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LIFE-CYCLE COST ANALYSIS ON A MARINE ENGINE INNOVATION FOR RETROFIT: A COMPARATIVE STUDY

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ABSTRACT

Stricter regulations and ambitious targets regarding air emissions from ships have led the shipping industry to a tipping point necessitating disruptive technologies for green and ecological operation. This study introduces a dual-fuel engine innovation with high energy conversion efficiency, thereby reducing exhaust gas emissions. However, the total cost performance of such an innovation throughout its long lifespan can be a matter of concern for decision makers (i.e. ship owners) if they decide to retrofit their existing fleet. The purpose of this study is to provide insights into the economic performance of such an innovative dual-fuel engine when it is utilized as the main propulsion system. From a cradle-to-grave perspective ranging from construction, operation, maintenance to end-of-life, the life-cycle costing (LCC) framework is proposed to evaluate the long-term cost performance of the dual-fuel engine with that of a conventional diesel engine. By using the net present cost (NPC) as an evaluation indicator, the research results reveal that the dual-fuel engine is considered as a cost-effective option except for the high fuel price differential scenario, meaning that fuel prices are the most critical factor for ship owners. In addition, the environmental impact of these engines is included in the evaluation to show that 33% reduction in emissions of carbon dioxide (CO_2) can be achieved when running the dual-fuel engine, compared to the diesel engine. The proposed framework could conceivably be beneficial in selecting marine engine innovation that takes not only the environmental impact but also the economic performance into consideration.

Keywords: life-cycle cost analysis, dual-fuel marine engine, net present cost, CO_2 emissions.

1. INTRODUCTION

Over the past decades, the growth of international trade and global economy would not have been possible without shipping playing a prominent role. However, the shipping industry is dealing with a climate change reckoning. During the period from 2012 to 2018, the total greenhouse gas emissions (GHG) of shipping rose by approximately 10% [1]. Furthermore, it is responsible for emitting roughly 1 billion metric tons of carbon dioxide (CO_2) annually - that is the equivalent of the annual CO_2 emissions of Japan [2]. The industry is striving to eliminate these emissions by 2050 in order to be consistent with the Paris climate agreement's 1.5°C global warming goal. In this regard, the International Maritime Organization (IMO) set out a target, within the Initial Strategy, with a view of cutting the total annual GHG emissions from international shipping at least in half by 2050, while reducing CO_2 emissions intensity by at least 40% by 2030, and pursuing efforts towards 70% by 2050, compared to 2008 levels [3]. On a regional level, the European Commission (EU) has published several legislative proposals, namely Fit for 55, which sets a target of reducing its GHG emissions by at least 55% by 2030, compared to 1990 levels [4]. One of the most striking consequences within these proposals is the expansion of the EU Emissions Trading System (ETS) to the maritime sector. A new proposal under the ETS stipulates that by 2026 ship owners have to buy emissions allowance for each metric ton of CO_2 emissions reported from the current EU Monitoring, Reporting and Verification (MRV) system. A proposed fuel mandate has also been promoted by the EU on the use of zero or low-carbon fuels in maritime transport [5].

The afore-mentioned patchwork of regulations is expected to plot the industry's course towards decarbonization. In order to achieve this, there are several avenues: i) design measures, ii) operational measures, iii) innovative emission reduction technologies, iv) the utilization of alternative low-carbon/ zero-carbon fuels and v) a combination of these [6]. While the two former have already been introduced under a pallet of regulations such as the design indexes (i.e., the Energy Efficiency Design Index - EEDI for new-built vessels and the Energy Efficiency Existing Ship Index - EEXI for existing vessels), the operational indicator

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(i.e. the Carbon Intensity Indicator - CII) and the practical tool (i.e. the enhanced Ship Energy Efficiency Management Plan - SEEMP), the latter need sufficient regulatory and market incentives. Furthermore, investments in these avenues are expensive, with a study estimating that the total cost would be from \$1.4 to \$1.9 trillion in order to fully decarbonise the international shipping by 2050 [7]. Considering the IMO's 2030 and 2050 targets as well as the long lifespan of ships, this exerts intense pressure for the industry to act as soon as possible.

In this respect, retrofitting existing vessels with innovative emission reduction technologies has begun to gain momentum within the shipping industry. Retrofitting, i.e., the installation of state-of-the-art technologies on-boards ships, might provide a viable solution for ship-owners to not only meet the regulations/ targets but also raise their fleet's operational standards. The main focus of this study is a high efficiency modern dual-fuel engine which can be run in either liquid fuelled diesel mode or gas mode. In the gas mode, benefiting from the lean-burn Otto principle, a lean premixed air-gas mixture during the combustion process results in lower NO_x emissions and improved efficiency. Along with the use of a low-carbon fuel (i.e. liquefied natural gas (LNG)), the performance benefits includes the environmental gains with the reduction of exhaust gas emissions. However, the economic aspect is an important consideration that must be taken into account if technological investments are made by ship-owners [8]. At this point, the question arises as to how ship-owners can evaluate the most cost-effective retrofitting investments that can achieve the desired long-term service and meet the new environmental regulations/ targets. Having the dual-fuel engine in mind, this study aims to develop a life-cycle costing (LCC) framework that can be served as a decision support tool for the benefits of the shipping industry involved in retrofitting activities. This study proceeds as follows: the literature review is followed by the methodology where the proposed LCC framework is presented in detail. Afterwards, a case study with a focus on the economic comparison between the dual-fuel engine and a conventional diesel engine is demonstrated. In the end, the conclusion gives some concluding remarks.

