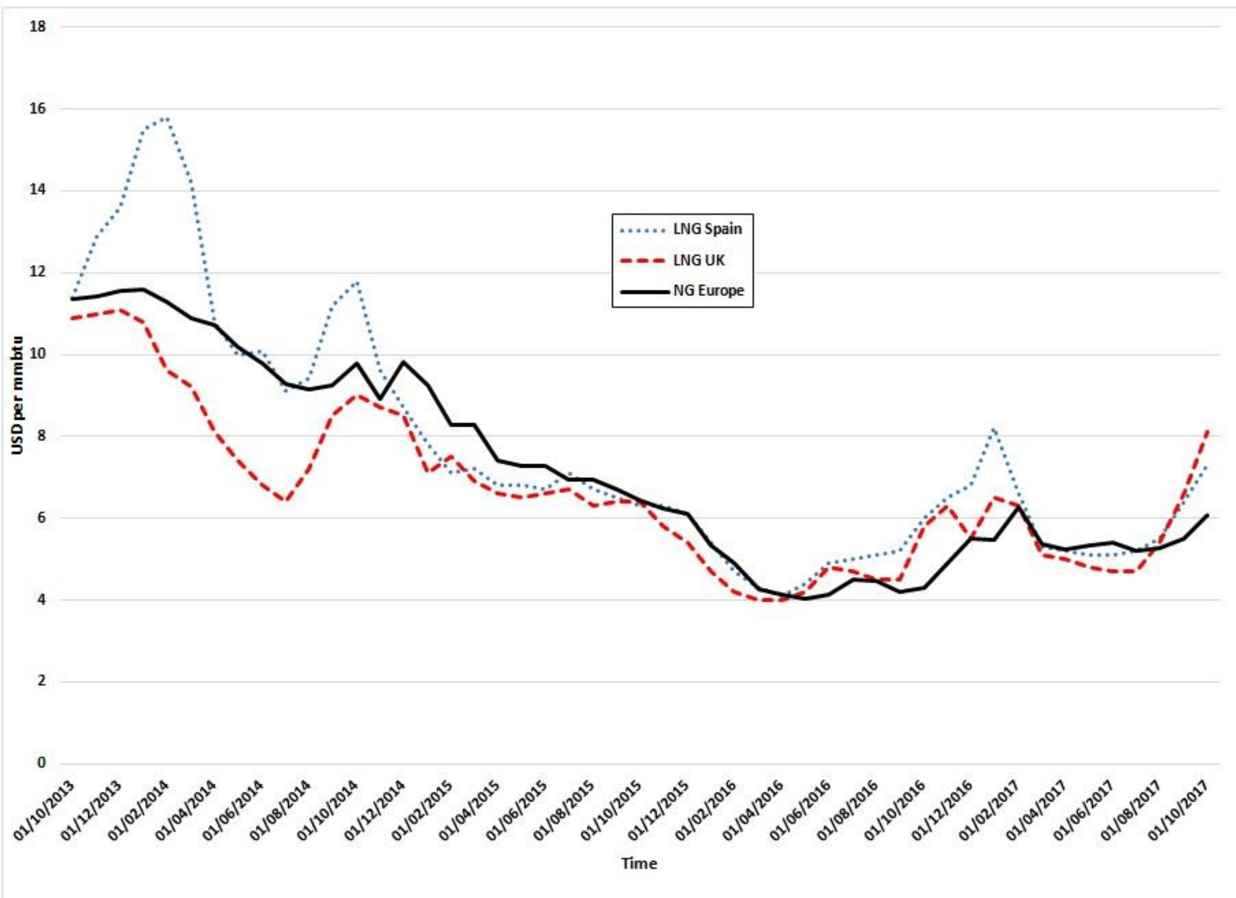

Fig. 3. LNG Landed prices and NG prices in Europe. Source LNG prices Bluegold Research from International Monetary Fund, World Bank, companies' reports. Source NG prices Europe: World Gas Intelligence; World Bank.

Figure 4 shows the term structure of Brent futures contracts from 1/2/2014 to 10/30/2017. In this graph we can see its the mean-reverting behavior.

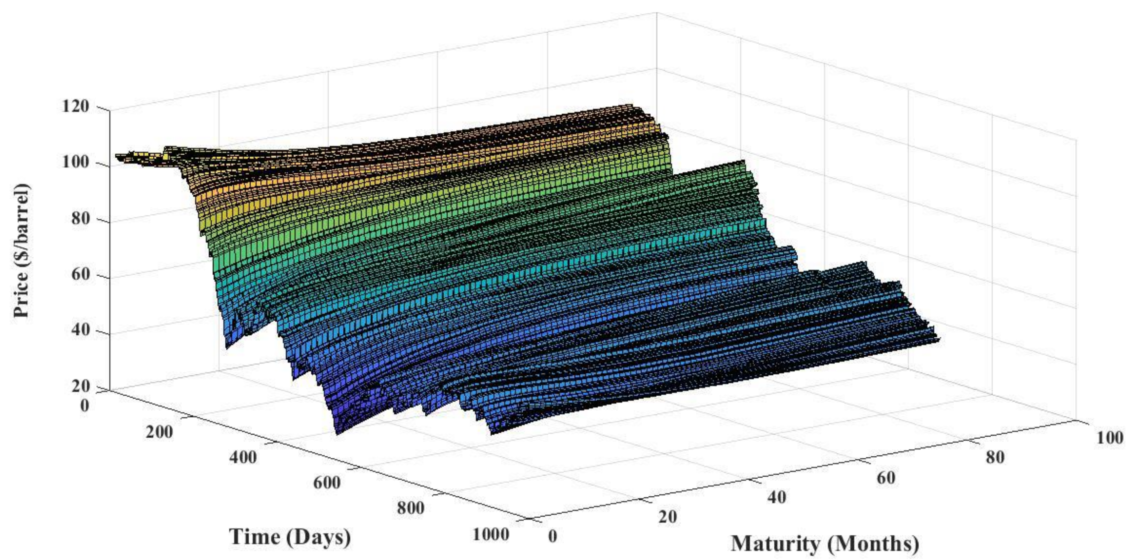

Fig. 4. Brent Crude Oil quotes of future market (from 1/2/2014 to 10/30/2017).

