Life cycle assessment of an antifouling coating based on time-dependent biofouling model

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Abstract

This paper presents a novel life cycle assessment (LCA) for antifouling coatings based on a time-dependent biofouling prediction model. The life cycle assessment covers environmental and monetary effects born from paint production to application, hull maintenance and added fuel consumption due to biofouling on the ship hull. The calculations related to the production and applications of the paints were made using the data provided by shipyards and coating manufacturers.The added frictional resistance due to biofouling accumulation and hence the added fuel consumptions during ship operations were predicted by time-dependent biofouling model proposed in the literature and then implemented into the overall life cycle assessment. The effects of ship operating profile and route on the fuel penalty due to biofouling accumulation on the antifouling coating were investigated for three case studies. The results were presented in terms of differences in increases in effective power, fuel oil consumption, fuel oil consumption costs, total costs and CO_2 *emissions due to different ship operating profiles and routes.*

1. Introduction

The use of fouling control coatings is the most effective method to keep ship hulls clean. There are several types of fouling control coatings mainly categorised into two groups in terms of their working principles such as biocidal and non-biocidal coatings. Biocidal coatings, for example, controlled depletion polymer (CDP), self-polishing copolymer (SPC), hybrid SPC type coatings, release biocides to delay biofouling accumulation on a ship hull. On the other hand, non-biocidal coatings, i.e. foul-release coatings, provide comparatively smooth surface and hence notably decreases the adhesion strength of fouling organisms (Judith et al. 2013). Although it is possible to find a large number of coating products within different types in the market, there is no scientifically grounded approach or method to select the most suitable coating for specific ships (Swain et al. 2007).

IMO (2011) published a guideline for the control and management of ships' biofouling to minimise the transfer of invasive aquatic species. As mentioned in this guideline there are factors to consider while choosing an antifouling system. These factors can be listed as follows:

- Planned maintenance schedule (dry-docking periods): schedule of underwater hull cleaning and dry-docking operations may influence on fouling control coating selection. For instance, CDP type paint could be more cost effective compared to SPC type paint for a ship which undergoes dry-docking every 3 years of operation (Lejars et al. 2012).
- Ship speed: fouling control coating selection may rely on the ship speed which is also a definitive parameter for ship type. Non-biocidal, foul-release coatings provide a self-cleaning feature for a certain range of ship speed (Yebra et al. 2004).
- Operating profile: ship operating profile may show varieties based on the type of ship and contract. Ship type and operational behavior play a significant role in coating selection as well. For example, slow polishing antifouling and foul-release coatings are more suitable for high-speed vessels with short idle time periods, while fast polishing coatings are more effective to keep the hull surface smooth for slow vessels with long idle time periods (Yebra et al. 2004).
- Any legal requirements for the sale and use of the antifouling system.

According to International Standard Organization (ISO), life cycle perspective is required to assess the whole consecutive and linked stages of a product system, from the raw material acquisition or generation from natural resources to final disposal (ISO 2006). As described by Curran (2006) life cycle assessment is a way to evaluate a system or product by taking everything into account in relation to the subject in question from beginning to end. This approach covers all processes for a product or system from manufacturing to the disposal or recycling of it (Wang and Zhou 2018). According to Curran (2017), there are four interactive steps to conduct LCA on a system or product. The first step should explain the *goal and scope* of the conducted LCA analysis. The next step, namely *Inventory analysis,* presents the collected information about materials, energy and emissions. The environmental impact is assessed in *Impact assessment* step, and finally, the results are presented to decision makers in the *Interpretation* step.

Although it is a well-established and extensively used method in many industrial sectors, its application in marine industry is recent and limited as the ship system is comparatively more complex than the industrial applications. Life cycle studies in marine industry were introduced by Fet (2002) and the study showed that LCA method could be employed for ships, however boundary selection plays an important role and may lead to conflicting results. Shama (2005) presented the detailed ship's life cycle and stated the importance of applying LCA in the marine industry. Based on a life cycle perspective, the design-software was used to assess various green technologies along with their environmental impacts (Tincelin et al., 2010). Chatzinikolaou and Ventikos (2015) conducted a detailed life cycle impact assessment on the hull subsystem of the ship. They estimated life cycle air emissions of a Panamax oil tanker by employing a mathematical framework (Chatzinikolaou and Ventikos 2015). Mountaneas et al. (2014) made a comparison for the environmental impacts of a tanker, bulk carrier and container ship. Wang et al. (2018) applied the LCA process to a short route ferry to investigate the optimum maintenance and construction choices by considering life cycle cost and environmental impacts. Dong and Cai (2019) compared the environmental impacts of two different design solutions, i.e. light hull and heavy hull, for a Panamax bulk carrier. Demirel et al. (2018) developed a model for life cycle assessment of antifouling coatings, and two different coatings were compared in terms of life cycle costs and environmental impacts.