2. LITERATURE REVIEW

LCC is a cost projection technique that encompasses all costs of a product that will incur throughout a cradle-to-grave perspective from its inception to its disposal. LCC has been deployed since the 1960s when the U.S. Department of Defense developed a formal analysis tool to improve its cost effectiveness [9]. From the defence system, the application of LCC has been further expanded to the industrial and consumer sectors. In the context of the maritime research domain, it appears to be gaining popularity, especially in transportation and logistic services [10]. It can perceived that LCC has been developed towards a result of specific decision-making support applications. It has been used as a single method or integrated with other methods such as life cycle assessment (LCA) in order to assist decision-makers in making investment decisions on technologies and ship systems. Integrating LCC with activity-based costing, [11] provides an effective cost management method with an application for a platform supply vessel. [12] conducted a life-cycle cost analysis (LCCA) with a view of sustainable development for the Norwegian fishing fleet. [10] carried out a cost-effectiveness analysis to assess ballast water treatment system alternatives for retrofitting purposes. A life cycle and cost assessment framework was proposed for selecting marine propulsion systems [13].

By using the LCC and the LCA methods, [14] developed a life cycle emission inventory and evaluated the cost performance of battery powered system on a catamaran ferry compared with conventional diesel engines. [15] examined the benefits of applying solar panel systems on a short route ferry through life cycle and economic assessment. Different design solutions for recreation vessels were evaluated by combining the LCC and the LCA methods [16]. [17] proposed an integrated approach where LCA and LCC were combined for assessing various marine fuels and engine system options for different Roll-on/ Roll-off (Ro-Ro) passenger ferries. LCC was integrated into a life cycle performance assessment tool for assessing the environmental and economic performance of a ship over its life-cycle [18]. With a focus on the maintenance phase, several studies applied the LCA and LCC methods for the evaluation of ship hull maintenance [19], and different ship propulsion layout solutions [20].

It is observed from the literature review that there has been no uniform framework was identified among the LCC studies and some of them have not taken the International Standard (i.e. ISO1586-5) into consideration.

3. METHODOLOGY

Figure 1 depicts the proposed framework that encompasses principles defined by the ISO LCC guidelines (ISO15686-5) [21] coupled with the frameworks proposed by [12, 22, 23].

3.1 Problem definition

Before adopting an innovative emission reduction engine, the cost performance of such an engine during its lifespan is arousing the interest of shipowners. The objective of this study is to compare the life-cycle cost performance of the dual-fuel engine with that of a conventional diesel engine. The boundary of this study is defined within the use of such engines as main propulsion systems. The LCCA conducted in this study is from both the manufacturer perspective (i.e. an engine manufacture) and the user perspective (i.e. ship owners).

3.2 Breakdown analysis

A Cost Breakdown Structure (CBS) is established to provide an overview of cost categories on different aggregation levels, as demonstrated in Fig. 2. From a cradle-to-grave perspective, the first level consists of the costs connected with four life-cycle phases of an engine: construction, operation, maintenance and end-of-life, following the ISO LCC guidelines (ISO1586-5) [21]. The second level provides details about different costs and factors associated with each phase in the engine's life-cycle.

3.2.1 Construction costs. The construction costs are defined as the costs to assemble the engine before putting it into initial service. In this respect, the Engine Breakdown Structure (EBS) is devised to offer an schematic outline of the engine's main components and systems, as depicted in Table 1.

