Life Cycle and Cost Assessment on Engine Selection for an Offshore Tug Vessel

E. Oguz, B. Jeong, H. Wang, P. Zhou
Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, G4 0LZ, Glasgow, UK

ABSTRACT: The objectives of this paper are to find the most cost effective and environmental friendly engine configuration and its application on an offshore tug vessel in aspects of cost-benefit and environmental impact. This aim was achieved by a comparison of two different engine configurations applicable to the propulsion system for a case ship, which is currently at design stage in a Turkish shipyard. Options of engine selections are to choose either two large medium speed diesel engines or four small high speed diesel engines connected to two gearbox and two shafts. A focus was placed on evaluating the cost-effectiveness and environmental-friendliness over the ship's potential life ranging from construction to scrapping/recycling including operation and maintenance. Throughout the life cycle of the case ship, this study tracked the flows of cash, energy and emission associated with the cradle-to-grave process of such engines application to the case ship and quantified them as meaningful data for decision-making. Research findings clearly revealed that the application of four smaller engines to the subject ship is more advantageous than two medium engines in terms of cost and environment. In a general view, the results indicate that the option of multiple small engines provides high flexibility in engine operation according to various load profiles, therefore less energy consumption and emissions can be achieved.

1 INTRODUCTION

As the pressure on maritime industry for environmental issues has increased, International Maritime Organization (IMO) has undertaken a number of efforts, particularly with regard to the Energy Efficiency Design Index (EEDI) and Energy Efficiency Operation Index (EEOI) in efforts to curb emission from ships activities (IMO, 2009). These guidelines - EEDI, EEOI and SEEMP - are mandatory requirements since January 2013 (IMO, 2011), being considered a great achievement as they are the first "legally binding climate change convention adopted after the Kyoto Protocol" (MARPOL, 2011). In addition, MARPOL Annex VI Regs 13 and 14 stipulate the phased requirements to reduce sulphur oxides (SO_x) and nitrogen oxides (NO_x) from ship emissions. Such stringent environmental regulations urge shipbuilders and marine engineers to develop a variety of new clean technologies while encouraging the trend of cleaner shipping to be one of the most urgent issues in the shipbuilding and maritime industries.

IMO's guidance, on the other hand, focuses on estimating CO_2 emissions, especially related to ship operations. As the ship progresses from cradle to grave in several stages, the high exactitude of environmental impact contributed by a certain ship may be achieved when investigating the holistic ship life cycle, evaluating on not only GHG emissions but also other potential pollutants. The process of Life Cycle Assessment (LCA) has been proven useful to estimate the holistic environmental impact of ships (Fet et al., 2010). LCA has been widely applied over a range of industries (Koch et al., 2013). As there is much evidence of the benefits of LCA application, this methodology appears to have much room for improvement in the marine, shipbuilding and shipping industries, compared to the IMO index in terms of the environmental impact assessment for ship's activities (Guinée et al 2002, SAIC and Curran, 2006, JRC, 2013, ISO 2006a-b).

In addition to environmental issue, equal efforts have been paid to the development of cost-effective ships through optimal designs and system applications in order to survive tough market competition. Meanwhile, decision makers' interests are generally placed on short-term perspectives, so that cost analysis cannot capture all financial impacts (Fuller, 2010). To remedy this problem, Life Cycle Cost Analysis (LCCA) can be used to calculate the value of a product or service throughout the ship lifecycle (ISO, 2008; Fet et al., 2010). An important role of the LCCA can be said to secure reliable decision

making in the early design stages by shifting focus from short-term costs/profits to long-term ones (Fuller, 2010).
Meanwhile, this paper aims to find the optimal engine configuration of an offshore supporting vessel. Two options were proposed at the conceptual design stage; one is for two medium-sized engines and the other for four small engines. Cost benefits and environmental impacts are investigated to assess which of these configurations is more desirable. To achieve this goal, the LCA and LCCA methodologies are used to drive trustworthy decisions that are useful to ship owners and shipyard representatives.

2 APPROACHES

A ship faces several different phase from the cradle-to-grave. In this study, ships' life cycle divided into four main phases: construction, operation, maintenance and scrapping for LCA and LCCA. Assuming that the vessel has a life expectancy of 30 years, the life cycle of the proposed systems is modelled and the flow of costs, energy and emissions - based on the resources spent and emissions produced - are analysed for each stage. The approach to analyse the impact of LCA and LCCA on a product or process during the lifecycle depends on the level of detail required, the resources available and the focus of priority (Koch et al., 2013).

