Life cycle cost and environmental impact analysis of ship hull maintenance strategies for a short route hybrid ferry

Haibin Wang[1], Elif Oguz[1], Byongug Jeong[1], Peilin Zhou[1, 2]*

[1] Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde,
100 Montrose Street, Glasgow, G4 0LZ, UK

[2] Zhejiang University, 1 Zheda Road, Zhoushan, Zhejiang Province, 316021, China

*Corresponding author; e-mail: haibin.wang.100@strath.ac.uk, phone: +44(0)1415484047

Abstract

This paper provides a general insight into the importance of proper hull maintenance and suggests an optimal maintenance strategy for ship operators from both an economic and environmental point of view. Results of life cycle assessment show that significant cost reductions can be obtained by renewing steels every 10 years within the proposed hull maintenance strategy. The assessment also indicates that annual hull inspections and re-coating can contribute to reducing hull resistance and hence fuel consumption, thereby reducing the overall operating costs and emissions. This paper provides ship owners a direct relationship between effective hull maintenance and the reduction in maintenance cost. It also provides information to inform policy makers of the benefits of following a maintenance optimization strategy. This study shows that life cycle assessment can provide information to shipyards and owners to facilitate reliable long-term maintenance decisions.

KEYWORDS Life cycle assessment, ship maintenance strategy, hull steel renewal, dry docking

1 Introduction

According to the third Greenhouse Gas Emission Study published by the International Maritime Organization (IMO), the vigorous and steadfast efforts paid globally to curb maritime emissions have achieved the desired results. The report pointed out the Greenhouse Gases (GHG) emission from international shipping has been reduced during the years from 2009 to 2014 (IMO, 2015). IMO guidelines for measuring and monitoring GHG emissions are based on fuel consumption, are limited to emissions during normal ship operations, thereby the reliability of such emission data is perceived as low. For example, Kavli et al. (2017) compared different environmentally-friendly power options by evaluating the GHG emissions of the ship from the operation phase.

To investigate the environmental impact of shipping in a more precise way, as seen in other industries, Life Cycle Analysis (LCA) has drawn a considerable attention in the marine industry. Styles and his team quantified the growing of willow on river buffer zones and found out the benefit of willow cultivation on these areas by using LCA (Styles et al., 2016). Research carried out by Vázquez-Rowe’s research group investigated the edible protein energy return on investment (ep-EROI) for the fishing industry in Spain and they applied LCA in order to evaluate the energy consumption and environmental impact of fishing fleets. These results were expected to provide recommendations for EU’s Common Fisheries Policy (Vázquez-Rowe et al., 2014). LCA is also applied to assess the state-of-art and under developed power systems by Fredga and Maler, especially on biofuel. Their research developed a full scope LCA model considering both emissions released and the resources required in order to provide precise results (Fredga and Maler, 2010). LCA is an appropriate tool for many industries and is considered as a practicable tool to evaluate holistic environmental impacts, e.g. the global warming potential (GWP), associated with the whole life span of a ship. In this study, GWP is considered due to its significant impact on greenhouse gas production and hence to climate change.

However, the application of LCA in the marine industry still appears to be limited since previous research has mainly focused on the investigation of environmental impacts of the shipbuilding process and machinery operation. Some notable research are found among the following:

Blanco-Davis applied LCA to aid the shipyards in order to evaluate retrofitting performance of innovative ballast water treatment systems and fouling release coating (Blanco-Davis et al., 2014; Blanco-Davis and Zhou, 2014). Alkaner and Zhou investigated and compared the performance of fuel cell and diesel engines for marine applications with the help of LCA (Alkaner and Zhou, 2005). Strazza's research team applied LCA in order to evaluate the environmental impact of paper stream on a cruise ship with implementation of different green practices (Strazza et al, 2015). In addition, using LCA, Nicolae and his team investigated the environmental impact related to commercial ships by optimization of raw material, energy consumption and recycle processes (Nicolae et al., 2016). Ling-Chin and Roskilly have carried out two case studies comparing a hybrid power system with a conventional marine engine system considering the comprehensive ship life cycle phases - namely, construction, operation, maintenance and scrapping (Ling-Chin and Roskilly, 2016[a]; Ling-Chin and Roskilly, 2016[b]). With inspiration from such previous work, the authors have carried out two case studies in order to determine an optimal propulsion system for a short-routed hybrid ferry and for an off-shore tug vessel in terms of economic and environmental views (Wang et al., 2017; Oguz et al., 2017). Jeong et al. (2018) applied LCA method in order to evaluate the environmental impact of alternative propulsion systems using two different case studies. Together with the results from life cycle cost assessments (LCCA), the optimal propulsion system was determined and the work also provided an effective framework for life cycle economic and environmental assessment.