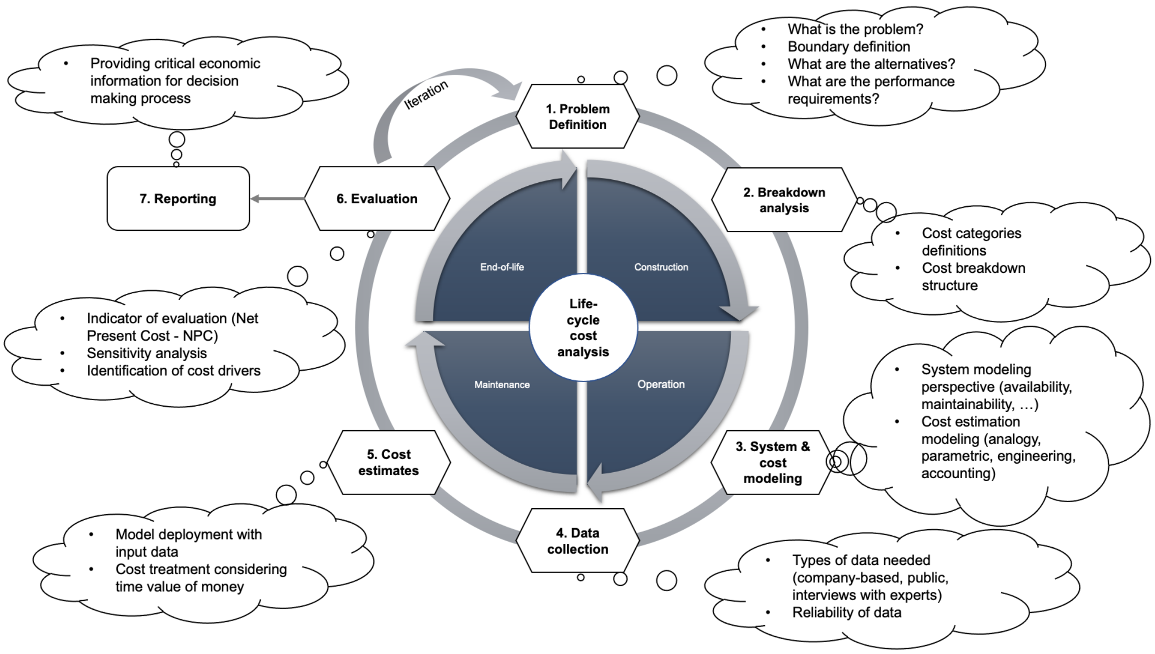

FIGURE 1: The proposed LCC framework

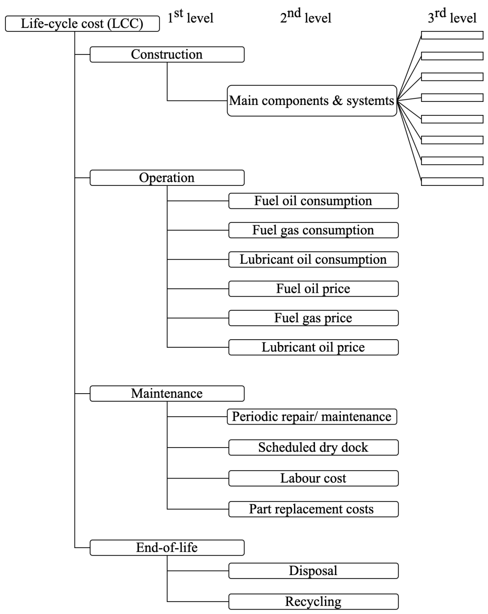

FIGURE 2: Cost breakdown structure (CBS) of a marine engine

TABLE 1: A general Engine Breakdown Structure (EBS) of a diesel engine

2nd level	3rd level	Cost
Main components & systems	Engine Basement	
	Camshaft & Valve Mechanism	
	Fuel Injection System	
	Turbocharging & Scavenging System	
	Ancillary System	
	Automation System	
	Low-value Parts	
	Exhaust Gas Cleaning System*	
	Total	989K

* Selective Catalytic Reduction (SCR) technology for NO_x reduction. The cost of the SCR was based on the International Association for Catalytic Control of Ship Emissions to Air (IACCSEA)

Unit K = 1000 €. Source: Wärtsilä, IACCSEA

3.2.2 Operation costs. The operation costs are connected with the annual routine operations intended to run the engine. In this study, the operation costs are the fuel costs (other non-fuel operating costs are assumed to be the same irrespective of the two engines). In order to obtain these costs, it is required to find the annual fuel consumption (e.g., oil, gas or pilot consumption) and the annual lubricant oil consumption (LOC) under different engine modes and engine loads. For the diesel engine, the total annual fuel oil consumption (FOC) and the total annual LOC can be obtained, as expressed in the following equations.

$$FOC = \sum_{i=1}^{N} P_i \times SFOC_i \times H_i \tag{1}$$

$$LOC = \sum_{i=1}^{N} P_i \times SLOC_i \times H_i \tag{2}$$

where P is the power required for each engine mode [kW], $SFOC$ is the specific fuel oil consumption under specific engine output, as the function of the engine load [g/kWh], $SLOC$ is the specific lubricant oil consumption under specific engine output [g/kWh], H is the annual operating hours for each engine mode [hour/year],

i refers to the i^{th} engine mode associated with the corresponding engine load, N is the total number of engine modes.

As mentioned before, the dual-fuel engine can be run either on diesel mode or gas mode. In the gas mode, it works based on the lean-burn Otto principle, with a lean premixed air–gas mixture in the combustion chamber. The lean burn combustion process leads to lower NO_x emissions and higher efficiency (i.e. due to the higher compression ratio and optimized injection timing). The main fuel in the gas mode is LNG which is injected into the engine at a low pressure condition. The lean air-gas mixture is ignited by injecting a small amount of pilot diesel fuel [24]. The total annual pilot fuel consumption (PFC) can be calculated by adopting Eqn. (1). Similarly, the total annual fuel gas consumption (FGC) can be determined by using the following equation.

$$FGC = \sum_{i=1}^{N} P_i \times SFGC_i \times H_i \tag{3}$$

where $SFGC$ is the specific fuel gas consumption under specific engine output, as the function of the engine load [g/kWh].

In the diesel mode, it is a normal diesel engine, therefore the total annual FOC can also be found by adopting Eqn. (1).

3.2.3 Maintenance costs. The maintenance costs include the costs that are planned for repair as well as maintenance activities in periodic and major dry-docking manners. In this regard, they can be divided into: 1) labor costs to do such activities and 2) part replacement costs when engine component's parts are replaced as recommended by the engine manufacturer. In order to obtain the labor costs, manpower from both personnel working on-board ships (i.e., Chief Engineers, Engine Officers) and technical personnel from the engine manufacturer are taken into consideration. For the part replacement costs, information from the engine manufacturer is essential.

3.2.4 End-of-life cost. The end-of-life cost is the value of the engine at the end of its life cycle. In this case, this is the economic benefits since the engine will go through the disposal and recycling process.

3.3 System and cost modelling

For the purpose of quantifying the cost categories under the CBS, the system can be modelled from different perspectives, such as availability, maintainability, logistics, risk, etc. Among of these, availability and maintainability are regarded as the most fundamental cost drivers in the LCCA [22]. It is also required to choose a cost estimation model in the LCCA. In the literature, four cost estimation models are commonly used as follows.

3.3.1 Analogous model. This is a case-based approach with an assumption having similar costs among similar products. This model is characterized by adjusting the cost of a similar product with respect to the differences between it and the target product [25]. The domain knowledge from experts is required to identify the similarities and differences between these two products. Based on the historic cost data, the cost calculation can be obtained with reasonable approximation within a minimum amount of time [26].

3.3.2 Parametric model. The most important characteristic of this model is the so-called "Cost Estimation Relationships" (CERs) which is derived from the mathematical relationships between the costs of a product and one or more of its parameters. Such parameters are known as "Cost Drivers". One example of the CERs establishment is the correlation between part size of the product and the manufacturing costs. When the part size increases, so does the manufacturing costs. Therefore, the part costs can be predicted based on the part size. More cost drivers can be used (e.g., size, weight) to establish different CERs within one model and they are have impacts on the cost changes or at least follow the cost trend. This model also depends on a historic data source and it is not recommended to be used outside of the data range. Moreover, it is not suited to depict technology changes or altered system requirements [25, 26].

3.3.3 Engineering build-up model. The principle of the bottom-up or the engineering build-up model is deriving the product's cost through summing up the costs of all the component parts and tasks that are associated with the product. The estimation of the product's cost depends heavily upon a detailed engineering analysis which requires an extensive amount of information regarding the design and configuration of the product's systems and accounting information for all material, equipment, and labor [25]. Although this method requires a great number of the product details, it provides a fairly understandable process and it is regarded as the only one method that could be applied to new products or technologies [26].