Figure 5 shows the quotes of UK natural gas futures, we can also see a mean-reverting behavior. This graph also shows a seasonal behavior.

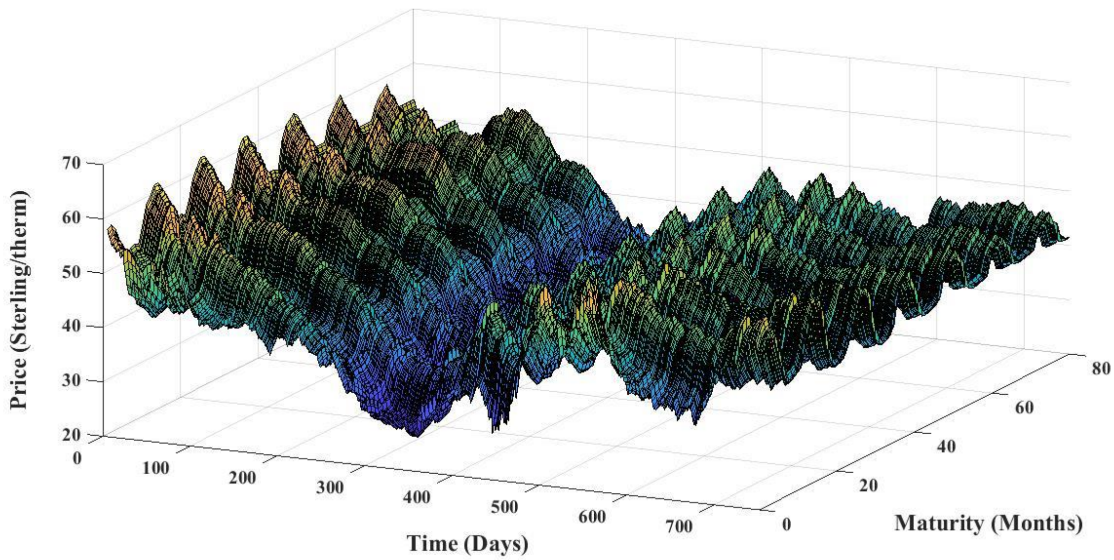

Fig. 5. UK Natural Gas Futures Prices (from 12/1/2014 to 10/30/2017).

When comparing these commodities, natural gas prices are assumed, according with futures quotes, to display a seasonal pattern; Brent crude oil, on the other hand, does not show such behaviour. These two price processes, show mean reversion. The time t (long-term) prices of natural gas are described by the Equation (1) in a risk neutral world (in this case the futures market), whereas that the Equation (2) describes the stochastic process of Brent crude oil also in a risk-neutral world:

$$dG_t = df^G(t) + [k^G G^* - (k^G + \lambda^G)(G_t - f_G(t))]dt + \sigma^G (G_t - f_G(t)) dW_t^G. \quad (1)$$

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$$dB_t = [k^B(B^* - B_t) - \lambda^B B_t]dt + \sigma^B B_t dW_t^B. \quad (2)$$

G and B are assumed to show mean reversion. G^* and B^* denote the long-term equilibrium levels; i.e., current (deseasonalized) gas and crude oil prices lean towards them in the long run. $f^G(t)$ is a deterministic function that captures the effect of seasonality in gas prices. In general the function is defined by $f^G(t) = \gamma e^{-\mu t}\cos(2\pi(t+\varphi))$, with the time t measured in years and the angle in radians; when $f(t = -\varphi) = \gamma$ the seasonal maximum value is reached. The parameter μ generates an amplitude decrease with time in accordance with future market quotes. k^G and k^B are the speed of reversion towards the " normal" level of gas and crude oil prices. They can be computed as $k^G = \ln 2/t_{1/2}^G$, where $t_{1/2}^G$ is the expected half-life for (deseasonalized) natural gas, i.e. the time required for the gap between $\left|G_0 - f^G(0)\right|$ and G_m to halve; similarly $k^B = \ln 2/t_{1/2}^B$. σ^G and σ^B are the instantaneous volatility of natural gas and crude oil. λ^G and λ^B denote the market price of risk for gas and crude oil. dW_t^G and dW_t^B are the increments to standard Wiener processes. They are normally distributed with mean zero and variance dt; besides:

$$dW_t^G dW_t^B = \rho_{GB} dt \quad (3)$$

Figure 6 shows the last day futures Brent quote and the predicted values estimated using a non-lineal least squares stimation procedure.

In Appendix A we describe the procedure to obtain crude oil and natural gas volatilities. We have $\sigma^B = 0.380$ and $\sigma^G = 0.352$. Also in Appendix A we explain the procedure to obtain the remaining stochastic process parameters shown in Tables 3 and 4.

Table 3 Brent crude oil and natural gas stochastic parameters.

Brent		Natural Gas	
$k^B + \lambda^B$	1.0187	$k^G + \lambda^G$	-0.3177
*B** ($/tonne)*	424.308	*G** (pence/therm)*	45.141
σ^B	0.380	σ^G	0.352
B_0 ($/tonne)	458.577	$(G_0 - f^G(0))$ (Pences/therm)	45.072

Table 4 Brent, LNG and marine fuel price gap correlations.