However, there exists no study investigating the effects of ship operating profile on fuel penalty due to biofouling accumulation on the antifouling coatings and hence on Greenhouse gases (GHG) emissions in the framework of a life cycle assessment.

In this study, the effect of ship operating profile on fuel penalty due to biofouling was evaluated using life cycle assessment (LCA) method. The LCA model used by Demirel et al. (2018) was adapted by employing the time-dependent biofouling growth model proposed by Uzun et al. (2018). Then, three case studies were carried out to investigate the effects of operating profile and route on the fuel penalty due to biofouling accumulation on the antifouling coating. The results were presented in terms of increases in effective due to biofouling, fuel oil consumptions and costs, overall costs and CO_2 emissions for 30 years of the life cycle of a bulk carrier ship.

This paper is organised as follows: The developed LCA model along with boundaries and inventory analysis are explained in Section 2. Three case studies were carried out, and the effect of ship operating profile on fuel penalty was evaluated in Section 3. Finally, Section 4 presents conclusions and discussions for the study.

2 LCA Modelling
2.1 Goal and scope definition

This study aims to investigate the effects of different ship operating profiles on the added fuel consumption due to biofouling accumulation and hence extra GHG emissions by using LCA method. The implementation of the model provides interpretations to end users, such as naval architects and ship owners/operators, to decide if the performance of the coating is satisfying for the operation in question. The scope of the LCA consists of three life phases for the antifouling coatings including the application of the coating, operation and maintenance (renewal or cleaning). Construction, dismantling and maintenance due to different reasons are ignored since they are not directly related to the life cycle of the antifouling coating. The performance categories to be compared in the case studies are fuel oil consumptions and costs, total costs and CO_2 emissions.

2.1.1 System boundary, assumptions and limitations

The boundary of developed LCA and series of assumptions and limitations are outlined as below:

- The maintenance schedule is limited only for dry-docking for hull maintenance in every three years; therefore neither machinery nor other maintenances are considered in this study.
- Hull maintenance at each time will provide clean hull surface so that initial fuel consumption values will be used after dry-docking.
- The emissions occurring during paint applications were ignored. However, the cost of each action related with paint application was considered.
- CO_2 emissions due to paint production are taken to be equivalent to the CO_2 emission due to the electricity consumption, and the conversion factor of 0.53936 kgCO_2e / kWh is used for calculations according to Defra and DECC (2010). CO_2 emissions due to main engine fuel consumption are calculated according to emission factors given by International Maritime Organization (IMO 2015). Emissions due to paint application in dry-docks are ignored
- Average vessel life for handy max bulk carrier is taken as 30 years.
- The increases in fuel consumption due to biofouling during the operation phase are calculated based on the time-dependent biofouling growth model presented in Uzun et al.(2018).
- The average market price for heavy fuel oil is taken as 390 $/ton, according to the January of 2019 prices (Global 20 ports average, 2019).
- Environmental impact assessment is made by comparing CO_2 emissions occurred in case studies and taking smooth condition as a benchmark.
- The increment in fuel oil consumption due to biofouling is assumed to be proportional with the increase in effective power.
- The loss of the paint during application is assumed to be 30% for each paint application process.