3.3.4 Accounting model. This model deals with cost management and accounting where the overhead costs are considered. There are several versions of this model that are mentioned in the literature: volume-based costing systems, unconventional costing methods and modern cost management systems [11].

The current study develops the LCC model based on the engineering build-up model. At some points, other models can be combined, depending on the availability of reliable data throughout different phases of the engine's life-cycle.

3.4 Data collection

Since the engineering build-up model is selected for conducting the LCCA in this study, the amount of data needed is extensive. Data needed to perform the LCCA in this study can be categorized into three main groups: company-based data source, public database and indirectly derived data. Examples of these data categories and their sources are demonstrated in Table 2.

3.5 Cost estimates

When deploying the LCC model, it is necessary to include cost treatment considering the time value of money (i.e., discounting and present value). They are key economic concepts in LCC because the value of money today is not equal to the one projected to be spent in the future. In order to account this, all future costs should be transformed to present value costs with the help of discounting. Discounting can be achieved by using a discount rate chosen to represent the time value of money. The formula of present value can be expressed as follows [31].

$$PV = FV \frac{1}{(1+r)^n} \tag{4}$$

TABLE 2: Data categories and sources

Category	Where to find?
Company-based data source	
Construction costs	From Engine Manufacturer
Operational profile	From Engine Manufacturer
Engine technical data	[27]
Maintenance schedule	O&MMs
Engine materials	From Engine Manufacturer
Engine weights	Engine Product Guide [24, 28]
Disposal/ Recycling rate	[29]
Public database	
Marine fuel oils	shipandbunker.com/prices
Wages	ec.europa.eu/eurostat
Currency exchange rates	xe.com/currencyconverter
Discount rate	[30]
Indirectly derived data	
Maintenance hour consumption	Questionnaires & Interviews

O&MMs: Operation & Maintenance Manuals

where PV is the present value of the cost or benefit [€], FV is the future value of the cost or benefit [€], r is the discount rate [%], n is the current time period in years.

Net present cost (NPC) is an indicator to be used to evaluate the life cycle cost performances of the engines. In this respect, the NPC is the summation of the present value of each cost that will occur over the lifespan of the engines (i.e. from construction, operation, maintenance and end-of-life), as expressed below.

$$NPC = PV(CST) + PV(OPR) + PV(MTN) - PV(EOL) \quad (5)$$

where CST is the construction cost [€], OPR is the operation cost [€], MTN is the maintenance cost [€], and EOL is the end-of-life value [€].

3.6 Evaluation & reporting

General speaking, the engine with the lowest NPC is chosen during the evaluation process. It is important to stress that this may not be the case when other considerations are taken into account. NPC can be served as a critical economic information to the overall decision-making process, but it is not the sole decision-making criterion. Another important decision-making criterion is the environmental impact of such engines. Since the main contributor in GHG emisions is CO_2, the estimations of the CO_2 emissions from these engines are also considered in the evaluation process, as expressed in the following equation.

$$M_{CO_2} = FC \times C_F \quad (6)$$

where M_{CO_2} is the annual amount of CO_2 emissions generated from fuel combustion [Ton], FC is the annual fuel consumption [Ton]. For the diesel engine, it is the annual FOC. For the dual-fuel engine, it includes the annual FGC, FPC in the gas mode and the annual FOC in the diesel mode, C_F is the carbon emission conversion factor [t-CO_2/t-Fuel].

Sensitivity analyses can also be performed during this process to handle the uncertainty attached to the costs in the LCC model. In this way, it is possible to investigate how variations across a probable range of uncertainties can have an impact on the relative merits of these engines. Such analyses can assist in identifying cost drivers that have the biggest impacts to the LCC model and how robust the model is. Several key assumptions that can affect the uncertainties are fuel prices, type of fuel, engine operating hours, discount rate, etc.

4. CASE STUDY

A case study comparing the life cycle cost of two main engines is used as an exemplification for the application of the proposed LCC framework. The case ship is a bulk carrier with the deadweight of 7600 [Ton], and the Length-Over-All (LOA) of 112 [m]. The two engines with their specifications are presented in Table 3. The analysis duration in this case study is 20 years.

TABLE 3: Specifications of two engines

Engine	Diesel engine	Dual-fuel engine
Cylinder configuration	8L32	8V31DF
No of cylinder	8	8
Cylinder bore	320	310
Power per cylinder	580	600
Power	4640	4800
RPM	750	750
Fuel type	MGO	ULSD (in diesel mode) LNG (in gas mode)

MGO: Marine Gas Oil; ULSD: Ultra Low Sulphur Diesel

4.1 Construction costs

The construction costs for the diesel engine and the dual-fuel engine are obtained by consulting with the engine manufacturer. It is noted that the dual-fuel engine does not require the installation of the Selective Catalytic Reduction (SCR) system. These construction costs (CST) are shown in Table 4.

TABLE 4: Construction costs (CST)

Engine	Diesel engine	Dual-fuel engine
Construction cost	989K	1200K

Unit K = 1000 €; Source: Wärtsilä

4.2 Operation costs

The ship's operational profile using the diesel engine is demonstrated in Table 5. The engine load, as a percentage of the maximum continuous rating (MCR) of the engine, varies under different engine modes. Since the SFOC is described as a function of the engine load; when the engine load changes, the SFOC should be calibrated accordingly. This can be achieved by interpolating or extrapolating the actual values with the reference values. Table 6 presents the respective reference values for the SFOC of the diesel engine [27]. The relationship between the

TABLE 5: The case ship's operational profile of the diesel engine

Operation Mode	Annual Hrs [h]	Speed [Knot]	%	Power [kW]	Engine Load [%]	SFOC [g/kWh]	Annual FOC [Ton]	SLOC [g/kWh]	Annual LOC [Ton]
Port	1200	0	14%	0	0	0	0	0	0
Manoeuvring	100	0	1%	846.7	18.2%	183.6	15.5	0.06	0.01
Engine Mode 1	300	18.1	3%	3139.6	67.7%	181.0	170.5	0.24	0.22
Engine Mode 2	7100	15.3	82%	1720.9	37.1%	182.6	2230.8	0.13	1.59
Total	8700						2416.8		1.81

engine load and the relative SFOC is depicted in Fig. 3. It is desirable to maintain the engine loads around the point with the lowest SFOC in order to reduce the fuel oil consumption and optimize the engine performance. The total annual FOC, LOC of the diesel engine can be determined by using Eqn. (1) and Eqn. (2) respectively, as shown in Table 5.

