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Fokkema, Jan Eise; Buijs, Paul; Vis, Iris F. A.

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An investment appraisal method to compare LNG-fueled and conventional vessels

Jan Eise Fokkema*, Paul Buijs, Iris F.A. Vis

University of Groningen, Faculty of Economics and Business, Department of Operations, P.O. Box 800, 9700 AV Groningen, The Netherlands

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ABSTRACT

Ever stricter emission regulations stimulate vessel owners to consider the adoption of alternative marine fuels, such as Liquefied Natural Gas (LNG). In deciding whether to invest in LNG-fueled vessels, initial investment and operating costs are decisive factors that have not yet been fully studied in the literature. In this paper, we present a new investment appraisal method to compare the costs of LNG-fueled vessels with conventional vessels. We analyze the fuel costs and overall exploitation costs by simulating bunker planning decisions under stochastic fuel prices, presence in emission controlled areas, and route lengths. Our analyses reveal that the fuel costs of LNG-fueled vessels are often lower than those of conventional vessels, even under unfavorable LNG prices. Due to the higher initial investment costs in LNG-fueled vessels, these fuel cost reductions do not always translate into lower overall exploitation costs. By conducting numerical experiments, we identified conditions under which the exploitation costs of LNG-fueled vessels are lower than conventional vessels.

1. Introduction

With more stringent vessel emission regulations executed by the International Maritime Organization (IMO), such as the Emission Control Areas (ECA) in the Baltic Sea and along the North American coast, vessel owners increasingly seek for cost-effective solutions to comply with those regulations (Wang & Notteboom, 2014). Conventional-fueled vessels can comply with ECA regulations by using expensive low sulfur fuels such as Marine Gas Oil (MGO) and/or by installing scrubbers. An interesting ECA-compliant alternative is using Liquefied Natural Gas (LNG) as a marine fuel. Many factors could hamper the adoption of LNG as a marine fuel, such as the lack of a clear regulatory frameworks for bunkering operations, the extra space needed for an LNG fuel tank, potential methane slip, and a limited LNG bunkering infrastructure (Wang & Notteboom, 2014). Nevertheless, the impact on the financial bottom line of the ship owner is often the deciding factor.

While, compared to conventional-fueled vessels, LNG-fueled vessels have a considerably higher initial investment cost due to more expensive equipment and extra engineering costs in the design phase, they also have the potential to considerably reduce fuel costs during the exploitation period (Wang & Notteboom, 2014). In this paper, we present a new investment appraisal method to study the relation between the higher initial investment costs and potentially lower fuel costs associated with LNG-fueled vessels. Our method uses an optimal bunker planning policy, takes fluctuating fuel prices into account and considers variable travel times in ECA. Below, we discuss each of these aspects in more detail.

Thus far, the literature on economic analyses of ECA-compliant alternative fuels has generally assumed that vessels utilize only one type of fuel, that is, either oil-fueled for conventional vessels or LNG for LNG-fueled vessels (Adachi et al., 2014; Burel et al.,

* Corresponding author at: P.O. Box 800, 9700 AV Groningen, The Netherlands.

E-mail addresses: J.e.fokkema@rug.nl (J. Eise Fokkema), p.buijs@rug.nl (P. Buijs), i.f.a.vis@rug.nl (I.F.A. Vis).

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2013; Cullinane and Bergqvist, 2014; Jiang et al., 2014). In practice, LNG-fueled vessels are usually powered by dual-fuel engines, where the crew can switch between any of the available fuel types during a trip. Since prior literature has not considered the option of using different fuels, bunker planning policies have not yet been incorporated in existing investment appraisal methods. Doing so is imperative, as the overall fuel costs are strongly depending on the bunker choices made.

Furthermore, prior studies have assumed fixed ECA presence in their economic analyses of different ECA-compliant alternatives. ECA presence is defined here as the operational time spent in ECA regions during a trip (Cullinane and Bergqvist, 2014). In practice, cargo vessels sail different routes in which their operational time in ECA is different for each trip. ECA presence levels affect the available fuel type options that can be employed. Heavy Fuel Oil (HFO), for instance, can only be used outside ECA regions. Consequently, ECA presence strongly affects fuel costs and evaluating the economic viability of different ECA-compliant alternatives requires incorporating variable ECA presence.

Lastly, extant literature has generally assumed deterministic fuel prices. Burel et al. (2013) and Adachi et al. (2014), for example, have used deterministic fuel prices in their economic analysis of LNG-fueled vessels. Jiang et al. (2014) consider changes in fuel prices over time, but assume deterministic price trends in evaluating different options to comply with ECA regulations. However, fuel prices not only change according to a known price trend, but also fluctuate from day to day. LNG fuel prices are particularly volatile compared to other fuels, because LNG does not have a stable international market yet (Acciaro, 2014b; Wang & Notteboom, 2014). Since fuel prices significantly affect fuel and operational costs in shipping (Holmgren et al., 2014), it is essential to include price volatility in investment appraisal methods for vessels.