The LCA and LCCA of this paper are demarcated to provide estimations that can compare the two different engine configurations according to the financial and environmental impacts during the life cycle process. Here we discuss the scope and basic methodology of LCA and LCCA.

2.1 *LCA*

This paper considers four types of environmental impacts: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and Photochemical Ozone Creation Potential (POCP). Likewise, this paper is identified the medium mainly contributing to such types of environmental impacts and the normalization factors of CML 2016 are also detailed in Table 1 (Gabi, 2017).

Table 1. Emission types considerations for different impact categories in GaBi model.

Emission	GWP kg CO_2	AP kg SO_2	EP kg PO_4	POCP kg ethene
Ammonia(air)	x	3.2	0.35	x
Ammonia(fresh water)	x	x	0.35	x
Ammonia(sea water)	x	x	0.35	x
Carbon dioxide	1.0	x	x	x
Carbon monoxide	x	x	x	0.027
Chemical oxygen demand	x	x	0.022	x
Dinitrogen oxide	265.0	x	0.27	x
Ethane	x	x	x	0.123
C_2H_4 (Ethene(ethylene))	x	x	x	1.0
Hydrogen chloride	x	0.749	x	x
Methane	28.0	x	x	0.006
Nitrogen oxides	x	0.5	0.13	0.028
Phosphate	x	x	1.0	x
Sulphur dioxide	x	1.2	x	0.048
Toluene	x	x	x	0.637

The quantity of pollutants calculated from the LCA model at each lifetime stage of the ship, multiplied by the normalization factor, present a more comprehensive picture of the actual environmental impacts. This formula can be shown in Eq. (1).

$$EI_t = \epsilon_e \cdot N_e \tag{1}$$

ϵ_e amount of pollutant for the given time frame
N_e normalization factor for any of GWP, AP, EP or POCP for each pollutant
EI_t environmental impact for any of GWP, AP, EP or POCP for each pollutant

2.2 *LCCA*

All relevant output costs contributing to the life cycle costs are grouped into construction costs (initial costs) $C_C = (C_1, \ldots, C_{nC})$, operation costs $C_O = (C_{nC+1}, \ldots, C_{nO})$, Maintenance costs $C_M = (C_{nO+1}, \ldots, C_{nM})$ and Scrapping costs $C_S = (C_{nM+1}, \ldots, C_{nS})$ (Niekamp et al., 2015). Thus, the total vector for the LCC can be expressed in Eq. (2).

$$\vec{C} = \begin{pmatrix} \vec{C}_C \\ \vec{C}_O \\ \vec{C}_M \\ \vec{C}_S \end{pmatrix} = (C_1, \ldots\ldots, C_{nC}, C_{nC+1}, \ldots\ldots, C_{nO}, C_{nO+1}, \ldots\ldots, C_{nM}, C_{nM+1}, \ldots\ldots, C_{nS}) \tag{2}$$

Therefore, Life-cycle cost calculation can be drawn in Eq. (3).

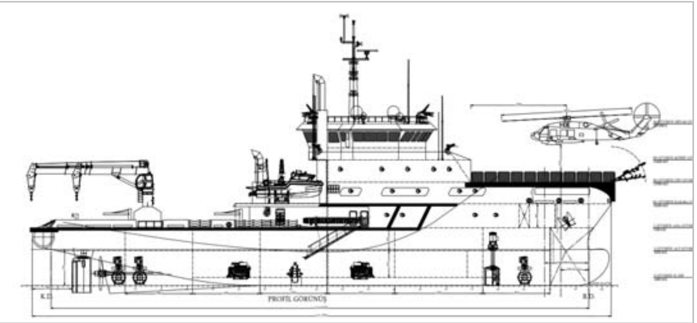
$$LCC = \sum_{i=1}^{nC} C_{C,i} + \sum_{i=nC+1}^{nO} C_{O,i} + \sum_{i=nO+1}^{nM} C_{M,i} + \sum_{i=nM+1}^{nS} C_{S,i} = \sum_{i=1}^{nT} C_i \tag{3}$$

The time value of the costs will affect the monetary value of the cost flow. The concept of net present value (NPV) can be used to measure the present value over a period of project time in consideration of discount rates. The present value (PV) of each types of costs C_i can be calculated by applying the discount rate and time spent as described in Eq. (4).

$$PV(C_i) = \frac{C_i}{(1+r)^t} \tag{4}$$

r discount rate
t time spent

The sum of all discounted cash flows can be, then, expressed in net present value (NPV) that represents the PV of all future cash flows related to the proposed engine configurations as formulated in Eq. (5).