TABLE 6: Reference values for the SFOC & SLOC of the diesel engine

Engine Load [%]	SFOC [g/kWh]	SLOC [g/kWh]
100	184.7	0.35
85	181	
75	180.6	
50	181.9	

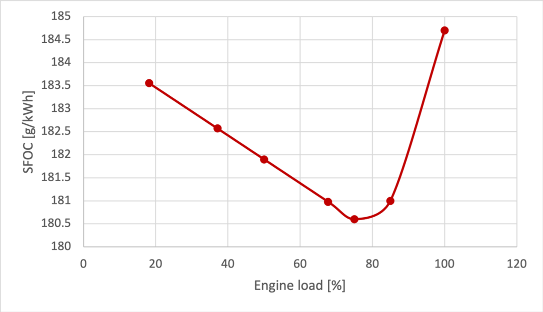

FIGURE 3: SFOC-engine load relation curve of the diesel engine

The same operational profile can be applied to the dual-fuel engine with an assumption that it is running on Ultra Low Sulphur Diesel (ULSD) in the diesel mode, i.e. in "Manoeuvring" and LNG in the gas mode, i.e., in "Engine Mode 1" and "Engine Mode 2", as demonstrated in Table 7. In the diesel mode, the calculations for the total annual FOC and LOC are similar to what we did for the diesel engine. In the gas mode, it is required to find the total annual PFC and the total annual FGC. The PFC can be calculated by adopting Eqn. (1) while the FGC can be found with the help of Eqn. (3). The reference values for the SFOC, SLOC, the specific pilot fuel consumption (SPFC) & SFGC are presented in Table 8 [27]. Figure 4 illustrates the curve of SFOC-engine load relation in the diesel mode. The curves for SFGC and SPFC in the gas mode are plotted in Fig. 5. Table 7 reports the total annual FOC, LOC, FGC, and PFC of the dual-fuel engine.

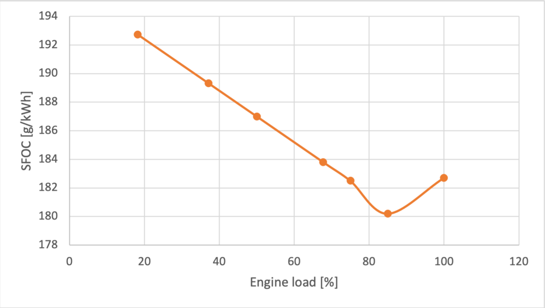

FIGURE 4: SFOC-engine load relation curve of the dual-fuel engine in the diesel mode

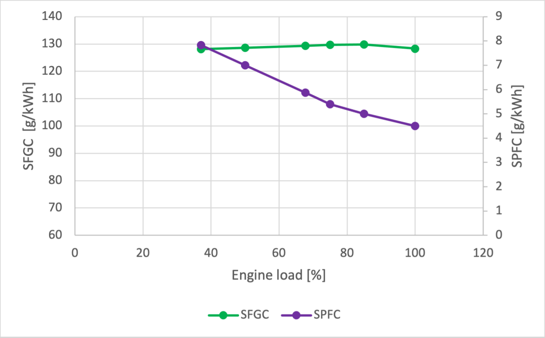

FIGURE 5: SFGC/ SPFC-engine load relation curves of the dual-fuel engine in the gas mode

Comparing the results of the main fuel consumption from the two engines, it can be seen from Table 5 and Table 7 that the annual FGC of the dual-fuel engine is less than the annual FOC of the diesel engine (1745.9 [Ton] versus 2416.8 [Ton]). The annual operation costs are therefore heavily dependent on fuel prices. The single most striking observation to emerge from the current fuel price data was that unlike before when the LNG price were lower than the MGO price, the LNG price has seen a spike for the time being of this paper. Having an assumption that LNG price is higher than MGO price, two fuel price scenarios were tested as follows.

- Scenario 1: Low price differential between LNG and MGO (110%) [32], as shown in Table 9.
    - LNG price: 561.1 [€/ Ton]
    - MGO price: 508.1 [€/ Ton]

TABLE 7: The case ship's operational profile of the dual-fuel engine

Operation Mode	Annual Hrs [h]	Speed [Knot]	%	Power [kW]	Engine Load [%]	SFOC [g/kWh]	Annual FOC [Ton]	SLOC [g/kWh]	Annual LOC [Ton]	SFGC [g/kWh]	Annual FGC [Ton]	SPFC [g/kWh]	Annual PFC [Ton]
Port	1200	0	14%	0	0	0	0	0	0	0	0	0	0
Manoeuvring	100	0	1%	873.6	18.2%	192.7	16.8	0.08	0.01	127.3	N/A	N/A	N/A
Engine Mode 1	300	18.8	3%	3249.6	67.7%	183.8	N/A	0.30	0.30	129.4	126.2	5.9	5.7
Engine Mode 2	7100	15.9	82%	1780.8	37.1%	189.3	N/A	0.16	2.11	128.1	1619.8	7.8	98.9
Total	8700						16.8		2.42		1745.9		104.7

TABLE 8: Reference values for the SFOC, SLOC, SPFC & SFGC of the dual-fuel engine

Engine Load [%]	SFOC [g/kWh]	SLOC [g/kWh]	SPFC [g/kWh]	Heat Rate [kJ/kWh]	SFGC [g/kWh]
100	182.7	0.45	4.5	7058	128.3
85	180.2		5.0	7138	129.8
75	182.5		5.4	7134	129.7
50	187.0		7.0	7076	128.7

The calorific value for LNG: 55000 [kJ/kg] is used to convert the heat rate into the SFGC

- Scenario 2: High price differential between LNG and MGO (180%) [33], as shown in Table 10.
  - LNG price: 938.3 [€/ Ton]
  - MGO price: 515.8 [€/ Ton]

Table 9 and Table 10 also report the lubricant prices, the ULSD prices which were found from [34]. The results obtained from the operation costs of the two engines in these scenarios can be compared in Table 9 and Table 10 respectively. In the first scenario, the dual-fuel engine has lower annual operation cost than the diesel engine. What is striking about the results in the second scenario is that the annual operation cost of the dual-fuel engine is higher than that of the diesel engine.

