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Development of a Life-cycle Cost Framework for Retrofitting Marine Engines towards Emission Reduction in Shipping

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Abstract: The shipping industry is striving to reduce its negative environmental footprint and become more energy-efficient. In order to achieve this, undergoing the transition towards innovative engine and propulsion systems is attracting considerable attention. However, the economic aspect is of paramount importance for decision-makers (e.g. ship owners) when it comes to investing in innovative technologies. For this reason, it is required to have a comprehensive and holistic view on the economic impacts of such technologies at an early stage. This paper proposes a life-cycle cost analysis (LCCA) framework to be implemented for innovative emission reduction marine engines. The proposed framework will be able to serve as a decision support tool that is beneficial for ship owners during the decision-making process for retrofitting investments.

Keywords: Life-cycle cost analysis (LCCA), emission reduction, marine engine, shipping industry.

1. INTRODUCTION

Climate change is regarded as a pressing social-economic challenge that every sector has ever faced. In this regard, the shipping industry is no exception. Considering that greenhouse gas (GHG) emissions from international shipping increased by roughly 10% from 2012 to 2018 (IMO, 2020), the industry has been under a heavy pressure to mitigate its negative environmental footprint. Ambitious targets were set out by the International Maritime Organization (IMO) under the Initial IMO Strategy with a vision phasing out maritime GHG emissions as soon as possible. These targets aim to reduce the total annual GHG emissions from international shipping by at least 50% by 2050, compared to 2008 levels; and to reduce annual CO_2 emissions per transport work by 40% by 2030, again compared with 2008 levels (IMO, 2018). Apart from that, within Chapter 4 of the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, technical and operational measures namely Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) are mandatory regulatory mechanisms limiting CO_2 emissions from ships (IMO, 2011). Furthermore, the shipping industry produces air pollutants such as sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM). Such air pollutants are addressed by the introduction of emission control areas (ECAs) in Chapter 3 of MARPOL Annex VI and the 2020 global sulphur limit (applies for ships operating outside ECAs) (Zisi et al., 2021).

Given the above-mentioned environmental targets and regulations, the shipping industry is striving to further improve technical- and operational energy efficiency and explore innovative engine and propulsion systems. In this respect, the EU H2020 SeaTech project (https://seatech2020.eu) has proposed two symbiotic ship engine and propulsion technologies, aiming at increasing fuel efficiency and reducing emissions. The project will develop a flapping-foil thruster propulsion innovation mounted at the ship bow to augment ship propulsion in moderate and higher sea states, capturing wave energy, producing extra thrust and damping ship motions. By doing this, the reduction in the propulsion power requirement is expected. Furthermore, such hydrofoil technology will be combined with an innovative dual fuel engine with a view to achieving ultra-high energy conversion efficiency by precisely controlling the combustion process (Perera et al., 2021). Therefore, with the high efficiency and the utilization of clean fuel (i.e. liquefied natural gas (LNG)), running the SeaTech engine in gas mode will result in extremely low exhaust gas emissions.

The development of such complex technologies is an interdisciplinary and lengthy process that involves numerous activities until the product delivery. If a decision can be made at the early design stage, it will exert favourable impacts on the product's life cycle with regard to economic performance. Moreover, the economic aspect is fundamental to decisions on technological investments (Bui et al., 2020). Therefore, it is highly desirable to develop an approach that provides a holistic picture of the total cost performance of the product in the design stage. In this regard, this study utilises the life-cycle cost analysis (LCCA) to develop a life-cycle cost framework for a diesel engine. The proposed framework is expected to serve as a tool for

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economic life-cycle evaluation during the decision-making process for converting such engine into the SeaTech engine.

