Life cycle and cost performance analysis on ship structural maintenance strategy of a short route hybrid

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ABSTRACT: This paper presents the importance of coating maintenance and suggests an optimal strategy from economic and environmental points of view. Life cycle analysis is introduced to estimate the economy and environment impacts so particular decision can be made. A case study of a hybrid ferry is carried out where cash, energy and emission flows are tracked and evaluated. With different maintenance intervals, the consumptions of energy, materials and fuels are evaluated to estimate their cost benefits. Emissions normalization is also applied to determine environmental potentials to determine the relation of environmental impacts which are converted and compared in monetary terms. Annual-based hull inspection and re-coating is proved to reduce hull resistance and fuel consumptions which is a way to achieve cost-saving operations. The assessment has been proven to be able to make reliable decision, so it is suggested to facilitate life cycle assessment in the marine industry.

1 INTRODUCTION

Marine industry has been focusing on maritime emission control for decades and the Greenhouse Gases emission from international shipping has been reduced according to the third Greenhouse Gas Emission Study published by International Maritime Organization (IMO). The document not only indicated the emission reduction from 2009 to 2014 but also emphasised the methodologies of GHG emission estimations (IMO, 2015). Life cycle analysis (LCA) has already been practically applied in many industries and in a wide range of different products and recently LCA started to draw attention in the maritime field.

As a fact, there are still very limited numbers of research focusing on the application of LCA in marine application and most of them are especially for ship building and machinery operation. With consideration on the whole life span of a ship, LCA is a reasonable and suitable tool to evaluate the environmental impact, especially the global warming potential (GWP).

The research work done by Blanco-Davis has applied LCA to aid the shipyards to evaluate retrofitting performances of innovative ballast water treatment system and fouling release coating (Blanco-Davis et al, 2014; Blanco-Davis, Zhou, 2014). Alkaner and Zhou also investigated and compared the performance of fuel cell and diesel engines for marine applications with the help of LCA (Alkaner, Zhou, 2005). Research work done by Strazza's research team applied LCA to evaluate the environmental impact of paper stream on a cruise ship with implementation of different green practices (Strazza et al, 2015). Another LCA analysis carried out by Nicolae and his team determined the environmental impact related to commercial ships by optimization of raw material and energy consumption, and recycle processes (Nicolae et al, 2016). Ling-Chin and Roskilly have carried out two case ship studies comparing conventional and hybrid power system with a comprehensive consideration on construction, operation, maintenance and scrapping phase (Ling-Chin and Roskilly, 2016[a]; Ling-Chin and Roskilly, 2016[b]). With inspiration from these previous works, authors have carried out two case studies focusing on the propulsion system of a short-routed ferry and an off-shore tug vessel. The studies have illustrated the lower cost and environmental impact with applications of battery packs for ferry and switching from 2 medium speed engines to 4 high speed engines for tug vessel (Wang et al, 2017; Oguz et al, 2017). These previous research works are striving to prove the availability of LCA tool in the field of shipping industry. This paper focuses on a more comprehensive LCA analysis to investigate the impacts of different alternative selections or decisions with consideration of life cycle cost and environment analysis for a whole ship life cycle.

Among ship life span, maintenance is one important phase, which usually is very much relevant and interesting to ship operators because the fuel consumption will be influenced by maintenance plan. As there are many research works carried out, the significance of hull coating on the operation fuel consumption is evidenced. Candries and his colleagues investigated three different coating and their impact on roughness and drag forces on ship hull (Candries et al, 2001). Dunnahoe indicated in his research that a more comprehensive dry-docking will help reduce the ship resistance. For example, with a 50% blasting and coating, the total resistance will be reduced by 20% (Dunnahoe, 2008). CFD model has been established by Demirel et al. to simulate different plate roughness due to different coating applied and experimental study has been carried out to determine the relationship between bio-fouling and ship resistance by Turan et al. (Demirel et al, 2014; Turan et al, 2016). The hull resistances were predicted for a tanker and a LNG tanker in their studies. From a long term of view, the hull roughness will impact the fuel consumption and is related to the bio-fouling on ship hull. It means with a regularly removal of bio-fouling the ship resistance could be kept low which will lead to a lower fuel cost. Hearin and his team tested the influence of mechanical grooming on coated panels which indicated that weekly grooming has a much lower fouling rate than a bi-weekly grooming (Hearin, 2015). Tribou and Swain investigated the effect of grooming on a copper ablative coating exposed statically for six years and their conclusions supports that more regular grooming can reduce more fouling on ship hull (Tribou and Swain, 2017). However, even though the dry-docking can greatly improve the energy efficiency, with the time going, the coating can be damaged or covered by bio-fouling which leads to the increasing of hull roughness. To avoid this situation, it is reasonable and practical to carried out regular re-coating to keep the hull roughness in an acceptable region, but the cost of re-coating will be increased which is due to hull washing, blasting and coating. This paper will evaluate the impact of re-coating interval on the ship life cycle financial and environmental performances and provide a guideline for shipyards and ship operators on their coating plans.