The main contributions of this paper are threefold. Firstly, our proposed investment appraisal method extends deterministic fuel price scenarios from the literature with daily fuel price fluctuations to better estimate fuel costs. Secondly, we include bunker planning decisions in our investment appraisal method by simulating bunker planning decisions for many days over the full exploitation period of a vessel. The corresponding bunker planning model is used with different stochastic fuel price scenarios and various trip profiles. Thirdly, we integrate our analyses of fuel costs into an appraisal of the overall exploitation costs to determine the economic viability of LNG-fueled vessels. By running an extensive set of experiments, this study compares the exploitation costs of an LNG-fueled vessel with its conventional-fueled counterpart for a real-world case and derives generic insights about the conditions under which the exploitation costs of LNG-fueled vessels are lower than conventional-fueled vessels.

The remainder of this paper is structured as follows. Section 2 describes the problem setting in more detail. It also presents the formal definitions of decision variables and parameters, and explains the modelling assumptions that were made. Section 3 describes the investment appraisal method. Section 4 introduces the Dutch shipping company that provided data for the case experiments. This section also describes the numerical experiments and explains the stochastic fuel price scenarios considered in our study. An overview and discussion of the experimental results is included in Section 5. The paper is concluded in Section 6.

2. Problem description

The problem addressed in this paper concerns the decision to invest in a new build vessel either propelled by an LNG dual-fuel engine or a conventional fuel engine. We address this decision from an economic perspective, assessing differences in the overall exploitation cost for each type of propulsion, which consist of the cost of capital, overhead costs and fuel costs. We consider the discounted investment per month as cost of capital, with a higher cost for LNG dual-fuel propulsion. Monthly overhead costs, which consist of labor and maintenance costs, are considered equal for both propulsion types. The final component of the monthly exploitation costs concerns fuel costs, which can strongly differ between LNG dual-fuel and conventional fuel engines.

Estimating the additional investment required for LNG dual-fuel propulsion can be done rather precisely and is easily translated into a stable monthly cost of capital. Given the equal overhead costs for both propulsion types, the additional investment for an LNG engine can only be recovered by a lower fuel cost component. Actual fuel costs differ per trip, and depend on the length of the trip, fuel efficiency, the sailing time in emission controlled areas, which fuel—or fuels—the vessel sails on, and the prices of those fuels. Taking these factors as input, vessel operators aim to minimize the fuel costs of a trip by deciding how much of each fuel to bunker before departure.

Since bunker planning decisions strongly affect fuel costs, our appraisal method considers the underlying bunker planning problem. For any trip k , departing at day i , the objective of the problem is to minimize the total fuel costs by determining the amount of sailing time S_f on fuel type f . A vessel can bunker multiple fuel types before departure. Vessels with an LNG dual-fuel engine can bunker LNG ($f = 1$), MGO ($f = 2$) or HFO ($f = 3$); conventional-fueled vessels can only bunker MGO and HFO. Each trip is specified by a total travel time T^{total} and a time in emission controlled areas T^{ECA} . Each fuel type f is associated with a different fuel consumption rate U_f due to differences in calorific contents of the fuels. The maximum travel time T_f^{max} on fuel type f is restricted due to fuel tank capacities. The underlying bunker planning problem can be modelled as follows:

$$\min \sum_{f \in F} S_f U_f P_f \quad (1)$$

subject to:

$$S_f \leq T_f^{max}, \forall f \in F \quad (2)$$

$$T^{ECA} \leq S_1 + S_2 \quad (3)$$

Table 1

An overview of the variables and parameters addressed in our problem.

Parameters	
U_f	Fuel consumption (in metric ton per hour) using fuel type $f \in F$
T_f^{max}	Maximum travel time (in hours) of fuel type $f \in F$
T_k^{total}	Total travel time (in hours) of trip $k \in K$
T_k^{ECA}	Travel time in ECA (in hours) of trip $k \in K$, where $T_k^{ECA} = E_k T_k^{total}$
P_{fi}	Fuel price (in dollars per metric ton) of fuel type $f \in F$ on departure day $i \in I$, where $P_{fi} = P_{fi}^{base} + D_{fi}$
E_k	ECA presence (in percentage) of trip
P_{fi}^{base}	Fuel base price (in dollars per metric ton) of fuel type $f \in F$ on day $i \in I$
D_{fi}	Fuel price deviation (in dollars per metric ton) of fuel type $f \in F$ on day $i \in I$
R_f^D	Probability distribution for price deviation D_{fi} for fuel type $f \in F$ on day $i \in I$
R^T	Probability distribution for total travel time T_k^{total} for trip k
R^E	Probability distribution for ECA presence E_k for trip k
Variables	
S_{fki}	Sailing time (in hours) on fuel type f for trip k departing at day i

$$\sum_{f \in F} S_f = T^{total} \quad (4)$$

The objective function (1) minimizes the total fuel cost per trip. Constraints (2) enforces that sailing times on a fuel type cannot exceed the maximum travel time. Constraints (3) imposes that only LNG and MGO can be utilized within emission controlled areas. Constraints (4) makes sure that the sum of fuel specific sailing times equals the total travel time of a trip.