2. LCCA IN THE MARITIME DOMAIN

LCCA was originally proposed in the 1960s by the U.S. Department of Defense for the acquisition of high cost defence systems (Sherif and Kolarik, 1981). It has now been successfully adopted in various industries such as oil & chemistry, materials production, railway systems, etc. This method has become widespread and it has been seen in contemporary management practices. Albeit its popularity in many sectors, the use of LCCA in the maritime industry is scarce. However, over the past few years, it has been gained in popularity following the global trend of life cycle assessment for service chain improvements, especially in transportation and logistic services (Blanco-Davis and Zhou, 2014). It can be observed from the literature that LCCA has been used in parallel with life cycle assessment for the design, construction, operation and maintenance of ships or for the selection of retrofit technologies. The usefulness of LCCA was examined for enhancing sustainable designs of fishing vessels for ship owners, thereby improving decision-making in fisheries management (Utne, 2009). Emblemsvåg (2003) proposed an activity-based life-cycle costing method for assessing the economic and environmental aspects of a platform supply vessel. Blanco-Davis and Zhou (2014) carried out a cost-effectiveness analysis in order to assess ballast water treatment system alternatives for retrofit. Jeong et al. (2018) proposed an effective framework for life cycle and cost assessment for the selection of marine propulsion systems. Wang et al. (2018) examined the life cycle cost and the environmental impact on ship hull maintenance and suggested an optimal maintenance strategy for ship operators. Wang et al. (2019) conducted an investigation on the benefits of applying solar panel systems on a short route ferry through life cycle and economic assessment. LCCA was integrated into a life cycle performance assessment tool for the assessment of ship's performances throughout its life-cycle (Maggioncalda et al., 2019) and the evaluation of maintenance costs of different ship propulsion layout solutions (Gualeni et al., 2019).

3. THE PROPOSED LIFE-CYCLE COST FRAMEWORK

Fig. 1 depicts the process of the proposed framework adapted from (Utne, 2009). Furthermore, it is tailored with respect to a life-cycle perspective, including construction, operation, maintenance and end of life, based on the ISO 15686-5 (ISO, 2017). The proposed framework also encompasses the concept of circular economy (Jansson, 2016) along with economic Key Performance Indicators (KPIs). The feedback loop indicates that this is an iterative process where stages of the process should be improved due to the unavailability of information. In this way, the framework is revised on its own process while retaining a thorough formulation.

3.1 Problem definition

The objective of this study is to offer the benefits of using the proposed framework as a decision support tool for ship owners during the economic evaluation process for retrofitting technologies. The scope of this study is limited to a marine diesel engine. As such, it is used as a reference baseline to compare with the SeaTech dual-fuel engine with regard to the economic performance. In this way, the retrofitting cost (i.e including the part replacement costs) is taken into account when it is converted into the SeaTech engine.

3.2 Breakdown analysis

With a systematic and a cradle-to-grave view, a cost breakdown structure (CBS) is devised to divide the life-cycle cost into cost elements, including construction cost, operation cost, maintenance cost and end-of-life cost, as shown in Fig. 2. A Product Breakdown Structure (PBS), which is a physical breakdown of a product's components and systems, is commonly used. Similarly to PBS, we have specified an Engine Breakdown Structure (EBS) as a fundamental base for cost estimates of the diesel engine.

Construction phase In order to estimate the construction cost, the EBS is used to have a better understanding of the engine's main components and systems that can be modelled in the LCCA. Table 1 details the EBS of a diesel engine and the costs associated with its components and systems.

Table 1. A general Engine Breakdown Structure (EBS) of a diesel engine

2nd level	3rd level	Cost range	
Main components & systems	Engine Basement	328K	440K
	Fuel Injection System	32K	40K
	Camshaft & Valve Mechanism	72K	104K
	Turbocharging & Scavenging System	120K	160K
	Ancillary System	56K	80K
	Automation System	32K	48K
	Low value Parts	32K	40K
	Exhaust gas cleaning system*	52K	244K
	Total	724K	1 156K

* Selective Catalytic Reduction (SCR) technology for NO_x reduction. Cost range source: International Association for Catalytic Control of Ship Emissions to Air (IACCSEA)
Unit K = 1000 €. Source: Wärtsilä

Operation phase The main focus in the operation phase of the diesel engine is more or less in relation to its fuel consumption. Since the engine load will vary, subjected to different operation modes during a given year, the total annual fuel oil consumption (FOC) and the total annual lubricant oil consumption (LOC) can be determined through the following equations (Wang et al., 2019)