This paper extends the application of the LCA to investigate the economic and environmental impacts of different ship hull maintenance strategies. One of the key objectives of this paper is to provide a ship hull maintenance strategy. Since effective hull maintenance is essential to ship operators, a number of studies in this area have been carried out including the following:

Garbatov and Soares have used probabilistic analysis in order to determine optimum repair interval and times with a minimized total cost (Soares and Garbatov, 1998; Garbatov and Soares, 2009). Wang and his team carried out research on an estimation method for the corrosion rate of an oil tanker structure based on Garbatov's work (Wang et al., 2003). A number of research projects on the corrosion rate for aging ships have been carried out by Pusan National University, American Bureau of Shipping and Chevron Shipping Company LLC (Paik et al., 2003; Ivanov et al., 2003). Gratsos and Zachariadis proposed to increase the corrosion allowance on certain ship sections which have inadequate strength (Gratsos and Zachariadis, 2009).

It is critical to be able to predict the influence of different hull maintenance strategies on the ships overall performance. There is still a significant need for research concerning maintenance strategy in terms of the selection of the optimum maintenance frequency for a given route. Without having enough investigation in this issue, a ship-owner, who might be focused on minimizing construction costs may jeopardize the economic sustainability during the ship operation and maintenance phase due to considerable maintenance costs in the long-run. In this context, it may be imperative to provide ship operators with a deeper insight into an optimal maintenance strategy for their vessel in order to ensure minimum financial and environmental impacts.

In addition to corrosion on the ship hull, a poorly-maintained hull surface may increase the hull resistance, thereby fuel consumption. A large body of research has illustrated the relationship between ship hull coating and fuel consumption. Candries and his colleagues investigated three different coating types and their impact on roughness and drag forces on ship hull (Candries et al., 2001). Dunnahoe indicated that a comprehensive hull repair and maintenance at dry-docking may help to reduce ship resistance significantly. This research showed that the application of blasting and coating to 50% of the entire ship hull reduced the total resistance from 40% to less than 20% (Dunnahoe, 2008). Computational fluid dynamics (CFD) has been used extensively in order to estimate the effect of biofouling on ship resistance. For instance, Demirel et al. (2014) developed a CFD model to estimate the variation of plate roughness in different coating types. Demirel et al. (2017) carried out an experimental study to determine the relationship between bio-fouling and ship resistance for an oil tanker and an LNG carrier (Demirel et al., 2014; Demirel et al., 2017). Owen et al. (2018) validated their CFD results with experiments. The effect of fouling on the open water characteristics of the PPTC propeller proved to be drastic with the most severe fouling condition resulting in a ~11% efficiency loss at J=0.6 ranging to an alarming ~30% loss at J=1.2 compared to the smooth condition (Owen et al., 2018).

From a long term perspective, the increase in hull roughness is a result of the growth of bio-fouling and/or damage on ship hull. It follows that regular removal of bio-fouling will minimise the ship resistance e leading to a lower fuel cost. There are a number of research papers that highlight the importance of proper anti-fouling management of a ship hull.

Hearin and his team tested the influence of mechanical grooming on coated panels which indicated that weekly grooming has a lower fouling rate than a bi-weekly grooming (Hearin et al., 2015). Tribou and Swain investigated the effects of grooming on a copper ablative coating exposed statically for six years and their findings support that more regular grooming can reduce fouling on a ship hull (Tribou and Swain, 2017).

These research results pointed out that it would be vital to keep the hull roughness in an acceptable range by regular maintenance such as hull washing, blasting and re-coating. However, the indirect benefits of proper hull maintenance, such as reduction in fuel consumption and emissions, are often under-estimated by decision-makers who are in favour of immediate and direct benefits.

Terziev et al. (2018) carried out a numerical study in order to investigate the behavior and performance estimation techniques in shallow water for varying channel cross-sections and ship speeds. Their findings illustrated that resistance was highly sensitive to changes in the bathymetry of the channel. Due to the relationship between resistance and maintenance, this paper could be useful in terms of determining the optimal maintenance strategy taking into account channel geometries which the ship frequently operates.