2 CASE STUDY GENERAL ASPECTS

2.1 *Introduction*

Since the environmental performance becomes one criteria of ship building, many shipyards ship operators and ship owners are keen to embrace new technologies and strategies to sustain their business. Maintenance plans have been seldom considered as a fact of complexity and long operation period. However, the impacts of maintenance plans cannot be neglected as they will eventually reflect the life cycle performances of the vessel. Inevitably, what values most to the shipyards may not be important to the ship operators and ship owners but as a fact of increasing and intensive competitions of ship-building bids, more cost efficient and environmental friendly the ship is, higher competitiveness a shipyard could be. Therefore, this paper focuses on the maintenance plan which considers from the construction phase to the end of life of a ship, recommending shipyards, ship operators and ship owner to assess the ship life cycle performances to mitigate the impact on the aspects of both cost and environmental.

2.2 *Case vessel description*

The case vessel considered in this paper is a short-routed ferry who regularly serves between islands in Scotland. The selection of this vessel is due to too many manoeuvring in shallow water which leads to more contacts than ocean going vessel. These contacts lead to more re-coating and hull maintenances. The specification of the vessel is listed in the following

Table. To estimate the hull steel and coating area, equations and formulas are presented in the following sections.

Table 1. Case ship specification

Name	MV Hallaig
Gross weight	499 tons
Length	43.5 m
Breadth	12.2 m
Depth	3 m
Draught	1.73 m
C_b	0.45
Power	360kW*3
Superstructure decks	2
Builders	Ferguson Shipyard
Built year	2012

2.2.1 *Steel weight estimation*

To estimate the steel weight in the ship hull structure, two methods are used: cubic number method and empirical equations.

The first method uses a known base ship as a reference and applies block coefficient and length to depth ratio as corrections. The method can be described as following (Papanikolaou, 2014):

$$W_s = W_s{}' \times \frac{LBD}{L' B' D'} \times \frac{1-\frac{1}{2}\times Cb}{1-\frac{1}{2}\times Cb'} \times \frac{L/D}{L'/D'} \qquad (1)$$

Where

W_s is the steel weight for case ship, ton;

W_s' is the steel weight for base ship, ton;

L and L' are the lengths of case ship and base ship respectively, meter;

B and B' are the breadth of case ship and base ship respectively, meter;

D and D' are the depth of case ship and base ship respectively, meter;

C_b and C_b' are the block coefficient of case ship and base ship respectively.

The second method using the empirical equation developed by Garbatov's research team (Garbatov et al, 2017):

$$W_1 = 0.00072 \cdot Cb^{1/3} \cdot L^{2.5} \cdot T/D \cdot B \qquad (2)$$
$$W_2 = 0.011 \cdot L \cdot B \cdot D \qquad (3)$$
$$W_3 = 0.0198 \cdot L \cdot B \cdot D \qquad (4)$$
$$W_4 = 0.0388 \cdot L \cdot B \cdot NJ \qquad (5)$$
$$W_5 = 0.00275 \cdot L \cdot B \cdot D \qquad (6)$$
$$W_s = W_1 + W_2 + W_3 + W_4 + W_5 \qquad (7)$$

Where,

W_s is the steel weight of case ship, ton;

W_1 is the weight of the main hull, ton;

W_2 is the weight of bulkheads in the main hull, ton;

W_3 is the weight of decks and platforms, ton;

W_4 is the weight of the superstructure, ton;

W_5 is the weight of the foundation and other, ton;

L is the length of the case ship, meter;

B is the breadth of the case ship, meter;

D is the depth of the case ship, meter;

T is the draft of the case ship, meter;

NJ is the deck number of the case ship superstructure;

C_b is the block coefficient of the case ship

Applying the ship's particulars listed in

Table, the steel weight can be derived from both methods: applied with first method, the steel weight is about 126.38 ton; applied with second method, the weight of hull steel is approximate 126.22 ton. It is apparent that both methods give similar results, therefore, 126.38 is used as steel weight in this research.