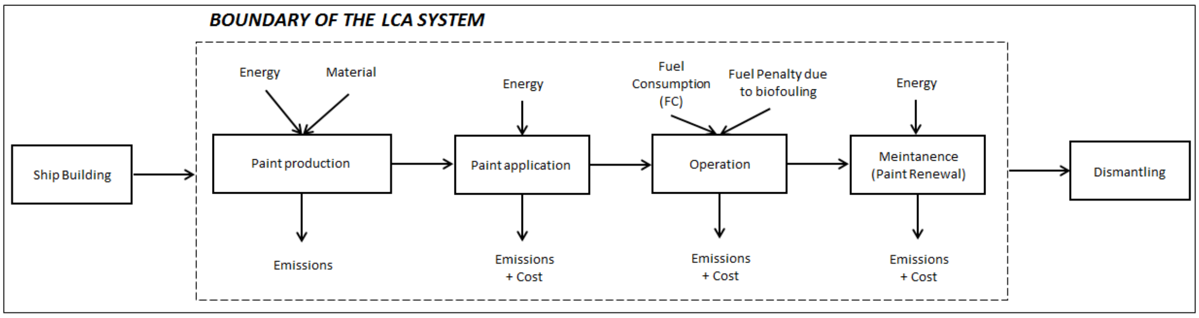

Fig. 1: Boundary of the LCA system

The approach used in Dong and Cai (2019) was adapted and altered according to demands of the present study. Fig.1 illustrates the diagram of the LCA system boundary along with energy, fuel, cost and emissions. As shown in the figure ship construction and dismantling is excluded.

2.2 Life cycle inventory analysis

The available data for LCA is presented in this section. The required data is divided into three categories to conduct this life cycle analysis for evaluating the performance of antifouling coatings. These are listed as follows. It is of note that, from this point onward, the data related to paint applications and costs are not shown explicitly due to the confidentiality issues. However, the examples of the required data are shown in Table III, Table IV and Table V.

2.2.1 Ship and Operation data

A handy size bulk carrier was taken to be operated in three different real bulk carrier operations with varying routes and operating profiles. The ship characteristics and required parameters are given in Table I.

Operating profiles are named as *Operation 1, 2*, *3*, and the details are given in Table II. As can be seen in Table II idle days, average ship speed, sailing days and operating days are available for each operation. In addition to this, three years of real noon reports were used for ship operating profile. The 30 years of ship operating profile was generated over the operating profile data in the first 3 years by assuming that the ship operating profile will be the same during the life cycle. Fig.2, Fig.3 and Fig.4 represent the observed ship routes of operations which are plotted by using GPS coordinates of ship reported in noon data. These figures show differences and similarities between sailing routes of operations as well as the regions of the ports where the ship spends time for loading or unloading operations.

Table I. Ship characteristics

Vessel type	Bulk-carrier
Deadweight	40 k ton
Length	179 m
Breadth	28 m
Design draft	10.6 m
Wetted surface area	7350 m^2
Engine power	6.6 kW
Endurance	25k NM
Fuel type	HFO
FO consumption(t/day) @design draft and speed	20.4

Table II: Ship operation data

Data	*Operation 1*	*Operation 2*	*Operation 3*
Idle days including port stays in 3 years (day)	326	507	284
Average speed (knot)	14	14	14
Sailing day in 3 years	769	588	811
Operating days in 3 years	1095	1095	1095

Fig. 2: Ship route of Operation 1

Fig. 3: Ship route of Operation 2

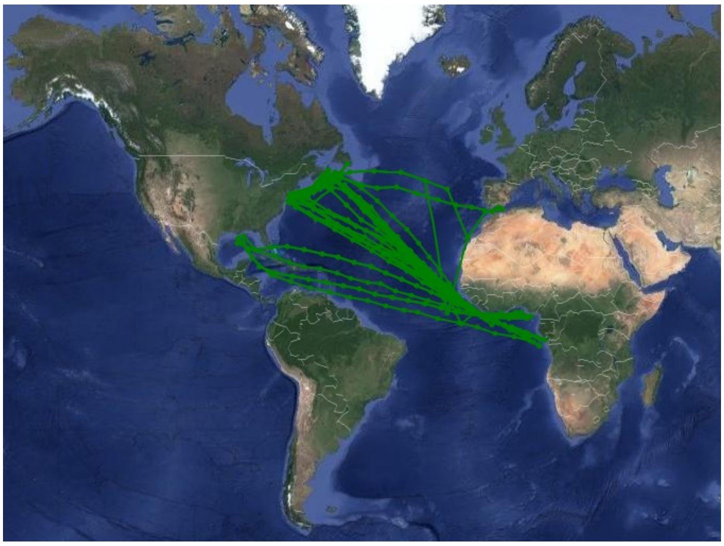

Fig. 4: Ship route of Operation 3

2.2.2 Antifouling coating production

The production of the paint generates emissions indirectly due to energy consumption in acquiring of raw material and processing these materials. However, the emissions only due to electric consumption are taken into consideration as output for this LCA. It is assumed that the paints are produced using the purchased electricity and the conversion factor of 0.53936 kgCO_2/kWh is used according to Defra and DECC (2010). Besides, the selling rate to ship owner is taken into consideration since the life cycle costs are to be also evaluated.