In this paper, a case study carried out in order to determine an optimal hull maintenance strategy for a short route ferry considering long term environmental effects and costs. This should provide useful guidelines on hull maintenance strategies to shipyards, ship-operators and other relevant decision-makers. Hence, the key objective of this paper is to contribute to enhancing cleaner and more economical shipping. In addition, it is also a goal to demonstrate LCA as an appropriate tool for evaluating optimal hull maintenance strategies.

2 Hybrid ship case study

2.1 Case ship description

Since operation in shallow water may cause higher level of damage on a ship hull due to shallow water effects, such as squat, combined with frequent manoeuvring, periodical hull maintenance should be critical, particularly, for a short route ferry. For this purpose, a short route ferry, which regularly serves in Scotland, was selected for this study (see Figure 1).

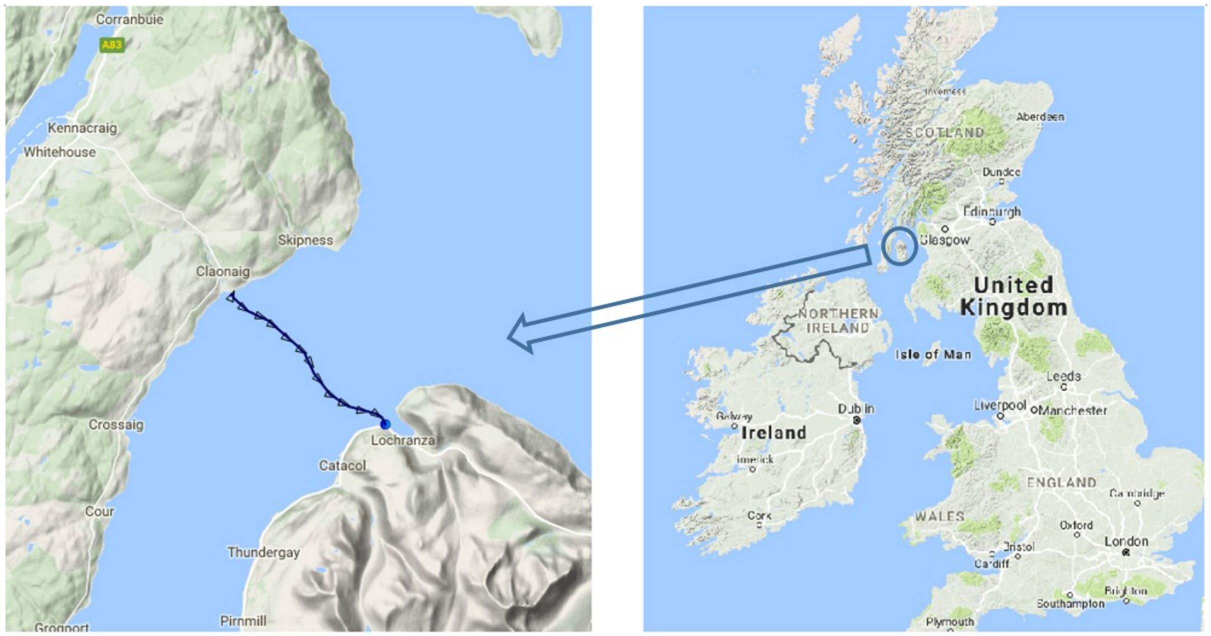

Figure 1 Operation route of hybrid ship

The details of the ship are listed in Table 1 Equations and formulas to estimate the quantity of steel used in hull construction and painting of the ship hull are presented in the following sections.

Table 1 Case ship specification

Name	**MV Hallaig**
Gross weight	499 tonnes
Length	43.50 m
Breadth	12.20 m
Depth	3 m
Draught	1.73 m
Block coefficient (Cb)	0.45

Power	360 kW × 3
Superstructure decks	2
Builders	Ferguson Shipyard Ltd.
Built year	2012

2.1.1 Steel weight estimation

In order to estimate the steel weight in the ship hull structure, two methods are used: cubic number method and empirical equation (Papanikolaou, 2014). By referring to a known base ship as a reference, the first method uses block coefficient and length to depth ratio as corrections as described in Eq. (1).