L x B x D	72.6 m x 16.0 m x 7.2 m	
Displacement	2,270 tons	
Main engine	Initial case	Alternative
	MAN 4,500kW x 720 RPM (2sets-each weight 51 tons)	MAN 2,220kW x 1900 RPM (4 sets-each weight 8.5 tons)

$$NPV = \sum_{i=1}^{n} PV(C_i) \quad (5)$$

3 MODELING FOR CASE STUDY

This section presents the life cycle models of the engine configuration for case ship. The general description of the case ship along with main engine characteristics used for two configurations are outlined in Table 2.

Table 2. Specification of case ship.

The basic option for main engine configuration is to install two sets of 4,500 kW engines, each of them is connected directly to the propeller shaft (hereafter referred to as 'base' option). Second option consists of four sets of 2,220 kW engines, each two of which is connected to a single shaft via a gearbox (hereafter referred to as 'alternative' option). Fig. 1 shows the engine configurations.

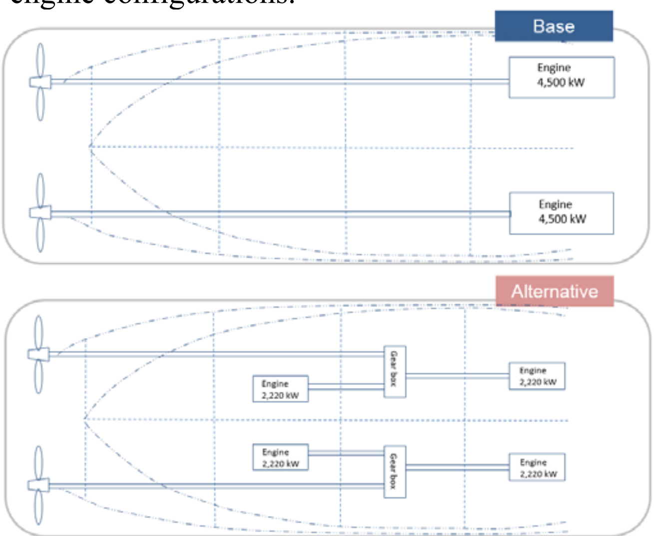


Figure 1 Diagram of engine configurations

3.1 *Construction*

Typically, the shipbuilding phase includes all activities to build, assemble and install all the materials and machinery selected at the early design stage and to deliver the new vessel to the ship-owner in order to operate the shipping business. Given the purpose of this study, meanwhile, the scope of ship construction phase is limited to the activities associated with the construction of main engines ranging from main engines at manufacture and its transportation to shipyard to on-board installation.

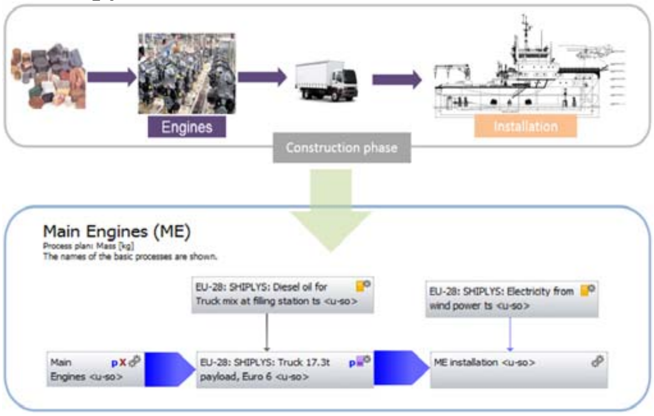


Figure 2 Engine construction processes

The life cycle model for construction phase was built with GaBi software and presented in Fig. 2. It indicates that the process and boundary of evaluation start with the purchase and include its transportation to the vessel and installation on board.

In the case of LCA, the consumption of fuel for transportation and electricity for installation were analysed. In particular, it is assumed that diesel oil supplied from a local gas station used for trucks that transport the engine from the factory to the shipyard. The distance was assumed to be 100 km.

Regarding LCCA, the costs associated with the prices of engines and energies consumed for the installations are listed in Table 3 based on Eurostate. The data were collected from a variety of sources, particularly literature and shipyard information.

Table 3. Cost assessment for engines construction: list of prices and quantities.

Category	Price			Quantity		
	Base	Alternative	Unit	Base	Alternative	Unit
Engine	373,500	182,600	€/set	2	4	Set
Transportation	1.615		€/km	1000		Km
Diesel	1350		€/ton	1507	502	Kg
Electricity	0.033		€/MJ	51,000	17,000	MJ

3.2 *Operation*

The production, transportation and consumption of fuel and lubricants are important issues with an emphasis on the operation of selected marine engines in relation to ship operation.