Above, we formulated the bunker planning decisions as a deterministic problem. However, both fuel consumption levels and fuel price differences may strongly differ throughout the lifetime of a vessel. Our investment appraisal method is designed specifically to address these uncertainties, for which we introduce a few additional parameters. For each fuel type f , we consider a linear price trend, resulting in a base price P_{fi}^{base} on a given day i . To express the stochastic behavior of fuel prices, we draw a daily price deviation D_{fi} from a probability distribution R_f^D to compute the fuel price P_{fi} . Since we assess monthly exploitation costs, we compute monthly fuel costs. The characteristics of a trip, in terms of its total length and ECA presence, will likely differ from trip to trip. Therefore, we obtain the length of a trip T_k^{total} from a probability distribution R^T and the proportion of travel time within emission controlled areas E_k from a probability distribution R^E . An overview of all variables and parameters is given in Table 1.

We make the following assumptions:

- It is assumed that vessel operators always attempt to minimize total fuel costs by making bunker planning decisions before the departure of a specific trip.
- For each fuel type f , the different fuel consumption rates U_f are considered known and constant. We perform a numerical validation to study the fuel cost behavior as a result of different consumption rates for the same fuel.
- Fuel bunker quantities are assumed to precisely cover fuel consumption needed for a trip. Hence, we do not consider leftover fuel from previous trips.
- We assume all fuel bunkers are bought at spot prices, which are not subjected to local price differences. Bunkering at spot prices is a common practice in the maritime transportation sector (Ghosh et al., 2015; Plum et al., 2014).

3. Investment appraisal method

Our investment appraisal method assesses differences in the overall exploitation cost for new build vessels with either LNG dual-fuel or conventional fuel propulsion. The method works with a fixed monthly cost of capital, which is higher for LNG dual-fuel than for conventional fuel propulsion, and a fixed monthly overhead cost, which is equal for both propulsion types. Determining the expected average fuel costs per month for both propulsion types is the main element of our method and computed by means of a simulation model.

The simulation model is implemented in Visual Basic for Applications (VBA) for Excel, according to the logic flow diagram presented in Fig. 1, using Xpress optimization software to find optimal bunker planning decisions for specific trips. To address the stochastic behavior of fuel prices and trip characteristics, the model iteratively calculates an optimal bunker planning for a large number of trips and days.

The simulation model is initiated with parameter values $n = 0$, $i = 0$ and $k = 0$. In each new iteration ($n = n + 1$), a new day ($i = i + 1$) is created with base prices P_{fi}^{base} for each fuel type. The “actual” fuel prices P_{fin} for that day are calculated by drawing a price deviation D_{fin} from probability distribution R_f^D and adding that deviation up to the base price. This represents the fuel prices, in dollars per metric ton, to be paid at the day of departure. Subsequently, a new trip ($k = k + 1$) is created by drawing a total travel time T_k^{total} from probability distribution R^T and a percentage of ECA presence E_k from probability distribution R^E . For that specific trip, an optimal bunker planning is found according to objective function (1), which enables calculating the fuel costs per hour for

Fig. 1. Logic flow diagram for the simulation model.

that trip.

For each day in the simulation, the mean fuel costs per hour are computed by considering multiple trips with different travel times and ECA presence. Since the input values are independent and randomly distributed, the mean fuel costs will converge. Using the confidence interval method (Law, 2014), a new trip is created as long as the estimated error from the real mean (ϵ) is larger than, or equal to 5% with a 95% confidence interval. For each day i , the simulation keeps creating new trips, computing optimal bunker planning decisions and updating the mean fuel costs per hour until the estimated error $\epsilon < 0.05$. Then, the mean fuel costs per hour are recorded for that day.

The simulation model repeats creating new days for the full length of the exploitation period, i.e., as long as $i < |I|$. When the end of the exploitation period is reached, the mean fuel costs per hour are calculated for iteration n . New iterations are started as long as the estimated error from the real mean is larger than, or equal to 5% and n is smaller than 30 iterations. Finally, the mean fuel costs per hour are obtained for all performed iterations for both LNG dual-fuel and conventional fuel propulsion. These values serve as the final hourly fuel costs, which are used as a component of the overall investment appraisal.

Table 2
Monthly exploitation costs without fuel costs.

	LNG dual-fuel	Conventional fuel
Monthly annuity on investment (3% interest)	€140.000	€110.000
Monthly overhead costs	€110.000	€110.000
Overall exploitation costs (without fuel)	€250.000	€220.000

4. Experiment definitions

This section provides an overview of the experiments we conducted in our study. Firstly, we present the case experiments in which we apply our investment appraisal method to a practical setting. Secondly, we execute experiments aimed at numerically validating our method and deriving generic insights on the behavior of fuel and overall exploitation costs under conditions that are different from the case setting.