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

Where,

W_s is the steel weight of case ship, [tonne]

$W_s{}'$ is the steel weight of base ship, [tonne]

L and L' are the lengths of case ship and base ship respectively, [m]

B and B' are the breadth of case ship and base ship respectively, [m]

D and D' are the depth of case ship and base ship respectively, [m]

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

Meanwhile, the empirical equation, the second method, developed by Garbatov's research team (Garbatov et al., 2017) is represented below:

$$W_1 = 0.00072 \cdot Cb^{\frac{1}{3}} \cdot L^{2.5} \cdot T/D \cdot B \qquad (2)$$

$$W_2 = 0.011 \cdot L \cdot B \cdot D \qquad (3)$$

$$W_3 = 0.0198 \cdot L \cdot B \cdot D \qquad (4)$$

$$W_4 = 0.0388 \cdot L \cdot B \cdot NJ \tag{5}$$

$$W_5 = 0.00275 \cdot L \cdot B \cdot D \tag{6}$$

$$W_s = W_1 + W_2 + W_3 + W_4 + W_5 \tag{7}$$

Where,

W_s is the steel weight of case ship, [tonne];

W_1 is the weight of the main hull, [tonne]

W_2 is the weight of bulkheads in the main hull, [tonne]

W_3 is the weight of decks and platforms, [tonne]

W_4 is the weight of the superstructure, [tonne]

W_5 is the weight of the foundation and other, [tonne]

L is the length of the case ship, [m]

B is the breadth of the case ship, [m]

D is the depth of the case ship, [m]

T is the draft of the case ship, [m]

NJ is the deck number of the case ship superstructure;

C_b is the block coefficient of the case ship

Steel weight calculated as 126.38 tonnes using the cubic number method while it is calculated as 126.22 tonnes using the empirical equation.

2.1.2 Estimation of Coating area

The parts of the ship hull below the load-line are susceptible to the water contact, thereby prone to the growth of bio-fouling. To alleviate this, anti-fouling coating is applied to the wetted surface area which can be estimated using the Denny - Mumford formula (Molland et al., 2011) (Eq.2).

$$S = 1.7L \times T + L \times B \times Cb \tag{8}$$

Where,

S is the wetted surface, [m^2]

L is the length of the case ship, [m]

B is the breadth of the case ship, [m]

T is the draft of the case ship, [m]

C_b is the block coefficient of the case ship.

Figure 2 presents an area of the hull wetted surface which is partially covered by bio-fouling.

Based on abovementioned approaches to estimating steel weight and the coating area, proper hull maintenance strategies will be discussed in the next section.

Figure 2 Ship hull with bio-fouling before cleaning

2.2 Operation principles and maintenance strategies

The case ship has a regular route between two ports in Scotland with a ten-hour daily operation: 6 hours for sailing, 0.6 hours for maneuvering and 3.7 hours for berthing/departing. The current practice of hull maintenance for this ship is as follows:

a) Annual-based hull management
  - Dry-docking;
  - Hull inspection;
  - Partial management (steel patching or re-coating) where necessary.

b) Five year-base hull management
  - Dry-docking;
  - Hull inspection;
  - Steel patching and full re-coating.

During the partial coating process bio-fouling is removed and the hull is recoated in areas where the previous coating has been impaired hence returning the ship to its original condition. Maintenance costs and energy consumption vary depending on the length of maintenance intervals, therefore, it is vital to determine an optimal maintenance plan by minimizing the ships life cycle cost and environmental impact as described in the following section.

3 LCA modelling

The LCA model comprises four phases based on the ship's life span: construction, operation, maintenance and scrapping. The construction phase is when the ship under production in shipyards, mainly including the hull construction and machinery installation; during the operation phase the ship is in service and operated by ship operator; the maintenance of ship hull and machinery is carried out when the ship is in service or in dry dock.; scrapping is carried out when the ship reaches the end of its life and includes recycling and disposal.

3.1 Goal and scope of the study

3.1.1 Ship's maintenance strategies

The goal of this LCA modelling is to evaluate the ship performance associated with a number of hull maintenance practices considering the four life phases of the ship: construction, operation, maintenance and scrapping. The category of performances to be assessed consists of the life cycle cost and environmental impacts which can be evaluated by tracking and estimating the element flows such as material purchases, energy consumption and emissions release. To develop a proper hull maintenance strategy, several scenarios using different maintenance intervals were devised.