Table III: CO_2 emissions conversions during the production stage of antifouling coating

Paint conversions	Litre/m^2	e kWh/litre	e kWh/m^2	Conversion factor kgCO_2/kWh	kg CO_2/m^2
Anticorrosive					
Tie-coat					
Antifouling (1st coat)					
Antifouling ((2nd coat)					

2.2.3 Antifouling coating application

As a part of coating application on a ship, initial paint application in shipyards and maintenance processes in dry-docks include a series of surface operations listed in Table IV. These surface operations may show variety in price due to the usage of different materials and equipment. Surface operation costs are taken into account for the initial application and all maintenance operations in 30 years of the life cycle period.

Table IV: Cost of surface treatment operations

Surface operation Type	Cost per unit area (\$/m^2)
High pressure fresh water washing	
Wash down after the first coat	
Grit blasting 1st	
Grit blasting 2nd	
Anticorrosive	
Tie-coat	
Antifouling (1st coat)	
Antifouling (2nd coat)	

Table V shows the example of the required data about the costs of coating products and the required amount of these products for per m^2 on the hull surface.

Table V: Cost of paint products

Paint Data	Cost ($/litre)	Amount(litre/m^2)
Anticorrosive		
Tie-coat		
Antifouling(1st coat)		
Antifouling(2nd coat)		

The costs of each action of the initial and dry-dock paint application stage, as well as the paint costs, are considered.

3. Results

3.1 Increases in Effective power

Increases in effective power (P_E) due to biofouling accumulation at a design speed of 14 knots were calculated via time-dependent biofouling prediction model proposed by Uzun et al. (2018) and then were employed in the life cycle model. Three different 3-years of ship operation data were used in the model and at the end of three years ship was undergone to the maintenance operation. This process repeats itself for the 30 years of the life cycle. Calculations on increases in effective power were made for ship design speed.

As seen from Fig. 5, biofouling accumulation occurred during *Operation 2*, caused the most considerable effect on the P_E with an 86% increase with respect to the clean condition. The reason for this significant increase in P_E can be attributed the fact that the 47% of the total time of *Operation 2* was stagnant. In addition, it was observed that ~ 90% of idle days were in a region between 20 and 30 degrees in latitude which can be assessed as medium fouling risk region. It is important to note that *Operation 2* represents an extreme condition and it is used for comparison in this LCA assessment. The maintenance interval is 1 year for this operation in normal conditions.

The increase in P_E for *Operation 1* due to biofouling was predicted to be 37% with respect to the clean hull condition. As can be seen in Fig. 5, the ship was not active during ~ 30% of total operation time in 3 years. In addition to this, ~ 44% of the idle days took place in the region between 0 and 10 degrees in latitude which can be assessed as high fouling risk region. On the other hand, a considerable percentage of the idle days occurred in comparatively cold regions where latitude degrees higher than 30 degrees and hence biofouling growth is slow.