	Brent	ULSFO	IFO180	IFO380	LSMGO	Natural Gas
Brent	1.000					

ULSFO	-0.233	1.000				
IFO180	-0.110	0.605	1.000			
IFO380	-0.093	0.637	0.920	1.000		
LSMGO	-0.235	0.627	0.630	0.683	1.000	
Natural Gas	-0.088	-0.065	-0.129	-0.144	-0.071	1.000

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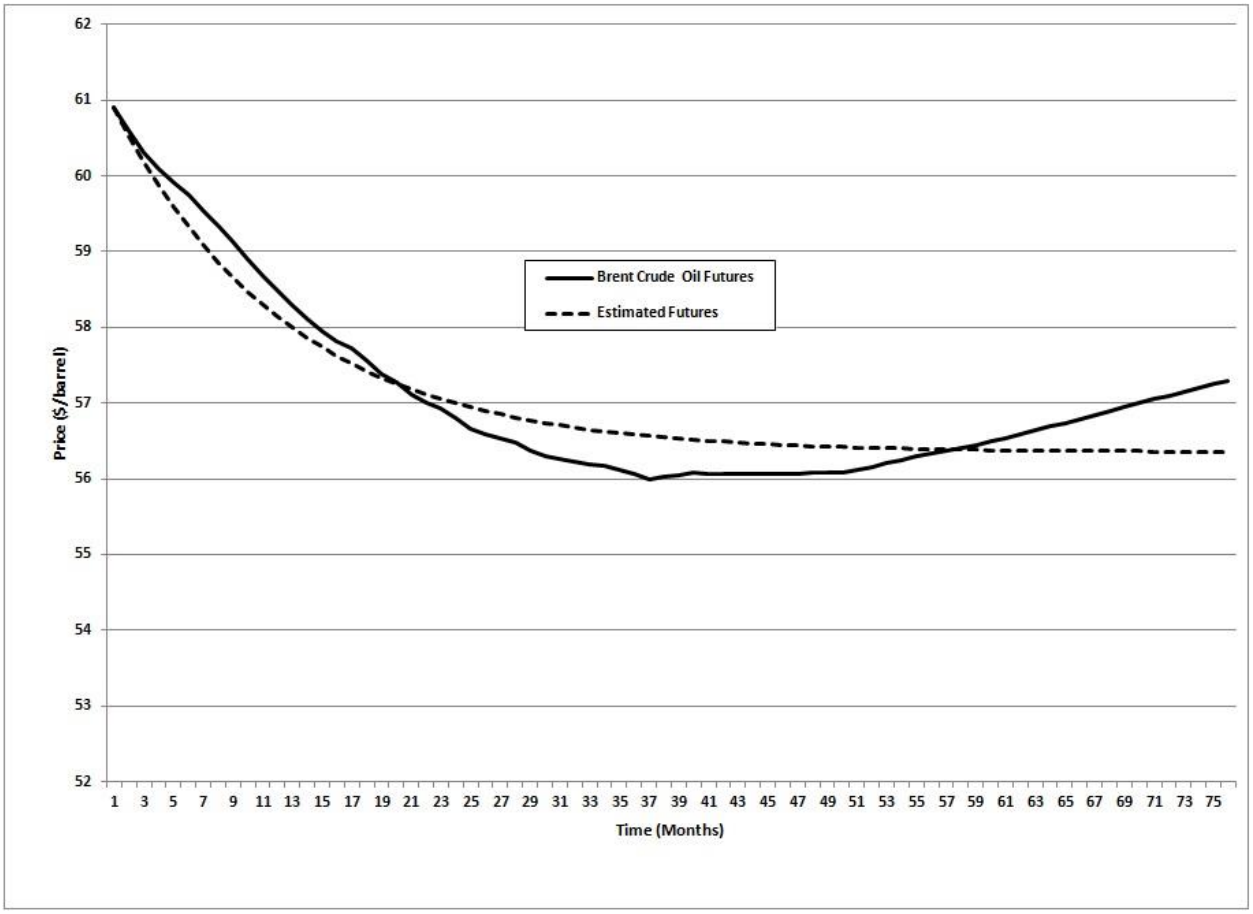

Fig. 6. Brent Crude Oil Futures Prices (10/30/2017).

Similarly, we use deseasionalized natural gas last day time serie to obtain the corresponding last day parameters. Figure 7 shows the real quotes, the estimated futures and the deseasonalized estimation for the last day of serie.