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

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

where

P is the power required for each operation mode [kW],
$SFOC$ is the specific fuel oil consumption under specific engine output [g/kWh],

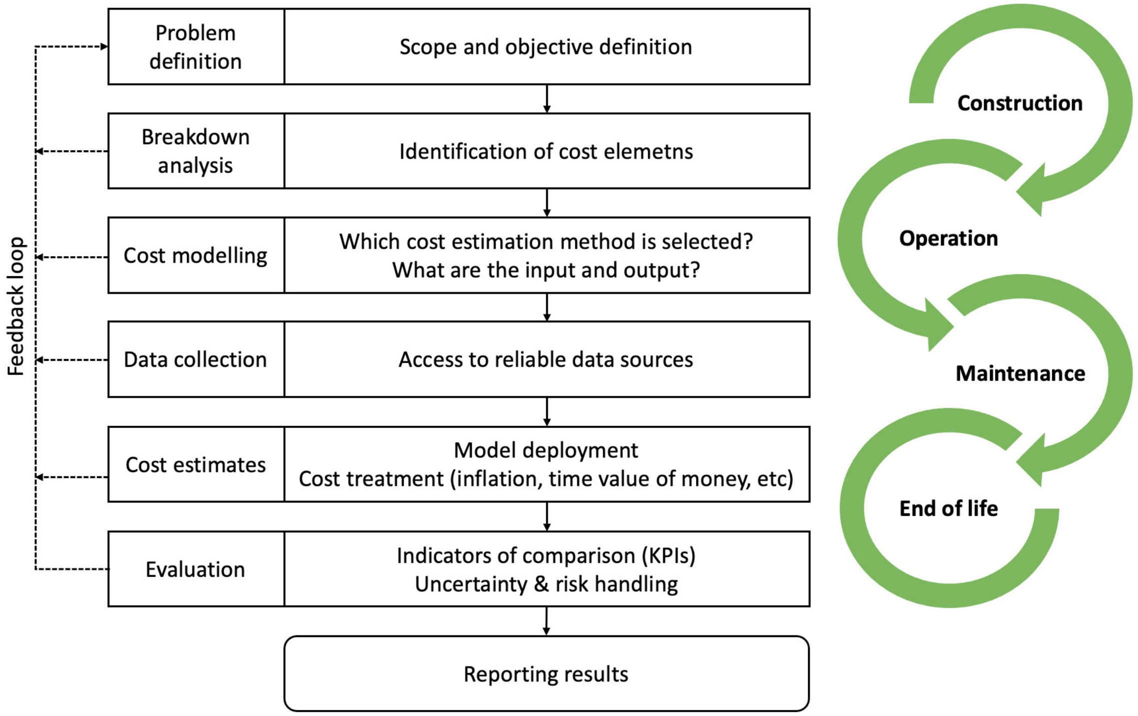

Fig. 1. The proposed LCCA framework

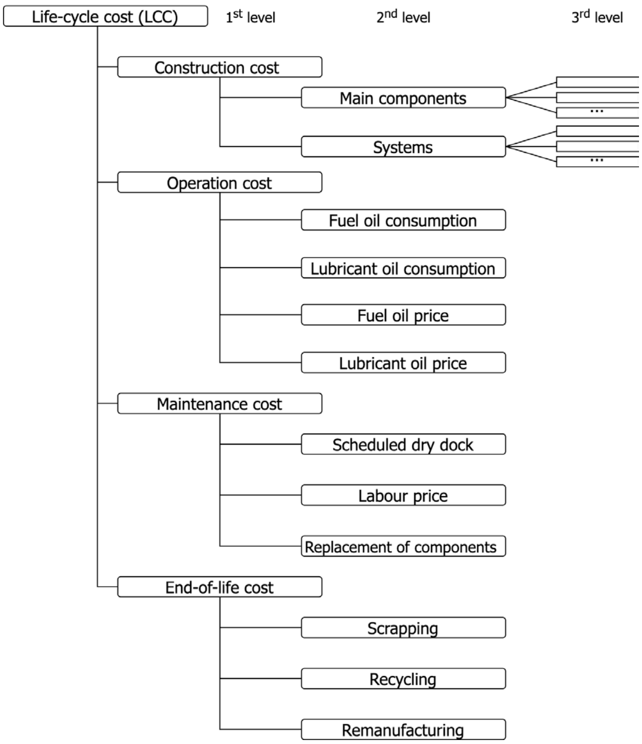

Fig. 2. Cost breakdown structure (CBS) of a marine engine

$SLOC$ is the specific lubricant oil consumption under specific engine output [g/kWh],
H is the yearly operating hours for each operation mode [hour/year],
i refers to different operation modes associated with different engine loads.