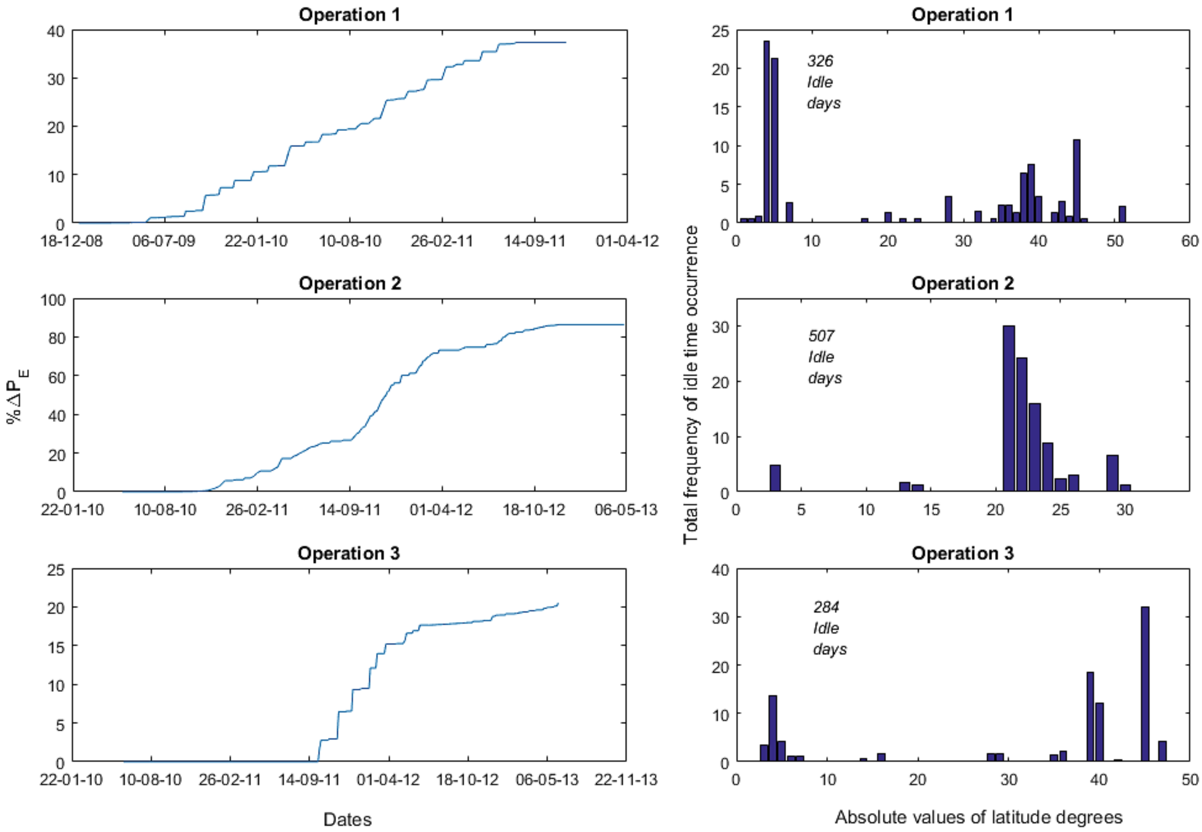

Fig. 5: Increase in effective power for 3 years ship operations along with the relative frequency of idle time occurrence in these operations

The results presented in Fig.5 indicate that the increment in P_E due to biofouling occurred while *Operation 3* was predicted to be 20%. The reason of this comparatively low increase can be attributed the fact that the *Operation 3* is the most active operation with only 26% of the stagnant time in three years of ship operation compared to *Operation 1* and *Operation 2.* In addition to that, the ship spent only ~20% of total idle days in a region between 0 and 10 degrees in latitude which can be addressed as a high fouling risk region. The figure indicates that the important portion of the idle times in *Operation 3* is in a relatively cold region where biofouling growth is restricted because of low temperature.

3.2 Fuel oil consumption and costs

Fig.7 demonstrates the fuel oil consumptions in clean (*Benchmark clean*) and fouled (*Operation fouled*) conditions as well as the difference (*Operation difference*) between these two conditions for each operation over 30 years of the life cycle.

It is seen from the comparison in Fig. 6 that the fuel oil consumptions in clean condition showed a considerable difference for *Operation 2* compared to other operations. As can be seen from Fig.5 idle days of *Operation 2* is comparatively longer compared to other operations; therefore, this leads to lower fuel consumption. On the other hand, it was observed that fuel oil consumption values in clean condition for *Operation 1* and *Operation 2* are similar since the numbers of sailing days of these operations are close to each other. Fuel oil consumptions for the clean condition are ~153.4×10^3 ton for *Operation 1*, ~117.6× 10^3 ton for *Operation 2* and ~158.4 × 10^3 ton for *Operation 3*.

The results illustrated in Fig. 7 showed that fuel oil consumptions in fouled condition were predicted to be ~180.4 × 10^3, ~171.8 × 10^3 and ~172.1 × 10^3 ton for *Operation 1, 2* and *3* respectively over 30 years of the life cycle. The fuel penalties due to biofouling were predicted to be ~26.6× 10^3, ~54.3× 10^3 and ~13.7× 10^3 ton for *Operation 1, 2* and *3* respectively. It is interesting to note that the ship in

Operation 2 burned much less fuel oil as the ship has less sailing days. However, this situation led to a higher increase in effective power and hence extra fuel oil consumption due to biofouling accumulation at stagnant times.