The process and boundary of the analysis outlined were transformed into Gabi model as shown in Fig. 3. The process presented here beginning from production of the fuel and lubricants at refinery and finishing by burning them onboard while the initial production of the crude oil at reservoir and its transportation to the refinery were not considered. In this process, the flows of energy and emissions were tracked for LCA and the cash flow was monitored for LCC.

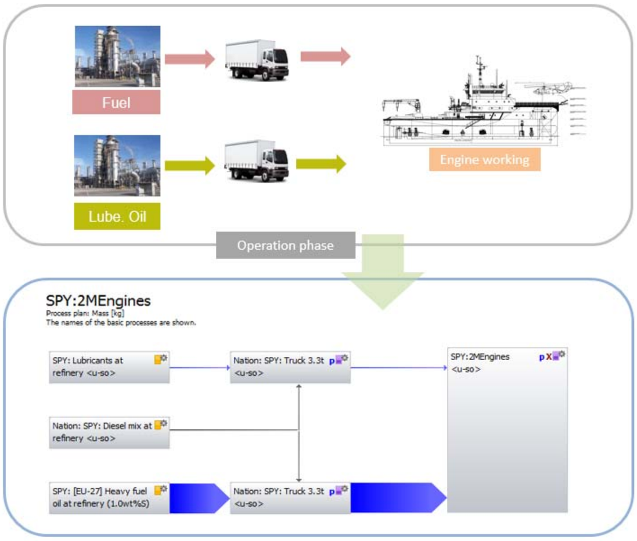


Figure 3 Engine operation processes

In the case ship, as a conventional benchmark, marine diesel oil (MDO) with Sulphur content 1.0% was assumed to be used in the main engines. For LCCA, fuel prices are determined as below.

- MDO price = 290.58 Euro / ton
- Lubricant price = 1681 Euro / ton

In any year, the load on the engine depends on the operating model, and the sum of the annual fuel consumption is the consumption of time spent in each operating mode as expressed in Eq. (6).

$$F = \sum_{i=1}^{n} FS_i \cdot P_i \cdot T_i \tag{6}$$

FS_i specific fuel consumption as a function of engine load

P_i engine load for each engine load

T_i Time spent in each operating mode

$$L = \sum_{i=1}^{n} LS \cdot P_i \cdot T_i \tag{7}$$

LS specific lubricant consumption

$$C_F = \sum_{i=1}^{n} \text{€}_{fc} \cdot FS_i \cdot P_i \cdot T_i = \text{€}_{fc} \cdot F \tag{8}$$

€_{fc} fuel price

$$C_L = \sum_{i=1}^{n} \text{€}_{lc} \cdot LS \cdot P_i \cdot T_i = \text{€}_{lc} \cdot L \tag{9}$$

€_{lc} Lubricant price

The proposed operational profile for the case ship was determined as shown in Table 4. Its propulsion power was estimated from the shipyard based on their previous ship building records. The fuel consumption and emissions are quantified in three different modes: 14, 16 and 18 knots while engine operation is disregarded in port and dynamic positioning (DP) mode. The emission specifications are derived from the published literature (Calton et al, 1995; Alkaner and Zhou, 2006).

Table 4 Operational profile of case ship.

Category		Port	14knot	16knot	18knot	DP
Operation (%)		20.0	60.0	10.0	5.0	5.0
Time (hrs/year)		1752	144	87	438	438
Propulsion power (kW)		0.0	1767.0	3451.0	5885.0	0.0
Base	Num. of Engines	0	2	2	2	0
	Load (%)	0.0	19.6	38.3	65.4	0.0
	SFOC (g/kWh)	0.0	240	243.2	216.2	0.0
	Fuel cons. (tons/year)	0.0	2562.7	735.1	557.4	0.0
	LO cons. (tons/year)	0.0	6.0	2.0	1.7	0.0
Alternative	Num. of Engines	0	2	2	4	0
	Load (%)	0.0	39.8	77.7	66.3	0.0
	SFOC (g/kWh)	0.0	241.1	212.0	215.8	0.0
	Fuel cons. (tons/year)	0.0	2239.3	640.8	556.2	0.0
	LO cons. (tons/year)	0.0	6.0	2.0	1.7	0.0

** Specific LO consumption is uniformly applied to 0.65 g/kWh*

Table 5 Emission factors for marine diesel engine operation

Engine Emission	Fuel based factor* (tonnes /fuel-ton)
NOx	0.0570
CO	0.0074
CH4	0.0024
CO2	3.1700
SOx	0.02 (=20×(1.0)%S content)

**Carlton et al, 1995; Alkaner and Zhou, 2006*

3.3 *Maintenance*

The structure of the marine engine consists of several parts and it is necessary to carry out regular maintenance work as planned to confirm that it works smoothly. A daily inspection is performed according to the instructions of the engine manufacturer as well as various uptime based maintenance such as 200 up to 100,000 hours. Table 6 indicates the periodical maintenance schedule specified by the manufacturer. The LCC for maintenance is carried out based on the engine operating time during its lifetime. Fig. 4 shows the relationship between the engine operating time and the driving year while the total costs for engine maintenance over time is presented in Fig. 5.