2.2.2 *Coating area estimation*

Coating area in this paper is the wetted surface of the ship which will be merged in the water and attached by bio-fouling.

Figure 1. Vessel hull with bio-fouling before cleaning

Figure 1 presents a hull wetted surface which is partially covered by bio-fouling and will be accumulated while staying in water.

The following Denny - Mumford formula (Molland et al., 2011) is applied to estimate the wetted surface:

$$S = 1.7L \times T + L \times B \times Cb \qquad (8)$$

Where

S is the wetted surface, m^2;

L is the length of the case ship, meter;

B is the breadth of the case ship, meter;

T is the draft of the case ship, meter;

C_b is the block coefficient of the case ship.

Since the steel weight and coating area are determined, the operation and maintenance principles will be discussed in the next section.

2.3 *Operation principle and maintenance plans*

The operation of the vessel is about 10 hours per day between two destinations. The operation can be divided into three parts: sailing, manoeuvring and in port. The daily operation hours are 6, 0.6 and 3.7 hours respectively.

Since this case study is based on a real case ship with its maintenance plans and operation profiles, the details are listed as following:

1. Partial coating: yearly;
2. Full coating: every five years.

The maintenance practice of partial coating is to annually remove bio-fouling accumulated on ship external surface and re-paint the area which will help to reduce the roughness of ship hull to return to its initial condition so that the increasing of the energy efficiency of the vessel can be achieved. As a fact, the vessel is regulated to be dry-docked every five years which will carry out a full coating for the ship hull. Therefore, for every five years, the ship hull roughness is assumed to be returned to its initial condition which leads to the changes in fuel consumption. With the principle of applying different maintenance intervals, costs and energy consumptions due to maintenance will be varied and it is reasonable to determine an optimal maintenance plan to reach a minimum cost and environmental impact. The next section LCA model will be established to carry out life cycle analysis of these impacts on ship performances based on maintenance plans.

3 LCA MODELLING

The LCA model mainly comprises of four phases based on ship life span: construction, operation, maintenance and scrapping. The construction phase is defined as the ship building in shipyards, mainly including the hull construction and machinery installations; the operation phase is when the ship construction is completed and the ship is launched, in service and operated by ship operator; the maintenance of ship is carried out when the ship is in or off services by ship operator on ship or in shipyards, especially including hull and machinery maintenances; scrapping will be carried out when the ship is end of life in order to recycle or disposal the materials and machineries on board. Figure presents an overall view of the four stages of a ship's life span.

3.1 *Goal and scope of the study*

3.1.1 *Ship's maintenance plans*

The goal of this LCA modelling is to evaluate the performances of the case ship considering four life stages: construction, operation, maintenance and scrapping. The performances to be assessed include life cycle cost and environmental impacts which mainly focus on material purchases, energy consumption and emission release (CO2 equivalent). To evaluate the maintenance intervals on their impact on the LCA cost and environmental impact, several different intervals will be considered and under these conditions, the cost and environmental impacts will be derived using the LCA model established.

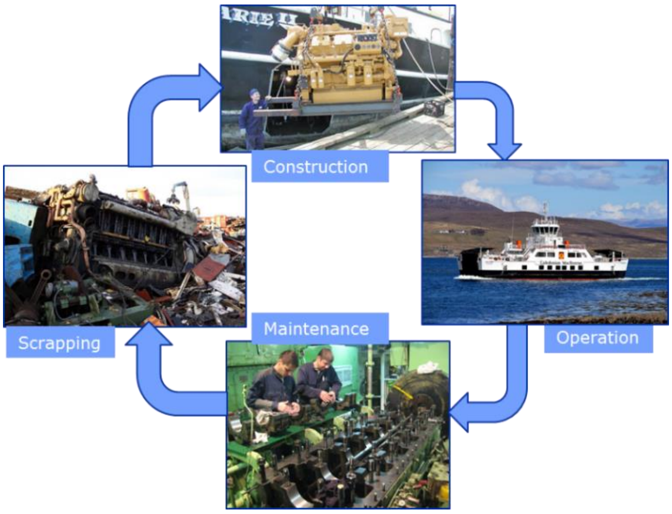

Figure 2. Outline of the LCA process

The reason behind the determination of the optimal ship performance is due to the relationships between maintenance plans with construction, operation and scrapping phase. If a long period coating maintenance is preferred, the hull roughness will be increased, and the fuel consumption will be increased which means the fuel cost in the operation phase will be higher. On the contrary, the dry-docking cost will be relatively reduced due to less frequent maintenance, considering coating materials investment and energy consumption.