4.1. Case experiments

For the case experiments, we obtained data from a Dutch shipping company that is active in the short-sea shipping sector. It primarily operates in the North Sea, Baltic Sea, Bay of Biscay and the Mediterranean Sea. At the start of our study, this shipping company had plans for the development of a new dry cargo vessel of roughly 13.000 dead weight ton and considered equipping it with either LNG dual-fuel or conventional fuel propulsion. The main engine should deliver around 3000 kW output, 1800 kW in service condition and the vessel should have a maximum speed of 13 knots. Vessel specifications were drawn up for both configurations, which indicated a 30% higher initial investment required for LNG dual-fuel propulsion. The shipping company expected similar overhead costs for both configurations. Table 2 shows the expected monthly exploitation costs (without fuel costs) for the LNG dual-fuel and conventional fuel configuration.

We also obtained data about the total travel times and time in ECA for over 200 trips of 13 vessels, mainly operating in the North sea, Baltic region and Mediterranean. These trips had a profile similar to that of the planned new build vessel, with a mean total travel time of 202.32 h and a standard deviation of 109.1. The trip data were fitted to probability distributions to enable the creation of many trips in the simulation model. Since Gamma distributions are commonly used in simulation studies for task completion times (Robinson, 2004), and because this distribution showed a good fit with the original total travel time data, R^T is given by a Gamma distribution with parameters $\alpha = 3.2839$, $\beta = 62.166$). Data on ECA presence E_k could not be fitted to a common probability distribution function due to a large occurrence of the values zero and one, i.e., trips that were either executed totally outside or totally within ECA. Therefore, we assigned probabilities to the occurrence of zero ($p = 0.266$) and one ($p = 0.297$) to express R^E ; while all values in between (with $p = 0.437$) fitted a normal distribution ($\mu = 0.247$, $\sigma^2 = 0.373$).

Fuel consumption and maximum travel time for the different fuels were computed according to several reports (U.S. Department of Energy, 2005; Confidential Lab report of Dutch shipping company; Wild Ingenieurbüro, 2005) and discussions with the employees of the Dutch shipping company. Fuel consumption for HFO provided the basis for determining the MGO and LNG consumption, which were derived using differences in calorific energy contents of the three fuel types. Maximum travel times are based on fuel tank capacities common for short-sea dry cargo shipping. An overview of the data used for our fuel consumption and maximum travel time calculations is shown in Table 3.

4.2. Price scenarios

In order to demonstrate the applicability of our investment appraisal method, we conduct experiments with five different price scenarios. The first price scenario is the most realistic one, and is based on an industry report (Deloitte, 2015) and fuel price projections by Acciaro (2014a). The remaining four scenarios represent different “What if” scenarios, which enable exploring several other future fuel price developments based on questions raised by practitioners during discussions of initial versions of our method. Each scenario is defined by linear price developments for the three fuel types over the full exploitation period of the new build vessel, i.e., defining P_{fi}^{base} for any given day in the simulation. The five scenarios (see Fig. A1 in the Appendix) are:

Table 3
Values used for fuel consumption and maximum travel time calculations.

	HFO	MGO	LNG
Fuel consumption U_f (metric ton per hour)	0.333	0.326	0.284
Maximum travel time T_f^{max} (in hours)	1229.4	525.3	1515
Calorific energy contents (MBTU per metric ton)	39.49	40.44	46.41
Fuel tank capacity (in m ³)	500	190	750
Density (in kg per m ³)	1010	900	465

- “Realistic” scenario: Fuel prices for HFO and MGO increase considerably while the price increase for LNG prices remains relatively limited (see Fig. A1a). This scenario reflects the common belief that oil prices will increase due to shrinking oil reserves while LNG prices remain stable due to ample natural gas reserves.
- Scenario “What if 1”: A low HFO price. Fuel prices for LNG and MGO are the same as in the “Realistic” scenario, while the price for HFO increases proportional to the price for LNG (see Fig. A1b). Compared to the “Realistic” scenario, this scenario reflects the expectation that more stringent ECA regulations will reduce the demand for—and hence the price of—HFO.
- Scenario “What if 2”: Proportional fuel price increases. All fuel prices increase proportional to that of LNG. Hence, the fuel price for LNG is the same as in previous scenarios, while both HFO and MGO increase proportionally (see Fig. A1c). This scenario reflects the expectation that the price of all marine fuels (including LNG) will be linked to crude oil prices in the future.
- Scenario “What if 3” High LNG price. Fuel prices for HFO and MGO are the same as in “Realistic” scenario, while the price for LNG increases sharply (see Fig. A1d). This reflects the expectation that LNG prices will increase rapidly due to an increasing demand and adoption of LNG.
- Scenario “What if 4” High fuel prices. Fuel prices for HFO and MGO increase sharply (and proportionally), while the price for LNG also increases (at a similar level as HFO). MGO remains the most expensive fuel (see Fig. A1e). This scenario reflects the expectation that all marine fuel types will increase relatively sharply due to societal pressure and corresponding (fiscal) actions from regulators.