3.1.2 Boundary setting and data quality requirement

The maintenance plan is inter-related to the ship design process. In particular, the initial hull thickness may significantly affect how often the hull steel needs to be inspected and renewed if necessary; the thicker hull requires the lesser maintenance. A ship-owner who prefers to carry out minimum hull maintenance may need to specify that maximum steel thickness is used in the hull design, thereby the initial cost of ship construction will be higher. In addition, different maintenance intervals may also affect the quantity of the steel to be recycled at scrapping stage.

In terms of hull coating, long maintenance intervals will increase the hull roughness, thereby increasing fuel consumption and fuel costs during the operation phase. On the contrary, the dry-docking cost can be reduced due to less frequent maintenance as well as lesser investment for steel renewal and re-coating and energy consumption.

The boundary of LCCA and LCA as well as a series of assumptions, partly originated from empirical judgements and partly from compensating for uncertainties, are outlined as below:

a) Steel patching will recover the original hull condition;
b) Re-coating will return the roughness of ship hull to its initial condition, thereby guaranteeing constant fuel consumption;
c) The LCA model takes account of the real production processes used at the Ferguson shipyard;
d) LCA modelling is carried out using GaBi 5.
e) Emissions due to engine fuel consumption are calculated based on emission factors provided by International Maritime Organization (IMO, 2015)
f) The scrapping processes use the methodology developed by Ling-Chin and Roskilly's research (Ling-Chin and Roskilly, 2016a);
g) Manufacturing process for the steel and machinery from raw materials are not considered in this paper ;
h) The increment in fuel consumption due to infrequent coating maintenance is estimated using an empirical equation based on a half year fuel consumption data provided by the ship operator, Caledonian MacBrayne Ltd.;
i) Properties of coating and welding materials are determined based on published papers and the GaBi database;
j) Machinery maintenance is not considered in this paper ;
k) The transportation process of materials and machinery are modelled;
l) In all the phases, the electrical power is supplied from wind farms.
m) Environmental impact assessment is limited to evaluating the GWP which is regarded as the most crucial marine contributor.

3.2 Life cycle inventory analysis

Based on the boundary setting and data quality requirements the information from various sources – shipyard, operator and literature is integrated into the case study in this section.

3.2.1 Flow chart and activity development

Figure 3 outlines the LCA model for holistic process of the case ship. Some important processes are noted below:

a) Hull construction;
b) Engine and battery constructions;
c) Engine and battery operations;
d) Hull structure and coating maintenances;
e) Hull scrapping;
f) Machinery scrapping.

For the hull construction, the following activities are considered: steel purchase, transportation, cutting, bending, welding, and coating. These activities also cover material and energy consumption and emissions released. For engine construction, purchase, transportation and installation activities are considered including the energy and material consumption and emissions released. For the rest of life phases (operation, maintenance and scrapping), different activities are included in the LCA model with consideration of material and energy consumption and emissions released.