4.3 Maintenance costs

The labor costs for maintenance are driven by the hourly wages and the maintenance hour consumption (i.e. time spent in reality when on-board and ashore personnel doing maintenance activities for each engine's component). The maintenance activities can be divided into several groups: a) Check/ Inspect, b) Take oil sample, c) Clean/ Wash, d) Maintain, e) Renew/ Replace and f) Overhaul. Most of the maintenance activities are done when the ship is in service by the crew members while many overhaul activities are undertaken when the ship is in dry dock or in workshops by personnel from the engine manufacturer. The maintenance hour consumption was obtained by conducting questionnaires and interviews with the crew members (i.e., Chief Engineers, Engine Officers) with at least 5-year seafaring experience.

With the assumed hourly wages of 30 [€/ hour], the results of the maintenance costs of the engines are presented in Table 11. The results have not included the part replacement costs yet. This is due to the fact that getting this information is time-consuming and there is an involvement of various departments within the engine manufacturer. The maintenance costs of the LNG handling tanks are excluded in this study.

4.4 End-of-life value

In an attempt to determine the end-of-life values of the engines, information regarding the material content of the engines, the benefits of recycling the respective materials should be obtained, as presented in Table 12. The weights of the engines are given in Table 13. The end-of-life values of the engines are presented in Table 14.

4.5 Net present costs & evaluation

With the life cycle costs computed while considering the chosen discount rate of 2.5% [30], the results of the corresponding costs and the NPC in two scenarios are summarized in Table 15 and Table 16. These results are depicted in Fig. 6 and Fig. 7, respectively. It can be seen from these results and tables that among of the costs, the operation costs are the dominant ones. The results also show that the NPC of the dual-fuel engine is lower than that of the diesel engine in the first scenario. Contrary to the first scenario, the dual-fuel engine is seen as a higher-cost option in the second scenario when there is a high price differential between LNG and MGO. These results indicate that fuel prices are the most significant driver to the life cycle costs of these engines.

As regards the environmental impact, with the help of Eqn. (6) and the C_F values provided in Table 17, the results of the amount of CO_2 emissions emitted from the engines during 20 years of operation can be obtained, as presented in Table 18. There is a clear environmental benefit of running the dual-fuel engine with a CO_2 reduction of 33% regardless of fuel price scenarios.

5. CONCLUSION

A sense of urgency from regulations has compelled the shipping industry to opt for innovative emission reduction technologies to meet the emission targets by 2030 and 2050 respectively. This study has compared the economic performance of the dual-fuel engine against the conventional diesel engine with a life-cycle perspective. The most obvious result to emerge from this study

TABLE 9: Scenario 1

(a) Diesel engine

Item [Unit]	Value
MGO price [€/Ton]	508.1
Lub price [€/Ton]	2300
MGO cost [€]	1228K
Lub cost [€]	4K
Annual operation cost [€/year]	1232K

Unit K = 1000 €

(b) Dual-fuel engine

Item [Unit]	Value
LNG price [€/Ton]	561.1
ULSD price [€/Ton]	576.8
Lub price [€/Ton]	2300
LNG cost [€]	980K
ULSD cost [€]	70K
Lub cost [€]	6K
Annual operation cost [€/year]	1055K

Unit K = 1000 €

TABLE 10: Scenario 2

(a) Diesel engine

Item [Unit]	Value
MGO price [€/Ton]	515.8
Lub price [€/Ton]	2300
MGO cost [€]	1247K
Lub cost [€]	4K
Annual operation cost [€/year]	1251K

Unit K = 1000 €

(b) Dual-fuel engine

Item [Unit]	Value
LNG price [€/Ton]	938.3
ULSD price [€/Ton]	576.8
Lub price [€/Ton]	2300
LNG cost [€]	1638K
ULSD cost [€]	70K
Lub cost [€]	6K
Annual operation cost [€/year]	1714K

Unit K = 1000 €

TABLE 11: Maintenance costs (MTN)

Engine	Diesel engine	Dual-fuel engine
Maintenance cost	470K	513K

Unit K = 1000 €

TABLE 12: Metal material content of engines

Material	Weight ratio [%]	Benefits of recycling [€/kg]
Steel	16	0.25
Cast iron	80	0.25
Aluminium	2	0.7
Cooper	2	6.35

Source: Wärtsilä, [29]

TABLE 13: Engine weights

Engine	Diesel engine	Dual-fuel engine
Weight [Ton]	43.6	58.9

Source: [24, 28]

TABLE 14: End-of-life values (EOL)

Engine	Diesel engine	Dual-fuel engine
End-of-life value	17K	22K

Unit K = 1000 €

is that the operation costs (i.e. fuel costs in this study) have the highest proportion of the total life cycle costs. This is in accord with the previous study indicating that fuel costs comprise around two-thirds of the voyage costs of a ship [35]. Having the NPC (i.e. the present value of all the costs) as an evaluation indicator, the results have also identified that the NPC of the dual-fuel engine is lower than that of the diesel engine except for the high fuel price differential scenario. Future fuel prices are unpredictable due to the changes in demand and supply, as well as the price volatility of underlying raw material used for production (e.g., crude oil and natural gas). Therefore, fuel price together with the future global energy mix will exert tremendous impacts on technological investments from the perspective of ship-owners. However, running the dual-fuel engine with LNG brings flexibility to ship-owners since they can switch to ULSD under high gas price scenarios. Furthermore, the results have shown that a CO_2 reduction of 33% can be achieved when opting for the dual-fuel engine.