The environmental impacts associated with the production and transportation of marine engine spare parts during the maintenance phase were disregarded because the range of environmental impacts at this stage is relatively small compared to other stages and there is a limit to the LCA for maintenance with uncertainties.

Table 6 Engine maintenance profiles.

Interval (hours)	Working time (hours)	Spares to be renewed	Spare costs (% engine costs)
Daily	0.4	-	-
200	2.75	-	-
400	4.20	Oil changes	0.09 %
1,200	0.50	- spin on oil filter - seal ring - Fuel filter cartridge - Spin on fuel filter - Valve cover gasket	1.67 %
4,000	1.30	-	-
6,000	4.00	- v-belt - injection nozzle - seal ring - air cleaner cartridge Micro-station - filler cap	5.29%
10,000	30	- Repair kit for water pump - Rubber hose - Corrugated hose - Injectors - Turbocharger - Bearing fan - Belt pulley	49.21 %
20,000	40	- Connecting rod bearing - Keystone ring - Taper Face Compressing ring - Bevelled oil Scraper Ring - Cylinder liners - Alternator - Starter	20.75 %
40,000	70	- Pistons - Crankshaft main bearings - Thrust bearing - Valve guide intake - Valve guide exhaust	47.4 %

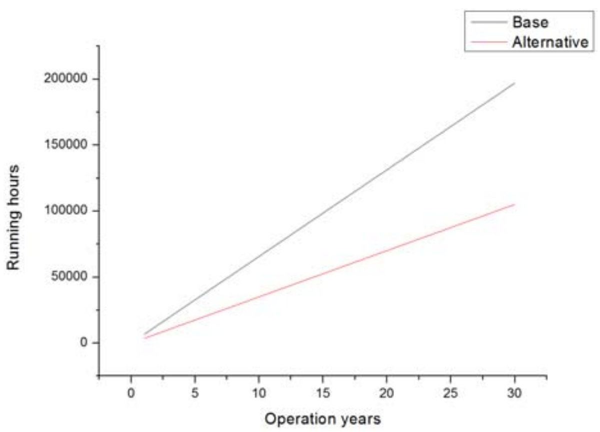


Figure 4 Running hours or each engine vs operation years

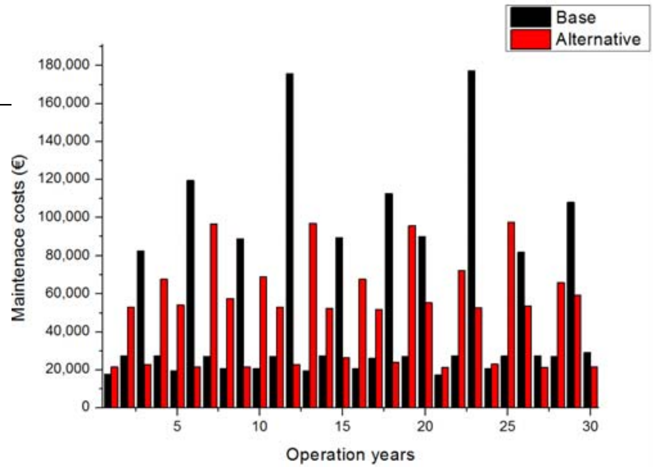


Figure 5 Annual costs of engine maintenance

3.4 *Scrapping*

The scrapping of a ship covers docking, disassembling, transportation and treatments for an end of life ship. For iron scrapping as an example, it will go through the following processes: collection, sorting and analysis, processing (shredder processing, dezincification treatment and briquette processing) and shipping to steeling maker or casting maker. Through these processes, parts of iron will be recycled for making steel and cast iron and the others will be disposal such as land fill and incineration.

As this case study focuses on the main engine, the scrapping of main engine will be indicated, modelled and analysed using GaBi software and the model is presented in Fig. 6. The evaluation of main engine scrapping starts from end of life ship where the engine is disassembled. Then the engine will be transported for scrapping and recycling after disassembling different materials from the main engine. Table 7 presents data about the contents of an engine and these materials will be considered in the scrapping model of ship life cycle analysis model. According to this table, steel and cast iron occupy the most of the mass of a main engine and other materials like aluminum, copper, zinc, lead and nickel only take small portion of mass.