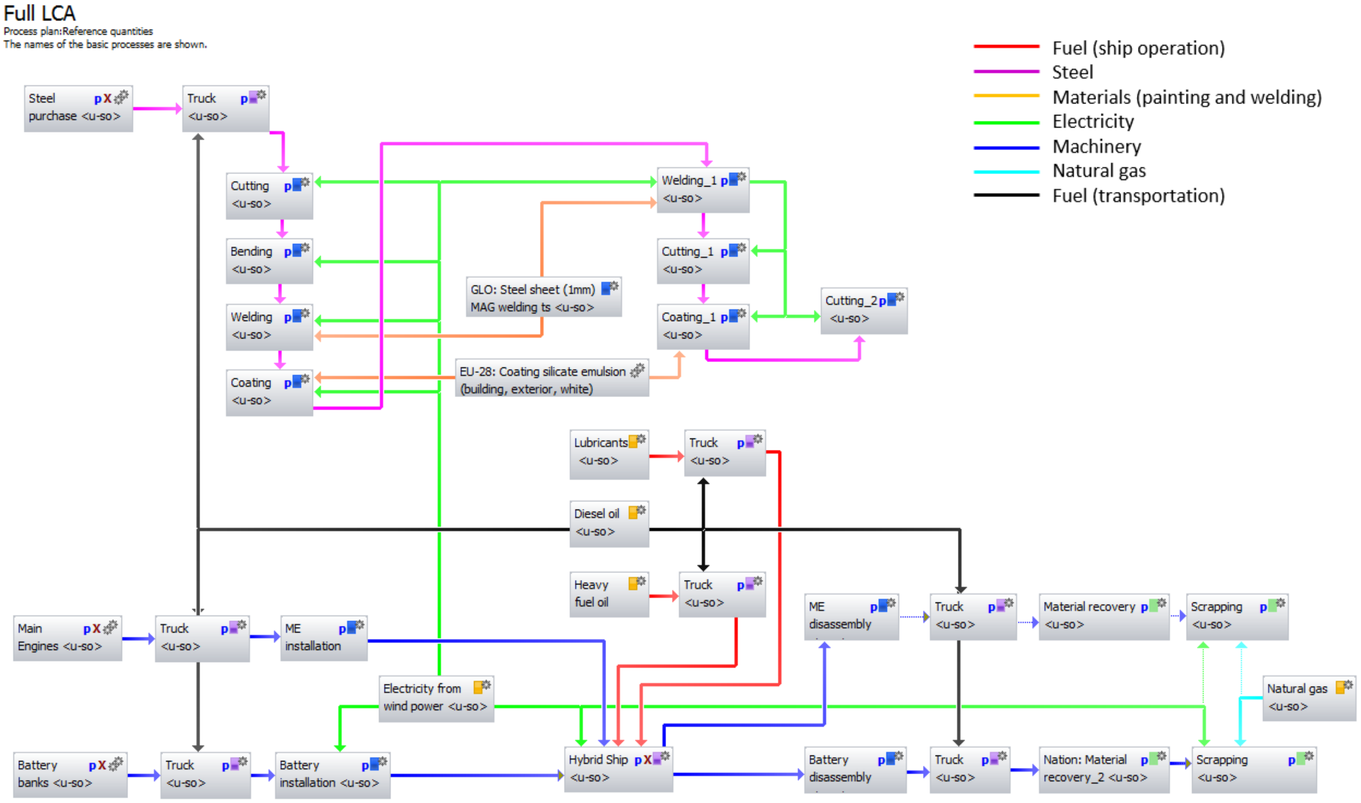

Figure 3 Flow chart of LCA model

3.2.2 *Inventory results*

Inventory results from the LCA model are evaluated in different phases as shown in Table 2 where the flows of the significant emissions are presented. It illustrates that, as expected, the largest amount of emissions is produced during the operation phase. Less frequent maintenance will have an adverse impact on the fuel consumption during the operation phase which will lead to an increase in CO_2, CO, NO_x and SO_2 emissions, which are considered to be most significant ones (IMO, 2015; Jeong et al., 2018; Kavli et al., 2018).

Table 2 Life cycle inventory analysis

Inorganic emissions to air during all life phases (kg)					
Emission flows	Construction	Operation	Maintenance	Scrapping	Total
CO_2	1.07×10^4	1.36×10^7	1.71×10^3	1.59×10^3	1.36×10^7

CO	13.1	3.10×10^{4}	6.2	2.03	3.10×10^{4}
NO_x	5.41	3.36×10^{5}	2.45	1.55	3.36×10^{5}
SO_2	5.91	6.37×10^{3}	2.5	1.47	6.38×10^{3}

3.3 Life cycle impact assessment

The life cycle impact in this study focuses on the GWP which has increasingly drawn attention from researchers. With the model and database in GaBi, four life cycle impact assessment results are derived and presented in Figure 4 using CML, ReCiPe, TRACI and ILCD respectively (CML 2016; RVIM 2011; IERE 2012, Wolf 2012). Comparing the results shows that the sensitivity of selected impact methods are negligibly small, showing no significant deviation in GWP among CML, ReCiPe, TRACI and ILCD; the equivalent CO_2 emission for the case ship was estimated around 14 million tonnes. Furthermore, under different maintenance intervals, these impact assessment methods provide similar results and trends. Hence, for this LCA model, it can be concluded that these methods are consistent with each other.

In this study, five different re-coating cases are investigated:

Case 1: Re-coating annually;

Case 2: Re-coating every two years;

Case 3: Re-coating every three years;

Case 4: Re-coating yearly and renewal hull steel every 10 years;

Case 5: Re-coating yearly and renewal hull steel every 7 years

The study indicates that when the coating interval is increased from a yearly to a two and three yearly basis, the level of GWP increases. An increase in steel renewal interval does not significantly effect the total emissions throughout the ship life cycle.