Taken together, the results of this study have suggested that the proposed LCC framework can be an useful decision-making tool to provide a holistic picture of technological investments for shipowners and fleet managers. The results have stressed that an alternative with the lowest NPC may not necessarily be chosen when other considerations (e.g. the environmental impact) are taken into account. Other dual-fuel engine options should also be further examined to identify the most robust options that fulfil the needs of ship owners. Furthermore, multiple fuel price scenarios, different discount rates and other factors that cause the uncertainty should be simulated in the sensitivity analyses. These topics are

TABLE 15: Cost results summary in scenario 1

Present value	Diesel engine	Dual-fuel engine
Construction costs	989K	1200K
Operation costs	19209K	16450K
Maintenance costs	365K	399K
End-of-life value	10K	14K
NPC	20553K	18035K

Unit K = 1000 €

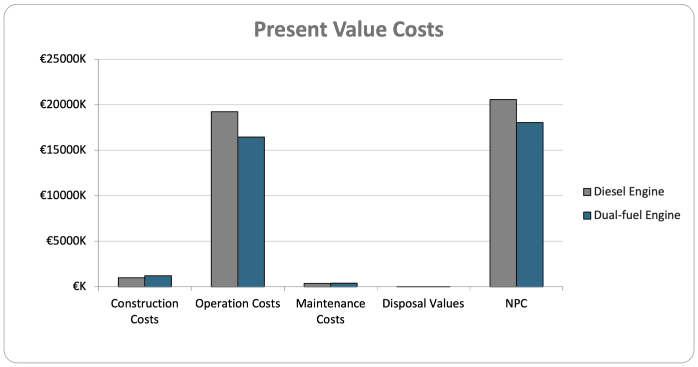

FIGURE 6: Results of scenario 1

TABLE 16: Cost results summary in scenario 2

Present value	Diesel engine	Dual-fuel engine
Construction costs	989K	1200K
Operation costs	19498K	26717K
Maintenance costs	365K	399K
End-of-life value	10K	14K
NPC	20842K	28303K

Unit K = 1000 €

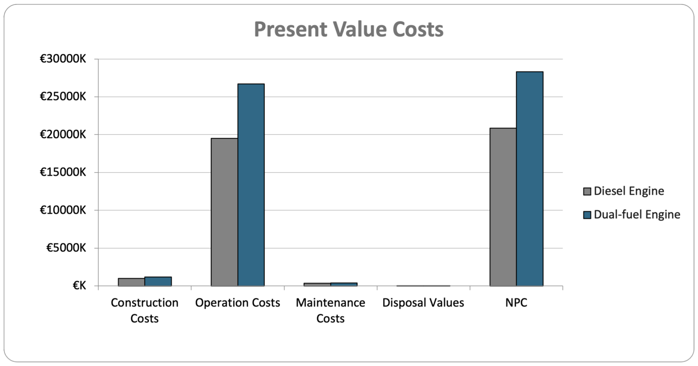

FIGURE 7: Results of scenario 2

TABLE 17: Carbon emission conversion factor C_F [1]

Type of fuel	C_F [t-CO2/t-Fuel]
MGO	3.20600
ULSD	3.15104
LNG	2.75000

TABLE 18: CO_2 emissions during 20 years operation of these engines

Engine	Diesel engine	Dual-fuel engine
Amount per 20 years [Ton]	154963	103684
Percentage reduction	N/A	33%

reserved for future work.

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REFERENCES

[1] IMO. "Fourth IMO GHG Study 2020." Technical report no. International Maritime Organization (IMO), London, UK. 2020.

[2] Ritchie, Hannah and Roser, Max. "CO_2 and Greenhouse Gas Emissions." https://ourworldindata.org/co2/country/japan (2020).

[3] IMO. "Initial IMO Strategy on Reduction of GHG Emissions from Ships. IMO Resolution MEPC.304(72)." Technical report no. International Maritime Organization (IMO), London, UK. 2018.

[4] European Commission (EU). "Delivering the European Green Deal." https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal_en.

[5] European Commission (EU). "Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the Use of Renewable and Low-Carbon Fuels in Maritime Transport and Amending Directive 2009/16/E." (2021).

[6] Bouman, Evert A., Lindstad, Elizabeth, Rialland, Agathe I. and Strømman, Anders H. "State-of-the-Art Technologies, Measures, and Potential for Reducing GHG Emissions from Shipping – A Review." *Transportation Research Part D: Transport and Environment* Vol. 52 (2017): pp. 408–421. DOI 10.1016/j.trd.2017.03.022.

[7] Carlo, Raucci, Marc, Bonello Jean, Fuente, Santiago, Suarez de la, Smith, Tristan and Søgaard, Kasper. "Aggregate Investment for the Decarbonisation of the Shipping Industry." (2020).

[8] Bui, Khanh Q, Ölçer, Aykut I, Kitada, Momoko and Ballini, Fabio. "Selecting Technological Alternatives for Regula-

tory Compliance towards Emissions Reduction from Shipping: An Integrated Fuzzy Multi-Criteria Decision-Making Approach under Vague Environment." *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* Vol. 235 No. 1 (2021): pp. 272–287. DOI 10.1177/1475090220917815.

[9] Sherif, Yosef S and Kolarik, William J. "Life Cycle Costing: Concept and Practice." *Omega* Vol. 9 No. 3 (1981): pp. 287–296. DOI 10.1016/0305-0483(81)90035-9.

[10] Blanco-Davis, Eduardo and Zhou, Peilin. "LCA as a Tool to Aid in the Selection of Retrofitting Alternatives." *Ocean Engineering* Vol. 77 (2014): pp. 33–41. DOI 10.1016/j.oceaneng.2013.12.010.

[11] Emblemsvåg, Jan. *Life-Cycle Costing: Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks*. Wiley, Hoboken, N.J (2003).