Such technical information can be obtained from the technical product guide given by an engine manufacturer combined with the operational profile from a selected ship. The annual fuel oil consumption cost C_{FOC} and annual lubricant oil consumption cost C_{LOC} are expressed as follows, where e_{FOC} and e_{LO} are fuel price [€] and lubricant oil price [€] respectively.

$$C_{FOC} = e_{FOC} \times FOC \tag{3}$$

$$C_{LOC} = e_{LO} \times LOC \tag{4}$$

Maintenance phase As recommended by the engine manufacturer, several components of the engine will undergo through maintenance periods when a number of procedures, including checks, overhauls, repairs and replacements will be performed. The maintenance periods, which provide overhaul intervals for the components, are listed in the engine's Operation & Maintenance Manual (O&MM) given by the engine manufacturer. The maintenance costs for the engine components are calculated by considering a job as basis. Based on the O&MM, the maintenance procedure for each component demands numerous jobs. Each job is associated with a maintenance activity (e.g., check, clean, inspect, replace or renew the respective component), a service interval, a component number, components costs, and labor hours.

End of life phase Scrapping and recycling are usual processes during the end-of-life phase of ships and its associated assets in the shipping industry. In this regard, it is of interest to introduce the concept of circular economy as depicted in Fig. 3. Apart from recycling, remanufacturing and reusing are within the circular economy while scrapping is an disadvantageous process since it produces more waste compared to others. This concept can open up opportunities for the application of the proposed framework in remanufacturing and recycling of the engine's components. Remanufacting opportunities can be observed in many occasions during the engine's life-cycle such as repair, maintenance, overhaul, retrofit/ refurbishment and conversion. By way of illustration, several associated parts of the engine such as piston, connecting rod, exhaust valves, cylinder cover, etc can be remanufactured or can be used for another purposes (second life).

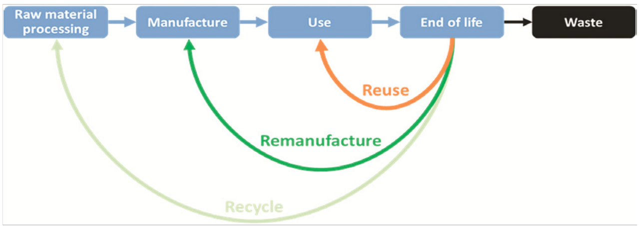

Fig. 3. Reuse, remanufacture and recycle under circular economy concept (Jansson, 2016)

3.3 Cost modelling

It can be perceived from the literature that cost estimation models can be categorized into three groups as follows.

- Analogy model: The principle of this model is to adjust the cost of a similar product in relation with the differences between it and the target product. It is assumed in this model that similar products have similar costs. This model is considered as a case-based approach and its effectiveness depends on the domain knowledge of identifying the similarities and differences between the actual case and the past case. Based on the past cost data, the cost estimation can be done with close and reasonable approximation (Curran et al., 2004; Hueber et al., 2016).
- Parametric model: The backbone of this model is the formulation of "Cost Estimation Relationships" (CERs) and associated mathematical relations between one or more parameters that have influence on the cost changes of a product. Such parameters are referred to "Cost Drivers". A typical example of this is the utilization of weight, size and and costs for establishing a mathematical correlation in order to predict the product costs. This model relies on historic data and cannot be used outside this historic data range. Moreover, it is unable to demonstrate technology changes or altered system requirements (Curran et al., 2004; Hueber et al., 2016).
- Engineering model: This model is also known as a bottom-up approach in which component tasks are identified and sized, and the individual estimates are then added up to provide the final estimate. In order to apply this model to any product, the detailed information regarding design, configuration of the product's systems and components as well as accounting information regarding materials, labour should be available. Although it requires a great deal of information, this approach provides a totally comprehensive process and is practical for new technologies or products (Curran et al., 2004; Hueber et al., 2016).