3.1.2 *Boundary setting and data quality requirement*

In this study, four stages of ship life span: construction, operation and maintenance, and scrapping will be considered. After considering different ship maintenance plan with coating interval, the LCCA and LCA can be derived and compared to determine an optimal maintenance plan.

To carry out this study, some assumptions and boundaries are necessary, due to lack of data and simplification of the model:

1. After coating, the roughness of ship hull will be in the same condition as initially launched so that the fuel consumption will be the same as initial condition;
2. The other processes apply similar technologies as hull production processes which are provided by ship manufacturer (Ferguson shipyard);

3. The modelling uses GaBi 5 and its database, but the emission released due to engine running is estimated using emission factors;
4. The scrapping processes are referred to Ling-Chin and Roskilly's research (Ling-Chin and Roskilly, 2016a);
5. The manufacturing of steel plates and machineries from raw material are not considered;
6. The fuel consumption increment due to delayed coating maintenance is estimated by an empirical equation based on a half year fuel consumption data provided by the ship operator, CalMac;
7. Properties of coating and welding materials are based on reference and GaBi database;
8. Machinery maintenance is not considered in this study;
9. To keep the processes realistic, the transportation of materials and machinery are considered;
10. All the phases use the same electricity supply from wind farm which is commonly used in Scotland.

3.2 *Life cycle inventory analysis*

According to the goal and scope of the study, together with all the information from shipyard, ship operator and literature, the life cycle analysis for the case ship is carried out.