Our investment appraisal method takes daily fuel price volatility into account. To this end, we analyzed historical fuel price data to determine daily deviations from (linear) price trends for each fuel. First, linear price trends were determined using ordinary least squares (OLS) regression modeling. We have chosen OLS because simple regression models have shown to be able to outperform complex volatility forecasting models in estimating price volatility (Brailsford and Faff, 1996). For HFO and MGO, fuel price trends were based on historical spot market prices in the Port of Rotterdam (Bunkerindex, 2015) in the period January 2009 to September 2012. For LNG, we used US-Henry Hub spot market prices (IEA, 2015) in the period December 2005 to May 2015.

Next, daily deviations from the regression lines were analyzed to determine probability distribution functions for R_f^D . These daily deviations were obtained and filtered by removing time intervals larger than one day because equally spaced intervals and removal of discontinuities facilitate time series analysis (Brockwell and Davis, 2013; Eckner, 2014). The historical data of daily price deviations for HFO could not be fitted to any theoretical probability function. Therefore, an empirical distribution was developed, in which input data was generated by selecting randomly from a pool of historical price deviations (Law, 2014). The MGO and LNG price deviations showed a good fit with a Beta distribution ($\alpha = 12.5$, $\beta = 3.9$, with a range between -420.1 and 129.8) and Dagum distribution ($p = 0.7$, $\alpha = 5.7$, $\beta = 4.5$, and $\gamma = -4.1$, where γ corrects for negative values in the original data), respectively. A statistically significant fit was confirmed using the Kolmogorov-Smirnov test, with $p = 0.64$ for the Beta and $p = 0.23$ for the Dagum distribution. These empirical and theoretical distribution functions are used to create values for D_{fin} during the experiments.

4.3. Numerical experiments

In addition to the case experiments, we performed experiments to numerically validate the proposed investment appraisal method and derive generic insights on the behavior of fuel and overall exploitation costs. Specifically, we examine the effects of daily price volatility, total travel times, fuel consumption levels and ECA presence on the expected monthly exploitation costs. Below, we introduce the experimental setup for studying each of these factors. An overview of all experiments is given in Table 4.

To study the effects of daily fuel price volatility, we ran experiments with a similar setup as the case experiments, but now with deterministic instead of stochastic fuel prices, hence where $P_{fin} = P_{fi}^{base}$ for each fuel type f and each day i . By conducting these experiments, we can assess the extent to which fuel price volatility is affecting the investment decision.

To study the effect of total travel time of trips, we ran experiments with a probability distribution R^T for total travel times. Specifically, the mean of the Gamma used in the case experiments was multiplied by two. Trips longer than 340 h were removed to prevent violation of fuel tank capacities for high fuel consumption levels and conventional vessels that sail fully in ECA and cannot use HFO.

To study the effect of fuel consumption levels, we ran experiments with different combinations of MGO and HFO fuel consumption levels relative to LNG fuel consumption. The fuel consumption levels considered in the case experiments are based on discussions with experts from the shipping company. As these figures are uncertain due to a variety of factors, we numerically test the outcomes with different consumption levels. Specifically, we ran 25 experiments in which we let the values for U_f range from 0.1 to 0.5 with steps of 0.1 for both LNG and conventional fuels, where fuel consumption levels of MGO and HFO are coupled. These experiments are repeated for each price scenario. Running these experiments enables finding the maximum LNG fuel consumption level for which the monthly exploitation costs of the LNG dual-fuel configuration remain below the conventional-fuel configuration.

To study the effect of ECA presence, we ran experiments where we change the percentage of travel time of a trip in ECA. To this end, we use deterministic total travel times, while step-wise increasing the values for ECA presence from 0 to 100% in steps of 20 percentage points. We do this for both shorter ($T_k^{total} = 250$) and longer trips ($T_k^{total} = 500$). In these experiments, the total travel time T_k^{total} is kept smaller than the MGO fuel capacity limit to ensure that this limit is not exceeded for conventional vessels that sail fully in ECA. These experiments aim to reveal if a certain ECA presence is required to render LNG dual-fuel propulsion economically viable.

The experiments for each of these factors are conducted for all five price scenarios. Including the case experiments, we ran 190 experiments on desktop PCs with Windows 7 and an Intel Core i5 processor. Computation times per experiment were 24 hours for each experiment for the “Case experiments”, “Total travel time” and “Fuel consumption levels” (see Table 4). The remaining experiments needed 1 to 2 hours per experiment.

Table 4
An overview of the experimental setup.