In this study, the engineering model will be chosen as a basis, combined with the others, depending on the detail level of data available in different phases of the engine's life-cycle.

3.4 Data collection

The data collected in this study have been derived from multiple sources such as the technical product guide, O&MM given by the engine manufacturer, and the operational profile of a selected vessel. Domain knowledge from experts along with data obtained from the literature are also useful for the deployment of the proposed framework.

3.5 Cost estimates

Cost treatment is taken into consideration when deploying the model. Since the value of money today and money that will be spent in the future are not equal, it is referred to as the time value of money. The costs that occur at different stages during the lifespan of the engine cannot be compared directly attributable to the varying time value of money. They shall be discounted back to their present value with the help of the following equation (Welch, 2017).

$$PV = FV \frac{1}{(1+r)^n} \tag{5}$$

where

PV is the present value [€],
FV is the future value in year n [€],
r is the discount rate [%],
n is the number of years.

One of methods employing the time value of money for engine technology evaluation is the net present value (NPV). The NPV calculation involves valuation of both costs and benefits. Since the cost streams are only taken into account, the net present value of costs (NPC) over the period of the engine's lifespan can be expressed as follows.

$$NPC = \sum_{j=1}^{LS} \frac{C_j}{(1+r)^j} \tag{6}$$

where

C_j is the future cost in year j [€],
r is the discount rate [%],
LS is the lifespan of the engine [year]
j refers to a specific year of the lifespan of the engine.

NPC can be used in comparing the cost performance of engine technologies. The engine with the lowest NPC will be preferred.

3.6 Evaluation

The key aspects of the engine technology evaluation can be listed as follows: the indicators of comparison and handling uncertainty and risks. The former offers several economic KPIs, expressed as Capital Expenditure (CAPEX) (i.e. directly related to the construction cost), Operating Expenditure (OPEX) (i.e the operation cost), NPC and so on. This is a performance-based approach to assess and compare the total cost performance of different engines based on the KPIs. The latter includes consideration of uncertainty and risks. In this regard, Monte Carlo analysis and sensitivity analysis can be beneficial to model the uncertainty attached to the costs. Several examples of what it meant by uncertainty are ship operation modes, loading conditions, operation hours, engine performances, fuel costs, discount rate, etc.

3.7 Reporting results

As shown in table 1, the construction cost of the diesel engine ranges from 724K to 1 156K [€]. On average, it is determined approximately as 940K [€].

Table 2 shows an overview of the specifications of the case ship and its diesel engine while table 4 shows the ship's operational profile. The engine load, as a percentage of the maximum continuous rating (MCR) of the engine, varies under different operation modes. Therefore the relative SFOC should be adjusted. This can be done by doing interpolation or extrapolation based on the reference values, as shown in table 3. Fig. 4 depicts the relative SFOC as a non-linear function of the relative engine load. It can be seen from this figure that the minimum value of the SFOC is located at the relative engine load of 75%. Therefore, maintaining the engine loads around this point is required in order to minimize the fuel oil consumption and optimize the engine performance.

Afterwards, the annual FOC in each operation mode can be obtained with the help of (1), as presented in table 4. Similar to the annual FOC, the annual LOC can be determined based on (2), as shown in the same table.

Table 2. Ship & engine specifications

Specification	Value	Unit
Deadweight	7600	Ton
LOA	112	m
Maximum speed	15	Knot
Fuel type	MGO	N/A
Engine maximum power output	3480	kW
Engine speed	750	rpm
Engine's lifespan of analysis	20	year
Annual operation hours	8700	hour

Source: Wärtsilä

Table 3. SFOC at different engine loads (Wärtsilä, 2021)

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

Therefore, the annual FOC and LOC of the engine can be determined as shown in table 5. Table 5 also reports the annual fuel costs and the annual operation cost. It is noted that market prices were used as the input data as follows (Ship & Bunker, 2021).