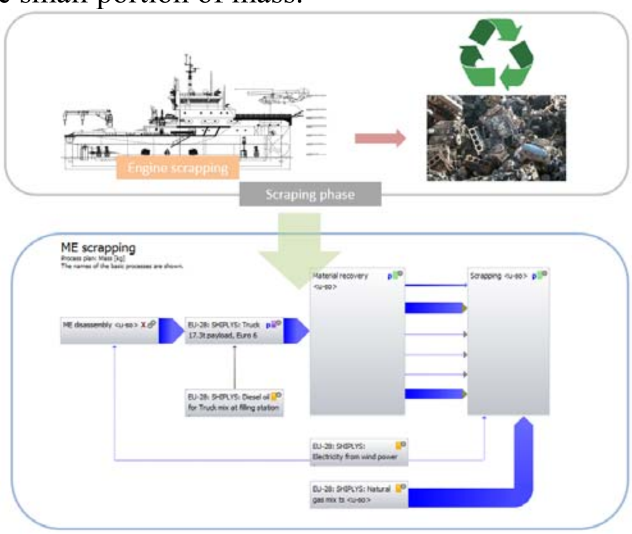


Figure 6 Engine scrapping processes

Table 7 Material content of main engine

Engine Material	Weight Ratio (%)	2200kW (8.5 t)	4500kW (51 t)
Steel	40	3.40	20.4
Cast iron	46	3.91	23.46
Aluminum	8	0.68	4.08
Copper, Bronze, Brass, Zinc	0.2	0.01275	0.0765
Lead	0.1	0.0085	0.051
Plastic	0.9	0.0765	0.459
Rubber	0.9	0.0765	0.459
Paints	0.9	0.0765	0.459
Oils and Grease	3.0	0.255	1.53
Total	100	3.2	4.0

4 RESULTS

4.1 *LCA Results*

As a result of evaluating the impact on the environment from the life cycle of the ship as shown in Fig. 7, it was shown that the operation phase is expected to generate a relatively large amount of pollutants compared to other three phases. It reveals that alternative case is preferable to base case. This is because the environmental impact is relatively smaller than that of the base case. To be specific, it revealed that GWP (4.17E+8), AP (8.05E+6), EP (1.31E+6) and POCP (4.33E+5) for Base case while GWP (3.71E+8), AP (7.16E+6), EP (1.17E+6) and POCP (3.86E+5) for Alternative case.

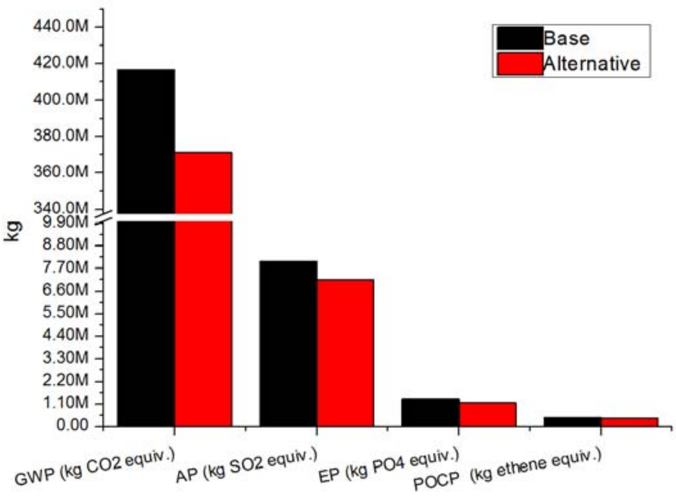


Fig. 7. Results of LCA

4.2 *LCCA Results*

The results of LCCA were illustrated in Figs. 7 and 8. In the same line with the LCA, it shows that the alternative case is more profitable as the costs of ships' life cycle is relatively smaller than the base case. This shows the benefit of approximately € 3,590,000 obtained when alternative case is applied to the case ship rather than base cases.