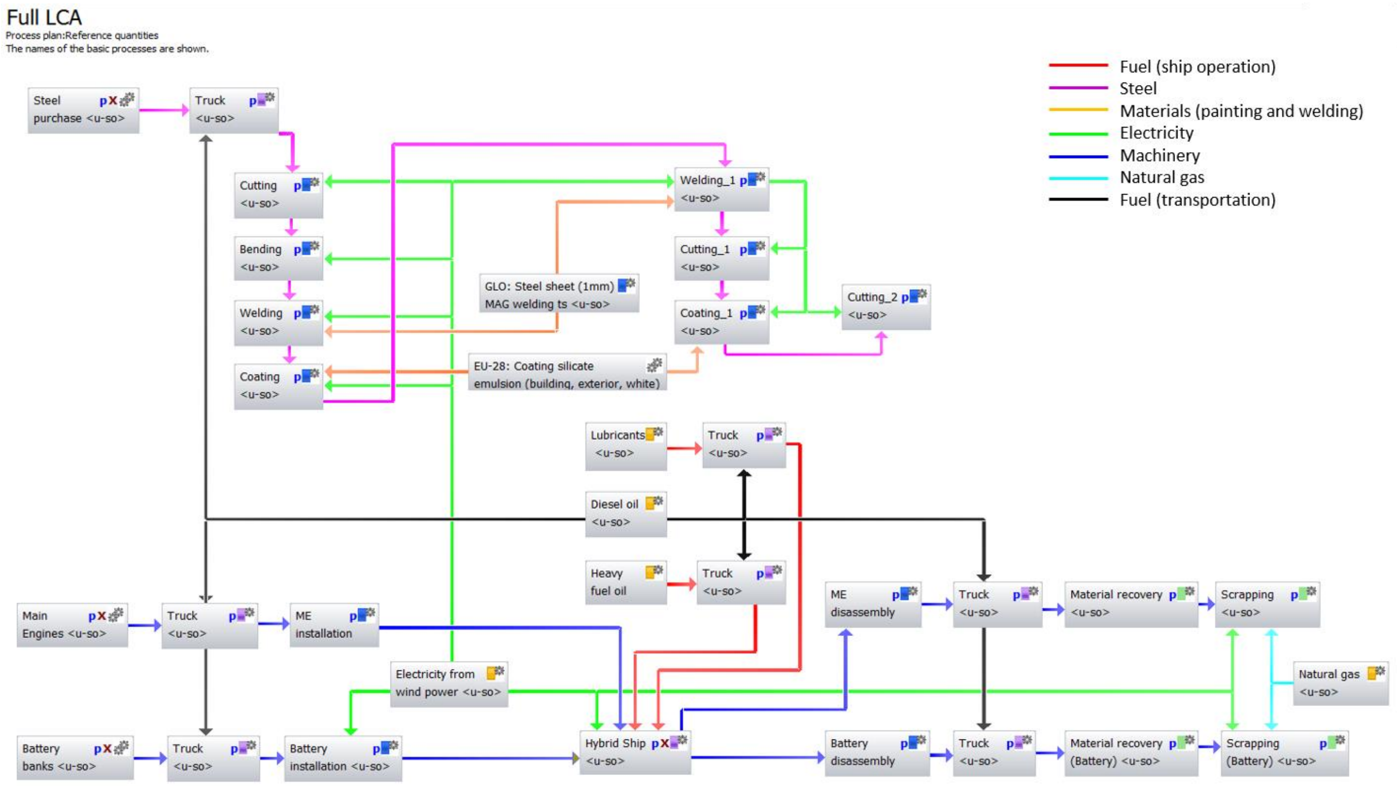

Figure 3. Flow chart of LCA model

3.2.1 *Flow chart development*

To present a full LCA analysis, Figure is introduced considering the following:

1. Hull constructions;
2. Engine and battery constructions;
3. Engine and battery operations;
4. Hull structure and coating maintenances;
5. Hull scrapping.
6. Machinery scrapping;

In Figure the red coloured lines present the flow of fuel supply for the case ship, including heavy fuel oil and lubrication oil.

3.2.2 *Inventory results*

After establishment of the LCA model, the results for different phases are evaluated. In

Table 2, the emission flows of significant emissions are presented. It is obvious that most of the emissions are from the operation phase. The application of less frequent maintenance will have an impact on the fuel consumption in operation phase which will lead to an increase in emission generation.

Table 2. Life cycle inventory analysis

Inorganic emissions to air during all life phases (kg)					
Emission flows	Construction	Operation	Maintenance	Scrapping	Total
CO_2	1.07E+04	1.36E+07	1.71E+03	1.59E+03	1.36E+07

CO	13.1	3.10E+04	6.2	2.03	3.10E+04
NO_x	5.41	3.36E+05	2.45	1.55	3.36E+05
SO_2	5.91	6.37E+03	2.5	1.47	6.38E+03

3.3 *Life cycle impact assessment*

The life cycle impact in this study was focused on global warming potential which has increasingly drawn attention from researchers. With the model and database in GaBi, three life cycle impact assessment results are derived in Figure-7, using CML, ReCiPe, TRACI and ILCD respectively (CML, 2016; RVIM, 2011; IERE, 2012, Wolf, 2012). It can be seen from these figures that there is no significant difference among CML, ReCiPe, TRACI and ILCD in GWP values (kg CO2 e). The equivalent CO_2 emission for the case ship is around 14 million ton. Furthermore, under different maintenance interval, these methods provide similar results and trends. Hence, for this LCA model, these methods have a good agreement with each other.