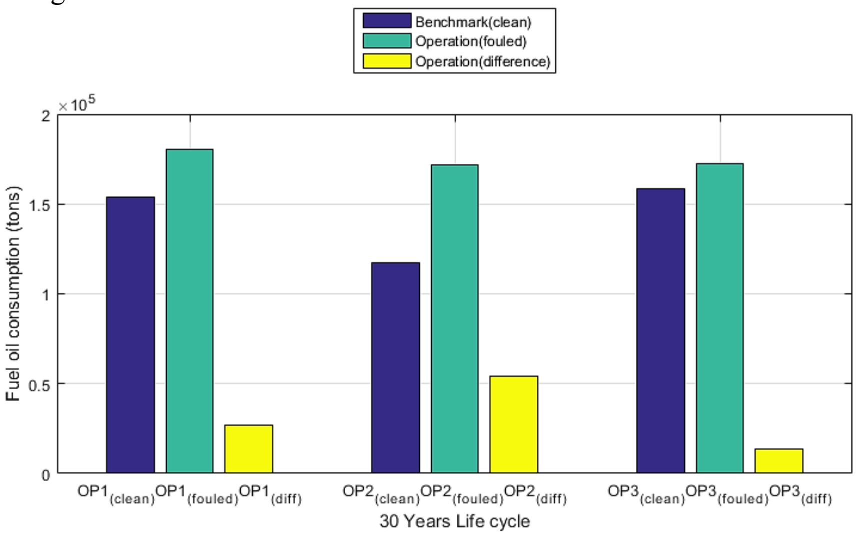

Fig. 6: Fuel oil consumptions over 30 years of life cycle

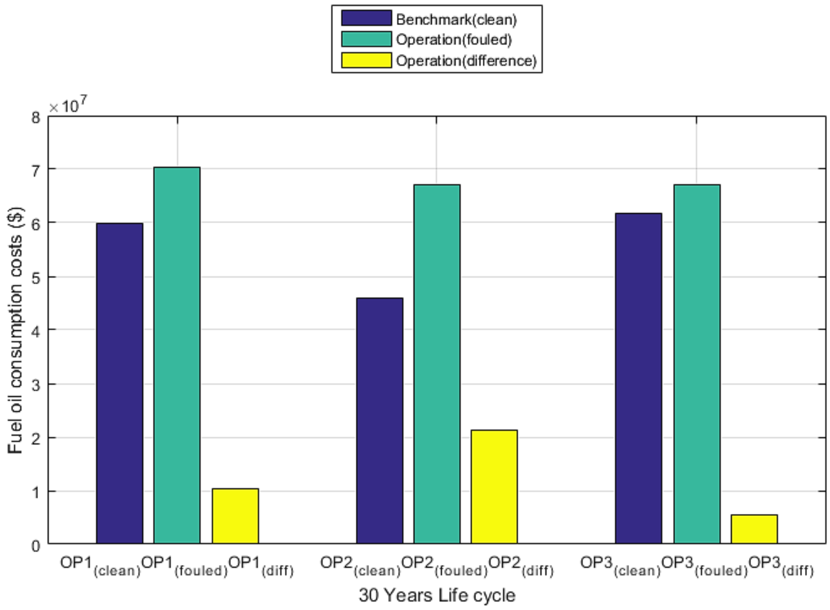

Fig. 7: Fuel oil consumption costs for 30 years life cycle.

Fig. 7 compares the fuel consumption costs for clean and fouled conditions and the differences between these conditions.

The fuel oil consumption costs were predicted to be ~$ 60 million for *Operation 1*, ~ $ 45.8 million for *Operation 2* and ~$ 61.8 million for *Operation 3* for clean conditions whereas these values altered to ~$70.4 million, ~ $ 67 million and ~$ 67.1 million for fouled conditions for *Operation 1, 2* and *3* respectively. The results presented in Fig.7 indicate that fuel penalty costs due to biofouling were calculated to be ~$ 10.4 million for Operation 1, ~ $ 21.2 million for *Operation 2* and ~$ 5.3 million for *Operation 3.*

3.3 Total costs

Fig.8 illustrates the total costs including initial paint application, maintenance and fuel oil costs over 30 years of the life cycle for each operation. As can be seen from the figure same paint application and maintenance procedure was conducted for each operation. Although this does not make any difference between operations, these costs were taken into account as the aim to find total costs over 30 years of the life cycle.