- MGO price: 506.37 €/Ton
- Lubricant price: 2300 €/Ton

The results of the operation cost suggest that the operation cost is driven by not only the engine loads but also the operation hours.

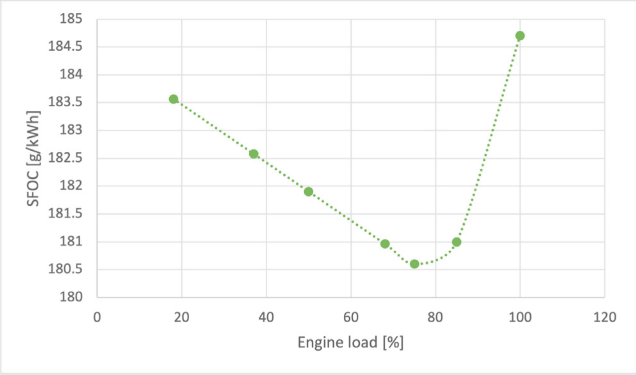

Fig. 4. The relative SFOC as a function of the relative engine load

Table 4. Ship's operational profile

Item	Port	Engine Mode 1 (Manoeuvring)	Engine Mode 2	Engine Mode 3
Annual operation hours [h]	1200	100	300	7100
Speed [Knot]	0	0	13.6	11.5
Percentage [%]	14	1	3	82
Power [kW]	0	635	2354.7	1290.7
Engine Load [%]	0	18.2	67.7	37.1
SFOC [g/kWh]	0	183.56	180.96	182.58
Annual FOC [Ton/year]	0	11.66	127.83	1673.12
SLOC [g/kWh]	0	0.064	0.237	0.130
Annual LOC [Ton/year]	0	0.004	0.167	1.190

Source: Wärtsilä

Table 5. Annual fuel consumption and costs

Item	Value	Unit
Annual FOC	1812.61	Ton/year
Annual LOC	1.361	Ton/year
Annual FOC cost	918K	€/year
Annual LOC cost	3K	€/year
Annual operation cost	921K	€/year

Unit K = 1000 €

The results of NPC for the operation cost are presented in table 6. It is noted that all of the costs are exposed to the effects of the inflation rate of 3.1% (TradingEconomics, 2021) and the nominated discount rate of 1.3%.

Table 6. Results of NPC

Item	Value	Unit
Discount Rate	1.30	%
Inflation Rate	3.10	%
NPC	-21 990K	€

Unit K = 1000 €

Sensitivity analyses were performed for NPC calculations by the application of higher and lower discount rates, as presented in table 7.

Table 7. Sensitivity analyses

Scenario 1	Value	Unit	Scenario 2	Value	Unit
Discount Rate	0.80	%	Discount Rate	1.80	%
Inflation Rate	3.10	%	Inflation Rate	3.10	%
NPC	-23 354K	€	NPC	-20 728K	€

Unit K = 1000 €

4. CONCLUSION AND FUTURE WORK

This study is the first step towards enhancing our understanding of economic impacts on retrofitting investment in a marine engine innovation throughout its lifespan. The results of this study indicate that the operation hours and the engine loads are major contributing factors in determining the operation cost, thereby influencing the total life-cycle cost of the engine. The proposed framework is capable of offering an evaluating tool to assist shipowners in making retrofitting decisions regarding emission reduction. Furthermore, it could potentially be applicable to economic evaluation on any technological investments at the early stage.

On the other hand, the proposed framework requires intensive data gathering and collection. For this reason, the study has only investigated the diesel engine (i.e. the reference baseline). We are currently in the process of gathering more data (i.e. O&MM from the engine manufacturer and domain knowledge through semi-structured interviews with experts) for the maintenance phase. Further studies, which take the LCCA on the SeaTech engine into account, will need to be undertaken. It will be important to compare the total cost performance of the SeaTech engine with that of a diesel engine in a similar context (e.g., power output, engine speed and operational profile). Future studies will also concentrate on performing the Monte Carlo analysis and the sensitivity analysis in order to deal with the uncertainty and the risks that have impacts on the engine's life cycle cost performance.

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