	Number of experiments	Price deviations (D_R)	Total travel time (T_k^{total})	Fuel consumption per hour (U_f)	ECA presence (E_k)
Case experiments	5	$R_1^D = D(5.7, 4.5, 0.7)$ $R_2^D = Be(5.7, 4.5, 0.7)$ R_3^D : Bootstrap	$R^T = \Gamma(3.28, 62.17)$ capped at 340	$U_1 = 0.333$ $U_2 = 0.326$ $U_3 = 0.284$	$R^E = \begin{cases} E_k = 0, \text{with } p = 0.266, \\ E_k = 1, \text{with } p = 0.297, \\ E_k \sim N(0.247, 0.373), \\ \text{with } p = 0.437 0 < E_k < 1 \end{cases}$
Daily fuel price volatility	5	Deterministic fuel prices	$R^T = \Gamma(3.28, 62.17)$ capped at 340	$U_1 = 0.333$ $U_2 = 0.326$ $U_3 = 0.284$	$R^E = \begin{cases} E_k = 0, \text{with } p = 0.266, \\ E_k = 1, \text{with } p = 0.297, \\ E_k \sim N(0.247, 0.373), \\ \text{with } p = 0.437 0 < E_k < 1 \end{cases}$
Total travel time	5	$R_1^D = D(5.7, 4.5, 0.7)$ $R_2^D = Be(5.7, 4.5, 0.7)$ R_3^D : Bootstrap	$R^T = \Gamma(6.56, 62.17)$ capped at 340	$U_1 = 0.333$ $U_2 = 0.326$ $U_3 = 0.284$	$R^E = \begin{cases} E_k = 0, \text{with } p = 0.266, \\ E_k = 1, \text{with } p = 0.297, \\ E_k \sim N(0.247, 0.373), \\ \text{with } p = 0.437 0 < E_k < 1 \end{cases}$
Fuel consumption levels	125	$R_1^D = D(5.7, 4.5, 0.7)$ $R_2^D = Be(5.7, 4.5, 0.7)$ R_3^D : Bootstrap	$R^T = \Gamma(3.28, 62.17)$ capped at 340	All combinations of U_f with steps of 0.1. U_1 from 0.1 to 0.5 U_2 and U_3 coupled from 0.1 to 0.5	$R^E = \begin{cases} E_k = 0, \text{with } p = 0.266, \\ E_k = 1, \text{with } p = 0.297, \\ E_k \sim N(0.247, 0.373), \\ \text{with } p = 0.437 0 < E_k < 1 \end{cases}$
ECA presence	50	$R_1^D = D(5.7, 4.5, 0.7)$ $R_2^D = Be(5.7, 4.5, 0.7)$ R_3^D : Bootstrap	$T_k^{total} = 250$ $T_k^{total} = 500$ $T_k^{total} < T_2^{max}$	$U_1 = 0.333$ $U_2 = 0.326$ $U_3 = 0.284$	Deterministic ranging from 0 to 100% with steps of 20 percentage point

5. Results and discussion

In this section, we present and discuss the results of the experiments. These results indicate how the exploitation costs for both types of vessels behave in response to the experimental factors and feed into a discussion about the conditions under which the exploitation costs of the LNG dual-fuel configuration are lower than the conventional configuration.

5.1. Case results

For the case experiments, we consider a specific trip profile to study the behavior of exploitation costs for both types of configurations. This enables examining whether the higher initial investment costs of the LNG dual-fuel configuration can be recovered by the potentially lower fuel costs.

The case results show that the fuel costs for the LNG dual-fuel configuration are lower than the conventional configuration for all price scenarios considered (See Fig. 2). Even when LNG prices end up considerably above than MGO and HFO (i.e., “What if 3”), fuel costs for the LNG dual-fuel configuration are 4% lower than conventional vessels. This somewhat counterintuitive outcome can be attributed to the fact that vessels with the LNG dual-fuel configuration simply have an additional fuel to choose from. Due to the stochastic nature of the fuel prices, the LNG dual-fuel configuration can save fuel cost every time the LNG fuel price drops below that of MGO or HFO. For the other price scenarios, fuel cost reductions are much higher, ranging from 24% up to 47%.

For the LNG dual-fuel configuration to be economically viable, the fuel cost reductions should outweigh the additional initial investment costs. This is reflected in our analyses of the overall exploitation costs (see Fig. 3). These reveal that LNG-fueled vessels are more cost-effective than conventional vessels for price scenarios where LNG prices are similar to, or remain below, HFO prices, as long as MGO prices remain the highest. These price developments are reflected in price scenarios “Realistic”, “What if 1” and “What if 4”. This implies that the additional initial investment costs of LNG-fueled vessels can even be recovered when the price for LNG rises above that of HFO, as long as the price for MGO remains—considerably—above that of LNG (e.g. price scenarios “What if 1” and “What if 4”). This can be attributed to the ECA regulations, which render conventional vessels more expensive because they have to sail on MGO within ECA.

For the other two what-if scenarios, the fuel cost reductions do not fully recover the additional investment required for the LNG dual-fuel configuration. These scenarios reflect the case where the current prices for MGO, LNG and HFO would keep increasing proportionally, with a price for LNG in between the price for MGO and HFO (i.e., “What if 2”), or where the LNG price rises sharply above the price for MGO and HFO (i.e., “What if 3”).

5.2. Numerical results

In this section, we discuss the behavior of exploitation costs for both fuel configurations and study the wider applicability of our investment appraisal method. To this end, we consider settings that are different from the case experiments by changing the values (or probability distributions) of the fuel prices, route profiles, fuel consumption levels and ECA presence.