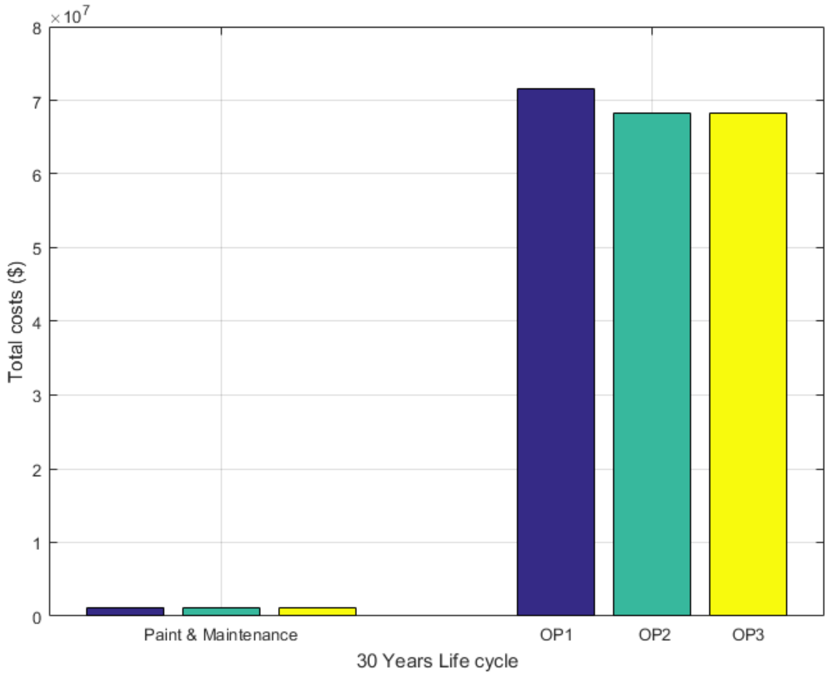

Fig. 8: Paint application and maintenance costs together with total costs for 30 years of life cycle

The results presented in Fig.8 show that total paint and maintenance costs were predicted to be ~$1.2 million for each operation whereas the total costs were predicted to be ~ $ 71.6 million, ~$68.2 million and ~ $ 68.3 million for *Operation 1 2* and *3* respectively.

3.4 Life Cycle Impact Analysis

Life cycle impact analysis was conducted based on the comparison with *benchmark (clean)* condition which is the clean and ideal condition. Since the study does not aim to show Global Warming Potential (GWP) of the operations, this sort of analysis was not conducted.

Fig.9 illustrates CO_2 emissions due to fuel oil consumption as well as the emissions due to paint production for each operation over 30 years of the life cycle. As can be seen from Fig.9 , CO_2 emissions due to fuel oil consumptions was found to be ~479 × 10^6 kg , ~ 430× 10^6 kg and ~493× 10^6 kg for *Operation 1 2* and *3* respectively at clean condition whereas these values changed to ~562 × 10^6 kg,~535× 10^6 kg and ~536 × 10^6 kg respectively at fouled condition.

The results shown in Fig.9 indicate that CO_2 emissions due to paint production were calculated to be only ~ 4×10^6 kg while total emissions were found to be 566× 10^6 kg for *Operation 1*, 539× 10^6 kg for *Operation 2* and 540× 10^6 kg for *Operation 3*.