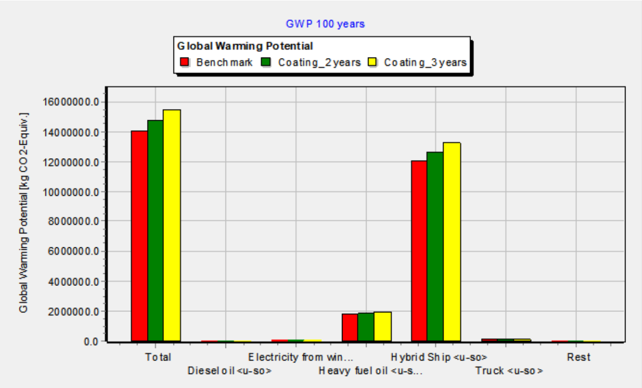

Figure 4. LCA results with application of CML 2001

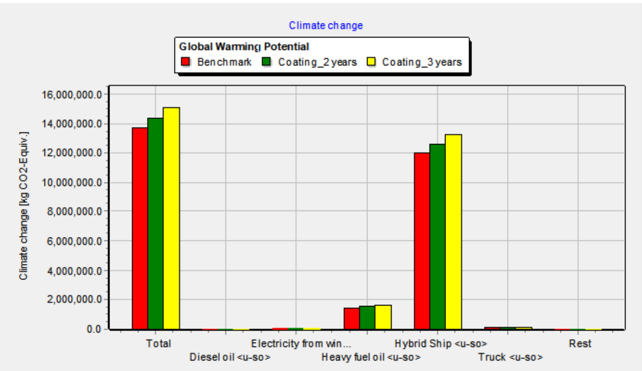

Figure 5. LCA results with application of ReCiPe

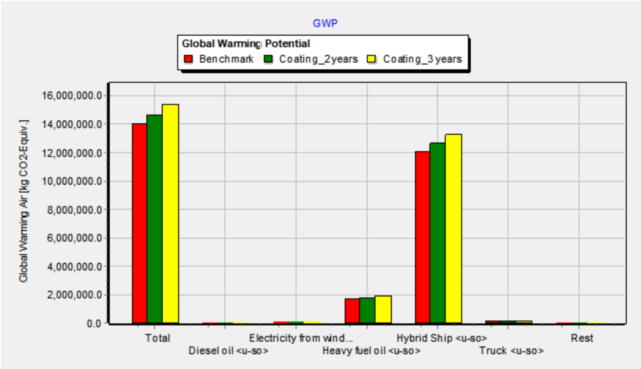

Figure 6. LCA results with application of TRACI

These figures also indicate that when the coating interval increased from 1 to 2 or from 1 to 3, the GWP value will be increased. It means more emission released compared to the case ship. However, with an increasing of steel renewal interval, the change between two results are minor because the steel renewal will not impact on the energy consumption of the vessel especially in the operation phase which occupies the more emission generation among all phases.

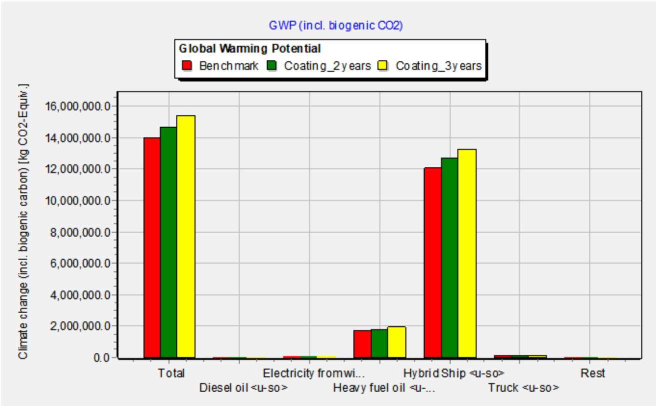

Figure 7. LCA results with application of ILCD

3.4 *Further results and identification of significant issues*

As the emission issue is not the only factor that affect the ship owners' decision, the cost of the vessel, including construction, operation, maintenance and scrapping may recommend them a different option. In this section, the emissions will be converted into cost or credits which can be compared between different scenarios together with life cycle cost.

3.4.1 *Conversion of environmental impact into costs*

The carbon credit policy in the UK is about \$29 per ton CO_2 emission (Maibach et al., 2008). Since the GWP for different scenarios has been determined, the difference value between cases can be applied for comparison.

For case 1 and case 2, the difference of GWPs (ΔGWP_1) is about 7E+5 kg/CO_2e. For case 1 and case 3, the difference of GWPs (ΔGWP_2) is about 1.4E+6 kg/CO_2e. As a consideration of carbon credit (\$29/ton

CO_2), the emission credits increased for case 2 is \$2.03E+4 and for case 3 is \$3.06E+4.