Fig. 2. Mean fuel costs per hour.

Fig. 3. Average monthly exploitation costs.

5.2.1. Daily fuel price volatility

Our experiments show that considering deterministic prices only slightly affects fuel and exploitation costs compared to stochastic prices (as can be seen in Table 5). It is noteworthy that fuel costs for the LNG dual-fuel configuration appear to be somewhat higher for deterministic prices when there is a relatively large price spread between LNG and MGO, while HFO is the cheapest fuel (i.e., scenario “What if 1” and “What if 2”). Overall, we conclude that using either stochastic or deterministic fuel prices yield very similar results. This implies that, in the long run, price volatility has little impact on the decision to invest in LNG-fueled vessels.

5.2.2. Total travel time

Our numerical results for experiments with a different route profile suggest that a different mean for the distribution R^T , which determines the length of trips, has little impact on the investment appraisal of LNG-fueled vessels. This change did not affect the mean fuel costs per hour for either of the two configurations (see Table 6).

Table 5
Mean fuel costs per hour for stochastic and deterministic fuel prices.

	LNG			Conventional		
	Stochastic prices	Deterministic prices	% Change	Stochastic prices	Deterministic prices	% Change
Realistic	€107.54	€107.54	0.00%	€201.09	€201.09	0.00%
What if 1	€102.72	€104.51	1.75%	€167.18	€167.09	−0.06%
What if 2	€102.51	€104.51	1.96%	€135.14	€134.35	−0.58%
What if 3	€192.50	€193.95	0.76%	€201.09	€200.70	−0.20%
What if 4	€156.92	€156.92	0.00%	€215.07	€215.07	0.00%

Table 6
Mean fuel costs per hour for different Gamma distribution parameters for R^T .

	LNG			Conventional		
	$\alpha = 3.2839$ $\beta = 62.166$ $\mu = 0.053$	$\alpha = 6.5678$ $\beta = 62.166$ $\mu = 0.106$	% Change	$\alpha = 3.2839$ $\beta = 62.166$ $\mu = 0.053$	$\alpha = 6.5678$ $\beta = 62.166$ $\mu = 0.106$	% Change
Realistic	€107.54	€107.54	0%	€201.09	€201.09	0%
What if 1	€102.72	€102.72	0%	€167.18	€167.18	0%
What if 2	€102.51	€102.51	0%	€135.14	€135.14	0%
What if 3	€192.50	€192.50	0%	€201.09	€201.09	0%
What if 4	€156.92	€156.92	0%	€215.07	€215.07	0%

5.2.3. Fuel consumption levels

Our analyses of different fuel consumption levels show the maximum allowed LNG consumption level, compared to a certain level of HFO and MGO consumption, before the LNG dual-fuel configuration becomes more expensive than a conventional configuration.

For fixed levels of HFO and MGO consumption, it was found that the overall exploitation costs increase and become constant when LNG consumption levels increase (see Fig. 4). This behavior can be explained by the fact that the optimal bunker planning chooses for HFO or MGO when LNG consumption levels are relatively high. In those cases, potentially higher HFO and MGO prices are offset by a large LNG fuel consumption. When LNG consumption becomes large ($U_2 \rightarrow 0.5$), the difference in exploitation costs between LNG-fueled and conventional vessels approaches the difference in monthly exploitation costs without fuel cost (i.e., €30,000) as can be seen in Fig. 4 for MGO and HFO consumption levels of 0.1 and 0.2. A similar pattern is found for the other price scenarios.

Our results indicate that the maximum allowed LNG consumption level increases for higher levels HFO and MGO consumption levels in all experiments (see Table 7). This suggests that LNG vessels are more economically viable than conventional vessels at higher fuel consumption levels of all fuel types. For example, LNG consumption can only be 10% above HFO and MGO consumption levels for low HFO and MGO consumption levels ($U_2 = U_3 = 0.2$) for scenario “Realistic”. However, LNG fuel consumption can be 45% above MGO and HFO consumption for high MGO and HFO consumption levels (see Table 7, $U_2 = U_3 = 0.4$). This was pattern was observed in all experiments.

Lastly, our method does not appear to be very sensitive to the estimated LNG fuel consumption level in the case experiments. In the “Realistic” price scenario, LNG consumption levels can be 33% above those of HFO and MGO before the overall exploitation costs of the LNG dual-fuel configuration become higher than the conventional configuration, when considering HFO and MGO consumption levels very similar to the case experiments ($U_2 = U_3 = 0.3$)

5.2.4. ECA presence

The results from the experiments with different percentages of ECA presence (ranging between 0 and 100% in steps of 20 percentage point), enable identifying the ECA presence at which the LNG dual-fuel configuration is more economically feasible than a conventional configuration.