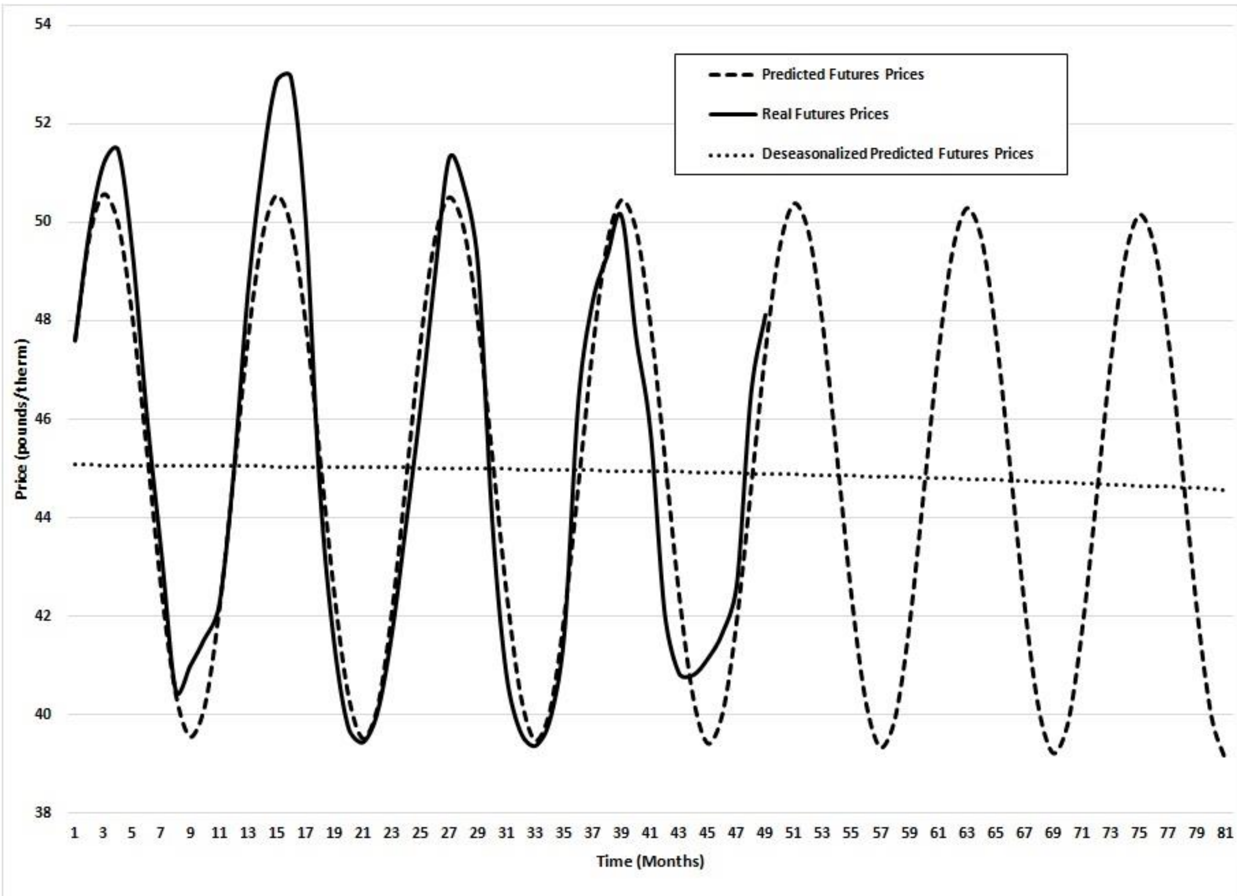

Fig. 7. UK Natural Gas Futures Prices (10/30/2017).

The Ship and Bunker[3] information is used to convert the Brent price into to \$/tonne from \$/barrel at a 7.53 rate. We also use as initial values the last day of the price series (10/30/2017).

[3] http://shipandbunker.com

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Europe is an importer of gas. The supply of gas enters either as natural gas transported by **pipelines and transferred to gas liquefaction storage plants or by large LNG ship carriers and stored in gas regasification import terminals. The LNG demand depends on its price and environmental regulation, so we think in a near future the demand will increase and this will affect the bunkering station** situation.

4 The marine engines technical and economical specifications

Over the last decade, marine engineering has evolved considerably, to the point where dual engine technology can be considered to be reliable using LNG, LSMGO or HFO as fuel without affecting safety at sea. This paper analyses the economic and environmental optimum propulsion of a newly built vessel based on initial investment and future fuel market prices. The choice of engine options analysed are dual engines and diesel engines.

The dual engine that has been taken as a reference is the new generation Wärtsilä 34 DF (Wärtsilä 34 DF, 2018). It is a four-stroke dual engine that can operate either in an Otto cycle or in a Diesel cycle. The new version of this engine is based on the Wärtsilä 32 diesel which was marketed in the mid-1990s. This is a medium-power engine whose configuration can vary between 6, 8 and 9 cylinders in line, and 12 or 16 cylinders in V. The power supplied by this model is between 2.8 MW and 8.0 MW and has a speed of 720-750 rpm. Specifically, the 8-cylinder engine has been chosen, 8L 34 DF 4T, which generates a power output of 500 kW per cylinder, obtaining a tractor power of 4 MW. The necessary auxiliary power required is 1 MW, generated from a two cylinder engine with similar characteristics to the main. The engine is able to operate alternately with gaseous or liquid fuel, being able to switch from gaseous to liquid fuel automatically, interrupting the gas supply. When running on gaseous fuel the Otto cycle mixture is poor and ignition is assured with a micro-pilot diesel-oil injection. This minimal amount of diesel-oil consumed has been omitted in the consumption analysis.

When considering the diesel motor solution, this paper opts for an engine of similar characteristics where either HFO or LSMGO can be burnt. This is the case with the Wärtsilä 8L 32 (Wärtsilä 32, 2016), whose output of power, dimension and consumption is practically the same as its dual twin. The main difference, apart from the type of fuel that burns, is the investment which is usually around 50- 65% less than its equivalent in the dual version.

The adaptation of the marine industry to the new emission regulation for new ships means that the technical layout of engines and auxiliary equipment is diverse. The choice of certain equipment implies the possibility of using only one fuel range. This paper is analyzing four arrangements in total, the first for a dual engine with and without scrubber and the second for a diesel engine with its two variants, with or without scrubber. The omission of scrubber equipment (Abadie et al., 2017) implies the absence of exhaust gas scrubbing as far as sulphur is concerned. This provision therefore makes it impossible to use HFO in ECA areas. On the other hand, the installation of a dual engine makes it possible to burn LNG and, obviously, if this is the case sulphur gas washing is unnecessary as the sulphur content is below the permitted limits.