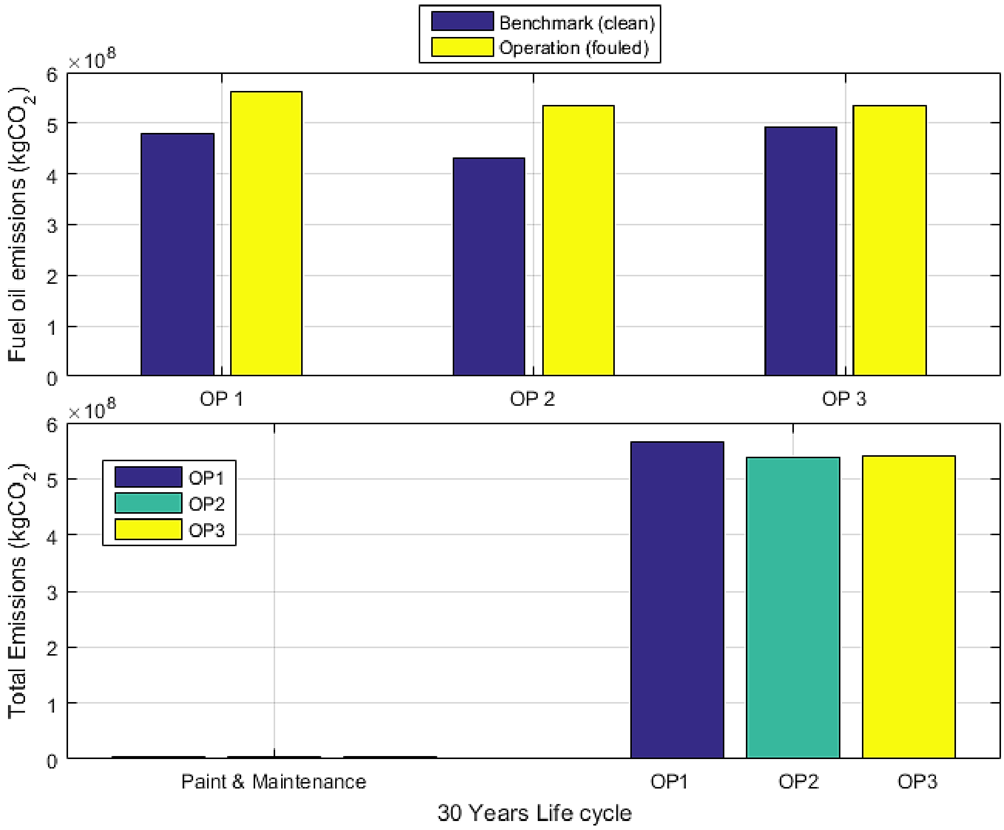

Fig. 9: CO_2 emissions due to fuel oil consumptions along with total emissions including paint and maintenance emissions.

It is of note that the CO_2 emissions due to paint production are negligible when it is compared with those due to fuel oil consumptions. It was observed that the highest amount of CO_2 emissions due to biofouling accumulation, occurred in *Operation 2* and this is followed by *Operation 1* and *Operation 3* respectively. Since this study focuses only on CO_2 emissions, other inorganic emissions were not assessed as a part of life cycle impact analysis. However, other emissions such as CH_4, N_2O, NO_x, *CO* and *NMVOC* can also be calculated with the emission factors provided by IMO (2015).

4. Conclusions and Discussions

The effects of ship operating profiles on the effective power of ship and fuel penalties due to biofouling were investigated via LCA assessment based on a time-dependent biofouling growth prediction model. Three different real 3-years of ship operation data were used to predict the increases in effective power and fuel oil consumptions due to biofouling. The increases in effective power were obtained at a design ship speed of 14 knots. The costs for paint applications and maintenance operations as well as the costs for paint productions were also taken into account. In addition, CO_2 emissions due to fuel oil consumption and paint production were included for the life cycle. The fuel oil consumptions, fuel oil costs, paint and maintenance costs, total costs and CO_2 emissions were presented over 30 years of the life cycle.

The increases in the effective power for the ship were predicted to be 37% for *Operation 1,* 86% for *Operation 2* and 20% for *Operation 3.* It was shown that these increases in effective power due to biofouling caused extra fuel costs of \$10.4 million, \$21.2 million and \$5.3 million for *Operation 1 2* and *3,* respectively.

The total costs were predicted to be ~ \$ 71.6 million, ~\$68.2 million and ~ \$ 68.3 million whereas total CO_2 emissions were found to be 566×10^6 kg, 539×10^6 kg and 540×10^6 kg for *Operation 1, 2* and *3,* respectively.

Having shown the applicability of the LCA method for investigating the effect of ship operational profiles on fuel penalty due to biofouling accumulation on ship hulls, this approach can be used to decide maintenance intervals for the specific ship and operation in question. In this way, paint application, maintenance and fuel oil consumption costs can be compared in order to have cost effective and environmentally friendly maintenance strategies.

By including GHG emissions due to maintenance processes, the model can be updated, and environmental impacts assessment can be conducted evaluating GWP which is regarded as an important marine contributor. This study also suggests that the LCA is an applicable method to evaluate the performance of an antifouling coating in terms of additional fuel oil consumption costs and GHG emissions.

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