The results indicate that LNG-fueled vessels are already economically beneficial, compared to conventional configurations, for very low ECA presence (0–30%) when LNG price trends remain much below the MGO price trend (i.e., the “Realistic”, “What if 1” and “What if 4” scenarios). Furthermore, the exploitation costs of LNG-fueled vessels react less strongly to differences in ECA presence than conventional vessels for all experiments conducted (e.g. scenario “Realistic”, see Fig. 5). This indicates that higher ECA presence favors LNG-fueled vessels, which confirms the findings of Wang and Notteboom (2014) and Burel et al. (2013). It also suggests that LNG-fueled vessels offer more stable exploitation cost under variable route profiles. Less strong reactions of LNG-fueled vessels to

Fig. 4. Monthly exploitation costs in “Realistic” scenario for different levels of LNG consumption relative to a fixed HFO and MGO consumption ($U_3 = U_2 = 0.2$).

Table 7

Approximated maximum LNG consumption for a given level of HFO and MGO consumption (in metric ton per hour).

HFO and MGO consumption (U_2 and U_3)	Realistic	What if 1	What if 2	What if 3	What if 4
0.2	0.22	0.17	0.11	0.12	0.15
0.3	0.40	0.34	0.22	0.18	0.29
0.4	0.58	0.69	0.34	0.27	0.41
0.5	N.A.	N.A.	0.47	0.35	0.54

Fig. 5. ECA presence and exploitation costs for scenario “Realistic” ($T_{ki}^{Total} = 250$).

ECA presence can be explained by a lower dependence on MGO prices when sailing in ECA zones.

A relatively high minimum ECA presence of 68% is required for price scenario “What if 2”. This implies that a relatively large ECA presence is needed for price spreads which reflect the fuel prices at the time of writing. When the LNG price increases (much) beyond the price for MGO and HFO (i.e., scenario “What if 3”), even 100% ECA presence would not be sufficient for LNG-fueled vessels to have lower exploitation costs than conventional vessels.

6. Conclusion

More stringent emission regulations stimulate vessel owners to consider the adoption of cleaner, alternative fuels, such as LNG. In this paper, we presented a new investment appraisal method to support vessel owners in their decision to invest in LNG-fueled vessels. We use this method to analyze the fuel costs and overall exploitation costs of LNG-fueled and conventional vessels by simulating bunker planning practices under stochastic fuel prices, ECA presence and route lengths. Moreover, we consider a broad range of future price developments for different marine fuels.

The results presented in this paper delineate the conditions under which LNG-fueled vessels have lower overall exploitation costs than their conventional counterparts. Firstly, the fuel costs of LNG-fueled vessels are lower than conventional vessels for all price scenarios considered in this study—even for the scenario where the fuel price for LNG grows considerably above the price of conventional fuels. To be economically viable, however, these lower fuel costs need to outweigh the additional initial investment associated with LNG-fueled vessels. Our analyses show that this is the case as long as the price for MGO stays considerably above that of LNG, regardless of the price for HFO. Secondly, the exploitation costs of LNG-fueled vessels are lower for larger fuel consumption levels of all fuel types. Finally, LNG-fueled vessels are more competitive at higher levels of ECA presence relative to conventional vessels, but in a realistic price scenario also a low ECA presence would already result in lower overall exploitation costs. The exploitation costs of conventional vessels react more strongly to changes in ECA presence than LNG-fueled vessels, which results in more stable costs for LNG-fueled vessels under variable route profiles.

We have also shown the broader applicability of our method and its outcomes by conducting a series of numerical analyses. These indicate that the results of our method remain unaffected by different route lengths and apply to a large range of route profiles. Our numerical study also suggests that price volatility does not notably affect the outcomes of our method. Marginal exploitation costs of LNG-fueled vessels decline for higher levels of LNG consumption when MGO and HFO consumption is low due to bunker choices that favor HFO or MGO. Lastly, it was found that our method is not very sensitive to fuel consumption levels, indicating that a mistake in the LNG fuel consumption estimation provided by the engine producer would not directly affect the outcomes.

Investment appraisal methods are prone to limitations, and ours forms no exception. Firstly, the results in this paper only apply when vessel operators seek to optimize their bunker planning decisions for every single trip. Indeed, bunker planning policies become particularly important when sailing with an LNG dual-fuel configuration as the economic benefits of this configuration mainly stem from having an additional, potentially cheaper, fuel to choose from. Secondly, our method determines the average expected monthly exploitation costs as a measure to compare LNG-fueled with conventional vessels. Yet, the economic benefits of LNG-fueled vessels are not evenly distributed over

the exploitation period. Depending on future price developments, fuel cost reductions may emerge only later and it is likely that some of the required extra initial investment must be born at the start of the exploitation period. Future work could expand our method to include cash flow differences during the exploitation period of the vessel. Thirdly, our study does not include lost revenue that stems from a reduced cargo space due to extra fuel tanks. Therefore, future research could investigate the extent to which reduced cargo space influences the economic viability of LNG-fueled vessels. Future work may also incorporate the effect of a limited LNG bunkering infrastructure on the economic feasibility of LNG-fueled vessels to further examine the nuances associated with the decision to adopt LNG as a marine fuel.

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Appendix A

See Fig. A1.

Fig. A1. Price scenarios $k \in K$.

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