The use of Selective Catalytic Reduction technology (SCR) to reduce nitrogen oxides and diatomic Nitrogen in air/sea water by means of a catalytic converter such as urea is necessary since the combustion emission of HFO and/or LSMGO contain a percentage of NOx not permitted by IMO Tier III regulations. Even a dual engine running in Diesel mode, burning both HFO or LSMGO and LNG, must be equipped with SCR. The use of SCR gives flexibility for choosing the cheapest fuel. The paper focuses on the effects of the SOx regulation in a new vessel investment. However, the NOx emissions are also considered; we can see in Table 5 that the use of Selective Catalytic Reduction technology (SCR) is considered in all configurations, therefore its cost and effects are included in the analysis.

These configurations are set out in columns in Table 5, and for each provision, depending on whether the vessel is sailing in an ECA or non ECA zone, highlights the type of fuel that technically can be used. In addition, the cost of the investment for each of the four arrangements is tabulated and broken down according to the equipment required, engines, sulphur scrubber, SCR, pump system and LNG Storage. The paper analyses the optimal configuration with minimum cost (fuels + investment).

In the case of installing a dual engine two LNG storage tanks are mandatory, specifically two Wärtsilä 194 LNGPac™ tanks (LNGPac, 2010). The range of these tanks is 427 MWh enough to cover 170.8 hours at a consumption rate of 5MW, and sail 2,135 nautical miles, approximately seven days of navigation at an average speed of 12.5 knots. The HFO and LSMGO storage would be arranged above the line of tracing the bottom liner plates including the area of the bilge curve. This cubic capacity depends on the hull design and construction materials. The tanks reduce the cargo area causing lower benefits, but in our model the benefits are not part of the optimization process (we assume that these income are determinist). This paper is trying to analyze the performance of the engine investment cost towards the fuel consumption based on a Diesel and Dual Fuel technology.

The different equipment for each layout is connected by means of pipes, valves, pumps, boilers and heat exchangers. The simpler the drafting, the lower the investment cost. This fact can be observed in the pump system row of Table 5.

The chosen engine it is a medium low power one in the Wartsila´s medium speed dual fuel portfolio availability for electrical and mechanical propulsion applications. The most powerful one it is 18V50 DF with 15.5 MW and in the other end 6L20DF giving 1.1 MW. The chosen motor, Wärtsila 32, if mounted as main engine can give service as an anchor handling tug supply, platform supply vessel or a fishing vessel. It can also be mounted using more than one engine. This configuration can be used in the cruise, ferry and Ro-Pax and for small to medium sized tankers, bulk carriers and container vessels.

The investment costs presented in Table 5 are prices provided by professionals in the shipping industry (personal interview). According to the interview these figures must be noted as preliminary because they depend on the final “as built” installation. Note these costs do not include other elements such as steering or the propulsion train not necessary for the purpose of this paper. The expected life of a vessel is assumed to be 30 years.

Table 5 Engine power and costs of equipment

	Dual		Diesel	
	with Scrubber	without Scrubber	with Scrubber	without Scrubber
Engine Power (MW)	**5**	**5**	**5**	**5**
. Principal Engine (8 cylinders)	4	4	4	4
. Auxiliar Engine (2 cylinders)	1	1	1	1
Cost (million €)	**5.95**	**4.90**	**3.10**	**2.05**
. Engines	2.50	2.50	1.75	1.75
. Scrubber (SOx)	1.00	-	1.00	-
. SCR (NOx)	0.30	0.30	0.30	0.30
. Pump System	0.15	0.10	0.05	0.00
. LNG Storage	2.00	2.00	-	-
Annual navigation (hours)	7,200	7,200	7,200	7,200
Fuels				
. ECA	HFO 180, HFO 360, LNG	LNG, LSMGO	HFO 180, HFO 360	LSMGO

. Non ECA	HFO 180, HFO 360, LNG	HFO 180, HFO 360, LNG	HFO 180, HFO 360	HFO 180, HFO 360
Expected Life (years)	30	30	30	30

As mentioned above, the route of the vessel is already established. The route is Port Said, Algeciras and Bergen. Therefore, it is necessary to obtain the consumption of each engine in tonnes per nautical mile. According to the Wärtsilä engine technical catalogue (Wärtsilä 32, 2016; Wärtsilä 34, 2018) consumption depends on the engine load and of course on the state of the sea. So, the motor consumption rate assumed is an approximate average value of the possible motor load combinations according to technical tables.

The consumption obtained is based on the total power, 5MW, this includes the eight cylinders from the main engine and the two cylinders from auxiliary engines. It has also been assumed that the theoretical speed of the vessel is 12.5 knots. This value obviously depends on the shape of the hull, the type of propeller, and the state of the sea. In addition the lower calorific value has been used to determine the value of the LNG consumption. Table 6 shows the fuel consumption for the different engine options and different fuels in tonnes per nautical mile.

Table 6 Fuel consumption upon the engine in tonnes per nautical mile

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Type of engine		**Fuel**	**Consumption per cylinder**	**Total consumption (tonne/mile)**
Dual Engine	Gas Mode	LNG	7280 KJ/KWh	0.0564285
	Diesel Mode	HFO (180 - 360)	190 gr/KWh	0.0730769
		LSMGO	190 gr/KWh	0.0730769
Diesel Engine		HFO (180 - 360)	190 gr/KWh	0.0730769
		LSMGO	190 gr/KWh	0.0730769

The aim of determining the consumption rate is to calculate the total fuel consumption in the expected life of a vessel, which is thirty years.