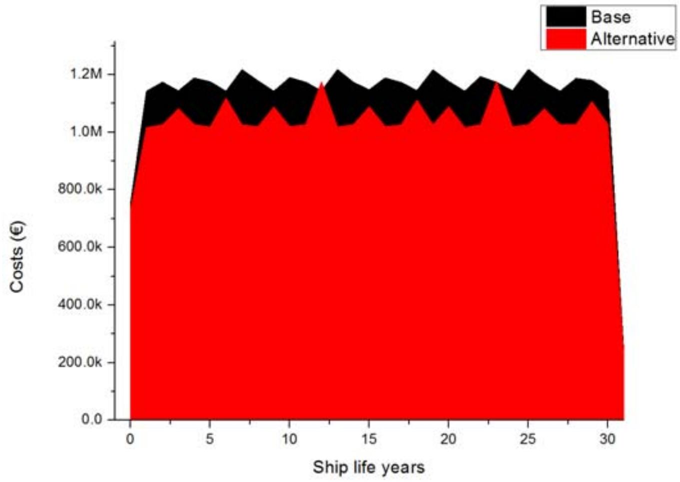


Fig. 8. Cost distribution over ship life years

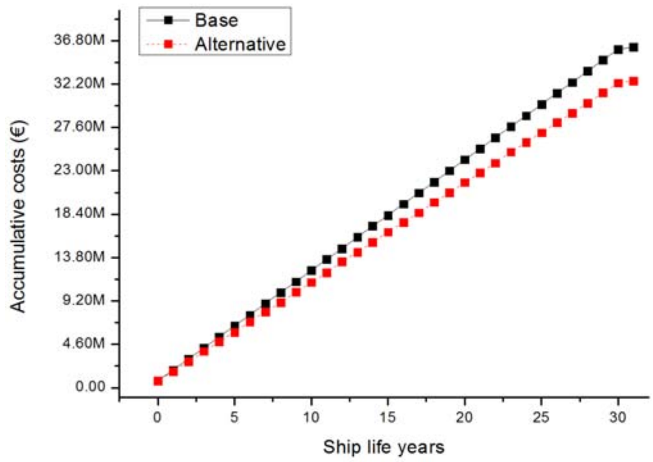


Fig. 9. Exceedance Cost over ship life years (without considering discount rate)

This paper considers discount rate of 5, 10, 15 % over time value. The results are shown in Fig. 10 indicate that the higher discount rate gives rise into higher cost flow and higher overall cost as expected. Also, the high discount rate increases the cost of the project exponentially, thereby worsening the cost gap between base and substitution.

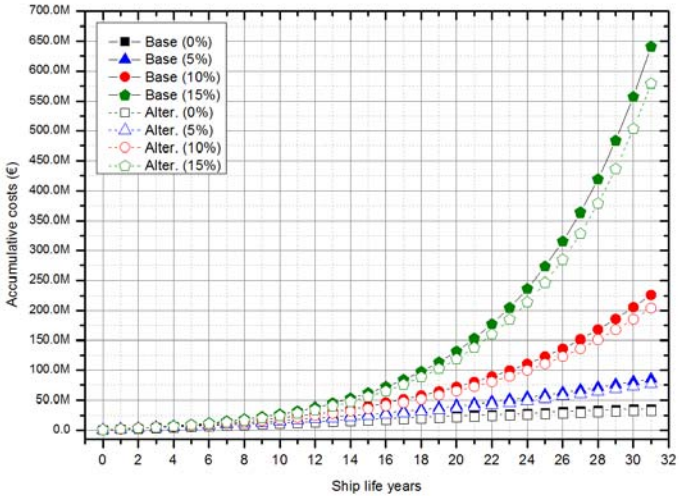


Fig. 10. Accumulative cost over ship life years (considering discount rates – 5, 10, 15%)

5 PARAMETRIC STUDY

This case study analyzed LCA and LCCA based on the shipyard proposed operational profile. However, it is also conceivable that in the long term the case vessel may be engaged in different operating conditions. This section examines the sensitivity of LCA and LCCA results for changes in mode of operation as a parametric analysis.

Based on the proposed operational profile, the vessel annually operates 95,484 nautical miles. Given the fact, two scenarios are assumed to confirm the sensitivity of different distribution of vessel speeds over LCA and LCCA.

- Case 1: The ship is only operating 14 knots in a slow steaming strategy.
- Case 2: The ship is only operating at full service speed of 19 knots.