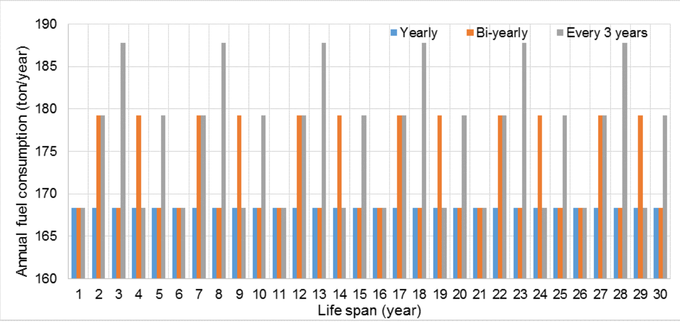

Figure 8. Specific fuel oil consumptions changes with coating interval

3.4.2 *Optimal partial coating plan*

Considering coating maintenances, the fuel consumption increment due to late coating is estimated to be about 5% based on operator's data (provided by CalMac) and their experiences. In a life cycle, total investments of coating materials and activities are lower for late coating than that for early coating and the annual coating degraded area is advised to be 10% by CalMac. Due to increment of fuel consumption, the operation costs and emission released are significantly growing. In Figure, the increment of annual fuel consumption rate due to coating interval changes has been shown in order to indicate the significant relation between each other. Figure presents how the total life cycle cost increased with increasing coating interval. When the coating interval increases from yearly to bi-yearly, the total cost increased by about \$34000. Similarly, if we increase the coating frequency up to 3 years, the cost will be increased by around \$75000 compared with yearly coating plan.

Table 3. Cost increased due to the changes in partial coating interval

Increased compared to yearly plan (\$)	Partial coating interval (year)		
	1	2	3
Fuel cost	0	51989	98576
Maintenance cost	0	-3580	-4773
CO2 credit	0	12179	23092
Total cost	0	60588	116895

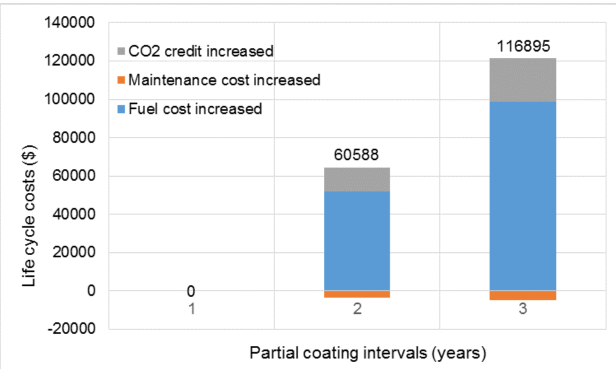

Figure 9. Costs increased under different coating intervals

3.4.3 *Discussion on other stage of structural degradation*

Since this research is focusing on the operation and maintenance stages, the significance of regular coating is presented. It is because regular coating has the most environmental and economic impact on operation phase. However, the impacts of regular coating on other phases are important as well so this section will present the structural degradation if coating would be irregular in the ships life time.

For construction phase, as the operation and maintenance plan has been established or estimated, ship yard and ship owner should consider a proper initial coating, such as application of high performance coating which means high investment. This situation is not considered in this paper due to the practice of shipyard and ship owner and lack of relevant data and information.

The scraping phase will be influnced by coating activities. In this research, one assumption was made to simplify the impact estimation in scrapping phase: the hull conditions will be recovered to its initial condition after every entry to the drydocking which is not practical. It is reasonable to predict that more regular maintenances will not only make every single maintenance simpler in the drydocking shipyard but also recover the ship hull nearer to its initial condition.

4 CONCLUSIONS

This paper applies LCA methodology to evaluate the life cycle cost and environment impact of maintenance intervals on a short-route ferry and provides a guide for ship LCA analysis and proves the availability of LCA application in marine field especially for ships' life cycle assessment. This paper presents a comprehensive LCA analysis to investigate the impacts of different alternative selections or decisions with the consideration of life cycle cost and environment analysis for a whole ship life cycle. Investigation in this paper is to change the maintenance interval which related to the construction of ship to determine an optimal maintenance plan with a minimized impact in the aspect of financial and environmental. The impacts of re-coating interval are also evaluated on the ship life cycle financial and environmental performances to not only indicate an optimal partial coating interval but also to provide a guideline for shipyards and ship operators on their coating plans.

Considering four life stages of a vessel, including, construction, operation, maintenance and scrapping, the LCA model is established in GaBi software. The model covers activities for steel processing and machinery installations in the shipyard; operation of the engine and batteries on board; maintenance of ship hull (coating) and scrapping of hull materials and machineries. For coating interval, it is evidenced that a frequent coating leads a fewer cost in the case study. The results support the coating practices made by CalMac who carried out yearly partial coating to decrease the accumulations of bio-fouling and the hull roughness to reduce the fuel cost.

5 ACKNOWLEDGEMENTS

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