[12] Utne, Ingrid Bouwer. "Life Cycle Cost (LCC) as a Tool for Improving Sustainability in the Norwegian Fishing Fleet." *Journal of Cleaner Production* Vol. 17 No. 3 (2009): pp. 335–344. DOI 10.1016/j.jclepro.2008.08.009.

[13] Jeong, Byongug, Wang, Haibin, Oguz, Elif and Zhou, Peilin. "An Effective Framework for Life Cycle and Cost Assessment for Marine Vessels Aiming to Select Optimal Propulsion Systems." *Journal of Cleaner Production* Vol. 187 (2018): pp. 111–130. DOI 10.1016/j.jclepro.2018.03.184.

[14] Wang, Haibin, Boulougouris, Evangelos, Theotokatos, Gerasimos, Zhou, Peilin, Priftis, Alexandros and Shi, Guangyu. "Life Cycle Analysis and Cost Assessment of a Battery Powered Ferry." *Ocean Engineering* Vol. 241 (2021): p. 110029. DOI 10.1016/j.oceaneng.2021.110029.

[15] Wang, Haibin, Oguz, Elif, Jeong, Byongug and Zhou, Peilin. "Life Cycle and Economic Assessment of a Solar Panel Array Applied to a Short Route Ferry." *Journal of Cleaner Production* Vol. 219 (2019): pp. 471–484. DOI 10.1016/j.jclepro.2019.02.124.

[16] Favi, Claudio, Campi, Federico, Germani, Michele and Manieri, Steve. "Using Design Information to Create a Data Framework and Tool for Life Cycle Analysis of Complex Maritime Vessels." *Journal of Cleaner Production* Vol. 192 (2018): pp. 887–905. DOI 10.1016/j.jclepro.2018.04.263.

[17] Perčić, Maja, Vladimir, Nikola and Fan, Ailong. "Techno-Economic Assessment of Alternative Marine Fuels for Inland Shipping in Croatia." *Renewable and Sustainable Energy Reviews* Vol. 148 (2021): p. 111363. DOI 10.1016/j.rser.2021.111363.

[18] Maggioncalda, Matteo, Gualeni, Paola, Notaro, Chiara, Cau, Carlo, Bonazountas, Markos and Stamatis, Spyridon. "Life Cycle Performance Assessment (LCPA) Tools." Papanikolaou, Apostolos (ed.). *A Holistic Approach to Ship Design: Volume 1: Optimisation of Ship Design and Operation for Life Cycle*. Springer International Publishing, Cham (2019): pp. 383–412. DOI 10.1007/978-3-030-02810-7_12.

[19] Wang, Haibin, Oguz, Elif, Jeong, Byongug and Zhou, Peilin. "Life Cycle Cost and Environmental Impact Analysis of Ship Hull Maintenance Strategies for a Short Route Hybrid Ferry." *Ocean Engineering* Vol. 161 (2018): pp. 20–28. DOI 10.1016/j.oceaneng.2018.04.084.

[20] Gualeni, Paola, Flore, Giordano, Maggioncalda, Matteo and Marsano, Giorgia. "Life Cycle Performance Assessment Tool Development and Application with a Focus on Maintenance Aspects." *Journal of Marine Science and Engineering* Vol. 7 No. 8 (2019): p. 280. DOI 10.3390/jmse7080280.

[21] ISO. "ISO 15686-5:2017 Buildings and Constructed Assets — Service Life Planning — Part 5: Life-cycle Costing." (2017).

[22] Kawauchi, Yoshio and Rausand, Marvin. "Life Cycle Cost (LCC) Analysis in Oil and Chemical Process Industries." Technical report no. Norwegian University of Science and Technology, Trondheim, Norway. 1999.

[23] Bui, Khanh Q., Perera, Lokukaluge P. and Emblemsvåg, Jan. "Development of a Life-cycle Cost Framework for Retrofitting Marine Engines towards Emission Reduction in Shipping." *IFAC-PapersOnLine* Vol. 54 No. 16 (2021): pp. 181–187. DOI 10.1016/j.ifacol.2021.10.091.

[24] Wärtsilä. "Wärtsilä 31DF Product Guide." (2020).

[25] Curran, R., Raghunathan, S. and Price, M. "Review of Aerospace Engineering Cost Modelling: The Genetic Causal Approach." *Progress in Aerospace Sciences* Vol. 40 No. 8 (2004): pp. 487–534. DOI 10.1016/j.paerosci.2004.10.001.

[26] Hueber, Ch, Horejsi, K. and Schledjewski, R. "Review of Cost Estimation: Methods and Models for Aerospace Composite Manufacturing." *Advanced Manufacturing: Polymer & Composites Science* Vol. 2 No. 1 (2016): pp. 1–13. DOI 10.1080/20550340.2016.1154642.

[27] Wärtsilä. "Engine Online Configurator | Wärtsilä." https://www.wartsila.com/marine/engine-configurator.

[28] Wärtsilä. "Wärtsilä 32 Product Guide." (2021).

[29] Greengate Metals. "UK Scrap Metal Prices 2021, Manchester - Greengate Metals Scrap Yard." https://www.greengatemetals.co.uk/scrapmetal/prices.

[30] Bureau of Reclamation. "Change in Discount Rate for Water Resources Planning." (2020).

[31] Welch, Ivo. *Corporate Finance*, 4th ed. Ivo Welch, Los Angeles (2017).

[32] Global Maritime Hub. "Bunker Prices Weekly Outlook – Week 24." https://globalmaritimehub.com/bunker-prices-weekly-outlook-week-24.html (2021).

[33] Global Maritime Hub. "Bunker Fuel Prices Outlook – Week 37." https://globalmaritimehub.com/bunker-fuel-prices-outlook-week-37.html (2021).

[34] Ship & Bunker. "World Bunker Prices." https://shipandbunker.com/prices (2021).

[35] Stopford, Martin. *Maritime Economics*, 3rd ed. Routledge, London ; New York (2009).