5 Results

We consider a vessel that usually sails between Algeciras and Port-Said or between Algeciras and Bergen. The alternation of these routes is not fixed, there is a 50% probability of covering either route. This choice affects the decision about which fuel should be burned due to the sailed area, ECA or non-ECA. The actual regulated areas for these routes are shown in Table 1.

During the total useful life of the vessel fuel tanks must be filled in port with the cheapest fuel. The selected type of fuel depends on the engine fuel tolerance, the vessel´s configuration (with or without scrubber), fuel prices (cost dependant on future prices), and the characteristic of the next route (ECA, non ECA).

As a base case, we assume a 75% possibility of the Mediterranean Sea becoming an ECA in 2025 and the Atlantic European coast from Algeciras to the English Channel having a 50% of probability of becoming an ECA in 2030. After, we carry out a sensitivity analysis changing these probabilities from 0% to 100% in the same years.

First, we simulate 25,000 paths each one with 1,080 steps (30 years with 36 steps per year). Each trip has its composition in miles within ECA and non ECA areas. We also simulate 50,000 paths of 1,080 steps for each fuel. In all cases we use LNG and marine fuels (ULSFO, LSMGO, IFO180, IFO380) gap prices according to the correlations stated in Table 4. We use the methodology from (Abadie et al., 2017) for the four marine fuels and also a deseasonalized and discretized version of Equation 1 for LNG. To calculate the present value of the fuel´s cost we use a discount rate of 2.88% corresponding to the yield of US bonds to 30 years from 30/10/2017, the last year of the series[4].

This analysis reveals two situations of high flexibility shown in Table 7. Firstly, the case of powering the vessel with a Dual engine and a scrubber using the cheapest of the five fuels all over its lifecycle independent of navigating in an ECA or non ECA area. And secondly, the case of powering a Diesel engine

[4] http://www.treasury.gov.

with scrubber using the cheapest of the four marine fuels (ULSFO, LSMGO, IFO180, IFO380), and also independent in the navigation area. Note that in a non ECA area ULSFO and LSMGO will not be burnt because of its higher price. In case LNG is available in port, the first option is the best.

Table 7 Costs with Scrubber (Millions US$)

Dual with Scrubber Cost (millions US$)	25.62
. Expected Fuel Costs	19.67
. Investment Costs	5.95
Diesel with Scrubber Cost (millions US$)	34.45
. Expected Fuel Costs	31.35
. Investment Costs	3.10

In case we do not install a scrubber, the cost depends on the distribution probability of the ECA zones (see Table 8). In the case of a Dual engine without scrubber we can burn LNG, ULSFO or LSMGO in an ECA area. Note that LNG will be chosen almost always due to its price. In this case in a non ECA area we will choose the cheapest option which in most cases will be LNG, but in some cases also IFO380 can be chosen. The present value of the total cost depends on the probabilities of a non ECA area becoming an ECA in the future as figures in Table 8 show.

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In the case of powering a Diesel engine without scrubber the fuel options are ULSFO or LSMGO in an ECA and in a non ECA, IFO180, IFO380, ULSFO and LSMGO can be burnt. Note, that in this last case, IFO380 will be chosen in most cases.

Table 8 Total cost without scrubber (Millions US$)

Expected Fuel + Investment Costs (millions US$)						
Dual without Scrubber		**Mediterranean ECA Probability 2025**				
		0%	25%	50%	75%	100%
Atlantic ECA Probability 2030	0%	25.06	25.24	25.42	25.61	25.79
	25%	25.12	25.30	25.49	25.67	25.85
	50%	25.18	25.37	25.55	25.73	25.92
	75%	25.25	25.43	25.61	25.80	25.98
	100%	25.31	25.49	25.68	25.86	26.04
Diesel without Scrubber		**Mediterranean ECA Probability 2025**				
		0%	25%	50%	75%	100%
Atlantic ECA Probability 2030	0%	36.85	38.11	39.36	40.62	41.87
	25%	37.29	38.54	39.80	41.05	42.31
	50%	37.72	38.98	40.23	41.49	42.74
	75%	38.15	39.41	40.67	41.92	43.18

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	100%	38.59	39.84	41.10	42.36	43.61

Table 9 shows the optimal vessel configuration depending on the ECA and non ECA probabilities distribution. We can see that the dual engine is in all cases the optimum decision to power a new vessel with 30 years of useful life. When the probability of the Mediterranean Sea becoming an ECA is low the no scrubber solution can be a good option because its use will be smaller.

Table 9 Optimal configuration

Minimum Cost Technology		**Mediterranean ECA Probability 2025**				
		0%	25%	50%	75%	100%
Atlantic ECA Probability 2030	0%	Dual without Scrubber	Dual without Scrubber	Dual without Scrubber	Dual without Scrubber	Dual with Scrubber
	25%	Dual without Scrubber	Dual without Scrubber	Dual without Scrubber	Dual with Scrubber	Dual with Scrubber
	50%	Dual without Scrubber	Dual without Scrubber	Dual without Scrubber	Dual with Scrubber	Dual with Scrubber
	75%	Dual without Scrubber	Dual without Scrubber	Dual without Scrubber	Dual with Scrubber	Dual with Scrubber

100%	Dual without Scrubber	Dual without Scrubber	Dual with Scrubber	Dual with Scrubber	Dual with Scrubber

Fuel cost has an expected present value and there is a risk of it been increased. Table 10 shows the Expected Present Value of fuel cost and the 95th percentile of its distribution for the base case; the 75% probability of the Mediterranean Sea becoming an ECA in 2025 and the 50% probability of the Atlantic Coast becoming an ECA in 2030. The last column in Table 10 shows the average of the 5% of worst cases, the Expected Shortfall ES 95%.