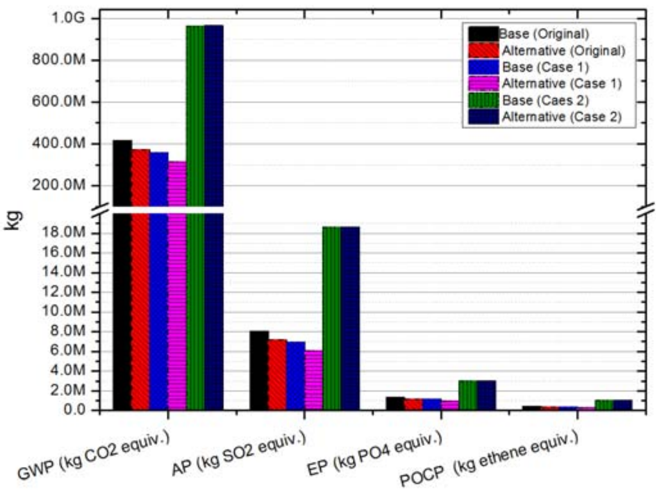


Fig.11 Results of LCA for parametric analysis

The LCA results presented in Fig. 11. Results reveal that Case 1 where slow-streaming strategy is applied has relatively low emission impacts while the Case 2 engaged in the full service speed leads to higher emission impacts overall. For Case 2, similar LCA results are driven: maximum GWP (9.64E+8), AP (1.86+7), EP (3.03E+6) and POCP (1.0E+6).

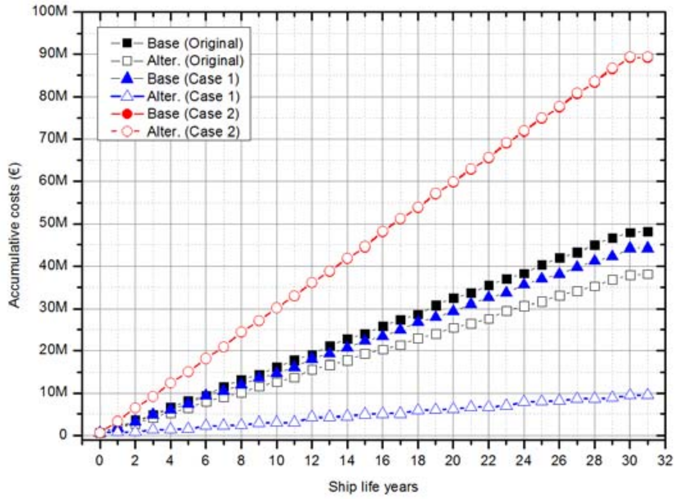


Fig.12 Accumulative cost over ship life years (without considering discount rate)

The parametric analysis shows that the trend of Case 1 has a growing gap between the base and alternative engine configurations while that of Case 2 has a narrowing one. This result implies that the small engines configuration is more beneficial when the case ship is operated in low loads rather than full load.

In addition, it can be expected, the full speed operation (Case 2) has more costs mainly from fuel consumptions and maintenance costs in needs compared to slow-steaming mode (Case 1) or original operational profile. This result also addresses and demonstrates the well-known knowledge that the operating ships in low speed is more desirable in terms of cost-benefit and environmental impacts.

6 DISCUSSION

This study was to apply life cycle and cost assessment technique into an offshore tug vessel to investigate appropriate propulsion systems in terms of cost and environmental impacts. In this context, it investigated potential cost savings and environmental impact reductions by choosing an optimized engine configuration. The analysis presented as cash flow, energy flow and all associated activities of the ship based on LCA and LCCA modelling.

The marine industry is still far away from using LCA and LCCA technique to carry out optimal decision making during the early design stage of ships. This paper focuses somewhat on the optimal selection of marine propulsion power system, so extending the application of this new framework to various other industrial cases is worthwhile.

It was shown that the iterative process of parametric analysis helps the ship-builder or ship-owner be able to compare different design options by reverting to and redefining the parameters, the results of analyses provide them an insight into optimal selection in either positive or negative environmental impact categories and cost benefit categories.

Meanwhile, additional work is still needed because there are some estimates and assumptions before case studies that may possibly effect the analysis results. It is therefore always advisable to derive an extensive amount of realistic data to perform detailed and accurate life cycle analysis.

7 CONCLUSION

This paper was mainly designed as a preliminary study to provide shipyards, ship-owners, and researchers with a toolkit that presents a lifecycle view of their systems and products according to various working scopes. The focus was placed on the general application of LCA and LCCA knowledge into the marine industry where is considerable space to develop. An optimal framework for life cycle ship design was introduced to facilitate analysis by modulating LCA and LCCA modelling or calculations.

The research findings suggested the alternative case (four smaller engines) can reduce costs and environmental impacts compared to the base case (two medium engines) in terms of flexibility of small engines and effectiveness of ship operation in a wide range of loading conditions.

It also revealed that operation is the most influential stage of all life cycle stage of ship activities, thereby choosing the optimal propulsion system is crucial to achieve energy-saving and green ship voyages.

Meanwhile, it also showed that LCCA can be extensively used to estimate the overall cost of shipping activities which allow ship designers and ship-owners make reliable decisions to ensure optimum choice at early design stage.

8 ACKNOWLEDGEMENT

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