Table 10 Expected fuel costs and risk measures in base case (millions US$)

Engine	Scrubber	Mean	95 percentile	ES(95%)
Dual	Yes	19.67	23.93	25.19
Dual	None	20.83	26.31	28.01
Diesel	Yes	31.35	36.50	38.20
Diesel	None	39.44	44.59	46.28

In Table 10 we present a risk profile of the four configurations, we include the expected present value used in the calculation of Tables 7-9 and also two risk measures for the expected fuels costs. The 95% percentile shows us a cost value that will be only exceeded in 5% of cases. The expected shortfall ES (95%) tell us the average of the worst cases when the 95 percentile is surpassed. For example, in the case of dual engine without scrubber, the expected cost is 20.83 million US$, but in an 5% of cases will be greater than 26.31 million US$, and when this happens the average of these cost will be 28.31 million US$.

This Table 10 allows us to analyse the risk profile of the four configurations.

We observe that the risk is much lower in the "Dual with Scrubber" configuration compared to the other cases. We also observe that in the 5% of the worst cases, the average fuel present value for the 5% worst case in the "Dual with Scrubber" configuration is 25.19 million US$.

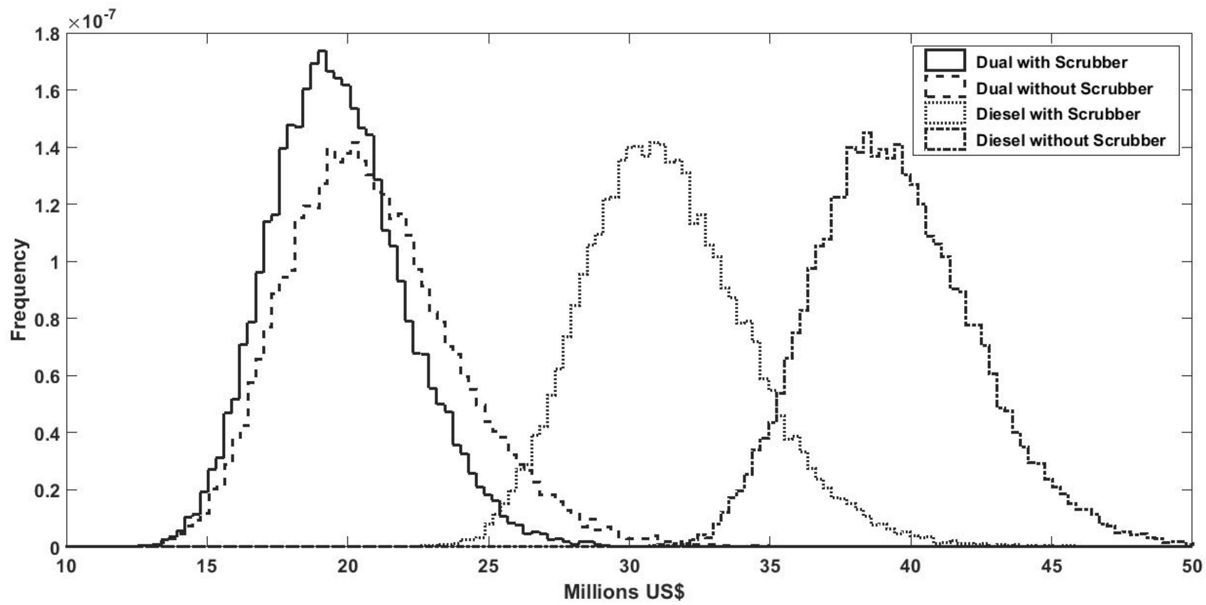

Figure 8 Risk Fuel Costs Profile Base Case.

Figure 8 illustrates the risk profile of the four configurations for the base case. We can observe that "Dual with Scrubber" is the least volatile. There are small differences in the base case between the present values of the two Dual configurations, but in this case we can see in Figure 8 that the Dual without Scrubber is more volatile, this reinforces the election of Dual engine with scrubber in this base case.

6 Conclusions

Optimal marine engine configuration and the decision about including a scrubber are significant choices when building a new vessel. Those factors determine the expected fuel cost which is an important item of variable cost. The least future fuel cost can be clearly obtained if a higher initial investment is assumed. This is the case choosing a more flexible engine and considering in some cases the installation of a scrubber. The sulphur regulation conditions importantly affect these configuration decisions.

This paper presents a stochastic model calibrated with market data that can be used for selecting the cheapest fuel in each sail under uncertainty fulfilling with SO_x and NO_x solutions. The model is applied for newly constructed vessels and four possible configurations are analysed; dual or diesel engines and the installation of a scrubber or not.

This model highlights the flexibility value and shows that a more flexible engine allows a wider range of fuel, permitting always to choose the cheapest. The configuration of a dual engine can be a good choice when building a new vessel of similar characteristics to those analysed assuming that LNG bunkering service exists at port. This configuration permits total flexibility in fuel selection. The case reveals that if in a short term future the probability of the Mediterranean Sea becoming an ECA is low the optimal configuration is a Dual engine without scrubber. But in our base case with a probability of 75% of the Mediterranean Sea becoming an ECA area in 2025 and also a probability that all the European Atlantic coast becomes an ECA area by 2030, we obtain a minimum of expected present value of investment and fuels cost of 25.62 million US$ with a Dual engine with scrubber configuration. Although the Dual engine is an optimal election, the decision of including scrubbers depend on the probabilities of the Mediterranean and Atlantic Sea becoming ECA areas in the future.

The work also presents risk measures corresponding to the expected net present value of the four configurations, the fuel prices volatility and its correlations.

In many cases the use of LNG can be a good method to fulfil the IMO Sulphur regulation in the present and in the future.

The present work can easily be adapted considering others sailing patterns, because the present value of marine fuels and LNG is approximately proportional to the day´s sailing. Also it is easily possible to analyse the effect of costs different from those used in Table 5, because the Tables 7 and 8 can easily be recalculated summing the differences between these costs.

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Appendix

A. The Stochastic Brent and Natural Gas Prices

In the real word, we have Equation (A.1) and (A.2) obtained from Equation 3 and 4 with a zero value for the market price of risk.

$$dG_t = df^G(t) + [k^G G^* - k^G(G_t - f^G(t))]dt + \sigma^G(G_t - f_G(t))dW_t^G. \quad \text{(A.1)}$$

$$dB_t = k^B(B^* - B_t)dt + \sigma^B B_t dW_t^B. \quad \text{(A.2)}$$

We can obtain the historic Brent crude oil volatility using Equation (A.3) which is equation A.2 discretezed.

$$\frac{B_{t+\Delta t} - B_t}{B_t} = -k^B \Delta t + k^B B^* \Delta t \frac{1}{B_t} + \sigma^B \sqrt{\Delta t}\,\varepsilon_t^B \quad \text{(A.3)}$$

Here, the volatility concept is distinct. In this model σ^B is the volatility of returns $\frac{B_{t+\Delta t}-B_t}{B_t}$ while in gap prices of marine fuel oil is the gap price´s volatility. The first one is related to the returns volatility and the later to price volatility.

Applying Equation (A.3) we can calculate the annualized Brent crude oil return volatility which is $\sigma^B = 0.380$.

To calculate the resting Brent crude oil stochastic processes´ parameters we use a different approach based on the Brent quotes of future market prices. This is the approach:

In the futures market (risk neutral world) the Brent crude oil price follows a different behaviour. This is due to the market price of risk must be discounted.

Abadie and Chamorro (2013) show the expected value in time *t* of the Brent crude oil under the equivalent martingale measure and it can be represented as Equation (A.4).

$$E^Q(B_t) = \frac{k^B B^*}{k^B+\lambda^B}(1-e^{-(k^B+\lambda^B)t}) + B_0 e^{-(k^B+\lambda^B)t} = B^{**}(1-e^{-(k^B+\lambda^B)t}) + B_0 e^{-(k^B+\lambda^B)t} \qquad \text{(A.4)}$$

Here, B^* is the long-term equilibrium value towards which B_t tends to revert in the long-term in the real word and $B^{**} = \frac{k^B B^*}{k^B+\lambda^B}$ is the equivalent value in the risk neutral world,

The numerical estimates of the relevant (composite) parameters using the last day all futures monthly contracts on natural gas with the Equation (A.4) appear in Table 2.

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With this procedure we can estimate for each day the deseasonalized front month futures price and witn these values we can estimate Equation (B.11)

$$\frac{(G_{t+\Delta t}-f^{G}(t+\Delta t))-(G_t-f^{G}(t))}{(G_t-f^{G}(t))}=-k^{G}\Delta t+k^{G}B^{*}\Delta t\frac{1}{(G_t-f^{G}(t))}+\sigma^{G}\sqrt{\Delta t}\,\varepsilon_t^{G} \qquad \text{(B.11)}$$

With this equation we obtain the volatility $\sigma^{G}=0.352$.

We can now calculate the correlations using the residual of the regressions. These results are shown in Table 4.

The correlation between the Brent crude oil return and the marine fuel gap prices is always negative, this is explained by the denominator of $\frac{B_{t+\Delta t}-B_t}{B_t}$. The correlations with the carbon return prices are very small and thus we assume zero correlation in this case.

B. List of abbreviations and nomenclature

Table B.1: List of Abbreviations

Abbreviation	Description
BAT	Best Available Technologies
ECAs	Emission Control Areas
EEDI	Energy Efficiency Design Index
EIA	Energy Information Administration
ES	Expected Shortfall
GHG	Green House Gas

HFO	Heavy Fuel Oil
ICS	International Chamber of Shipping
IMO	International Maritime Organization
LBG	Liquefied Bio Gas
LNG	Liquefied Natural Gas
LSMGO	Low Sulphur Marine Gas Oil.
MAP	Mediterranean Action Plan
MARPOL	International Convention for the Prevention of Pollution from Ships
MGO	Marine Gasoil
PM	Particulate Matter
REMPEC	Regional Marine Pollution Emergency Response Center
SCR	Catalytic Reduction Technology
SEEMP	Ship Energy Efficiency Management Plan
ULSFO	Low Sulphur Fuel OIL
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development

Table B.2: List of Nomenclature

Nomenclature	Description
M^i	Gap in price between marine fuel i and the Brent crude oil price B.
M^{*i}	Long-term equilibrium value towards which M^i tends to revert in the long-term.
k^i	Reversion speed gap price marine fuel i.
σ^i	Volatility gap price marine fuel i.
M_0^i	Initial Gap for marine fuel i.
G	Natural gas price.
B	Brent crude oil price.
G^*	Natural Gas long-term equilibrium price level.
B^*	Brent crude oil long-term equilibrium price level.
$f^G(t)$	Deterministic function that captures the effect of seasonality in gas prices.
φ	Angle in radians.

γ	Seasonal maximum value
k^G	Natural gas price speed of reversion.
k^B	Brent crude oil speed of reversion.
σ^G	Volatility natural gas price.
σ^B	Volatility Brent crude oil.
dW	Increment standard Wiener process.
ρ	Correlation.

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