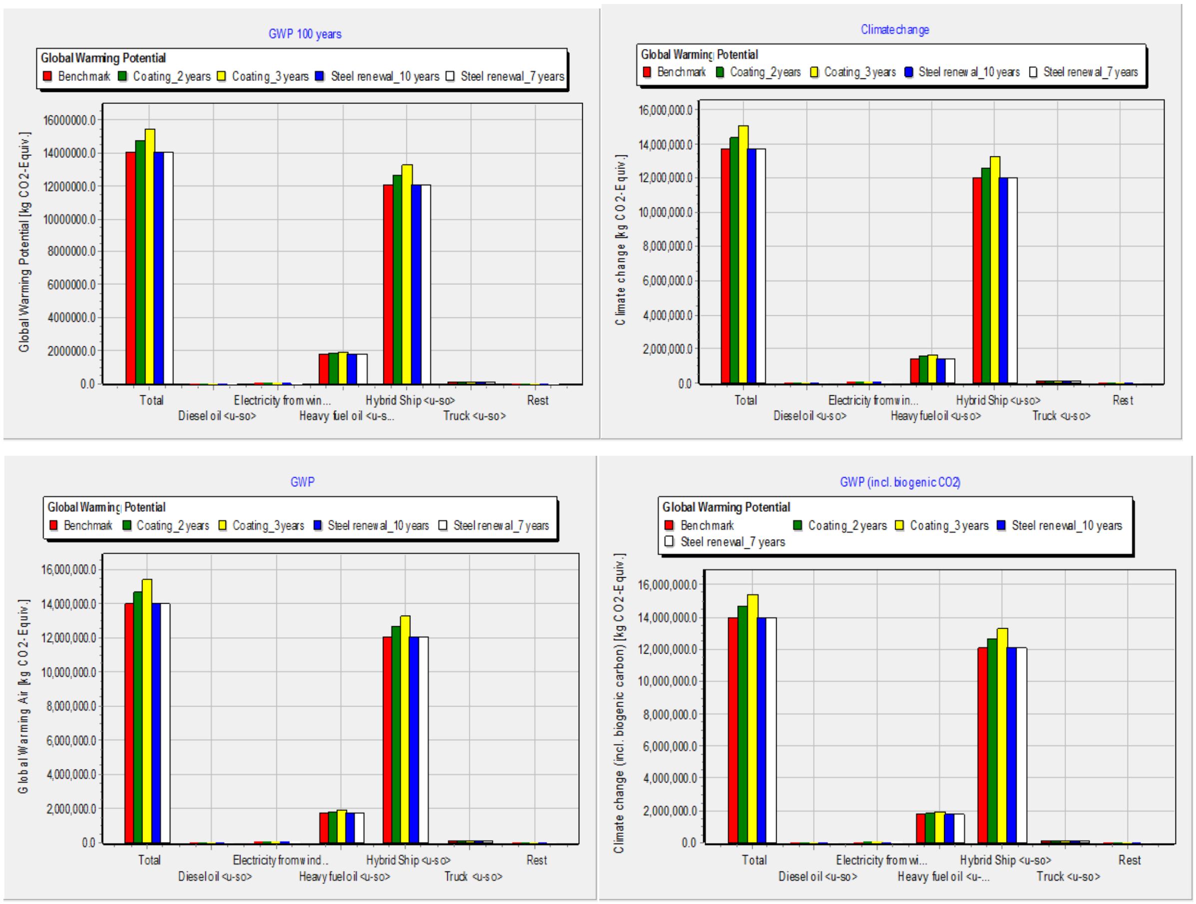

Figure 4 LCA results with application of CML2001, ReCiPe, TRACI and ILCD

3.4 Life cycle cost assessment

The LCA includes most activities during the four life phases of the ship. Since the study is focused on ship hull maintenance, the activities related to ship hull steel and painting are considered.

During the construction phase, the main activities considered are the purchasing, transportation, steel processing and painting. The quantity of construction steel, from the previous section, is 126 tonnes. The estimation of transportation costs is based on the GaBi build-in model (for fuel consumption estimation) and current diesel fuel price. During the construction phase, six main activities are considered: cutting, bending, welding, blasting, washing and coating. All the materials, energy and supplemental consumptions are derived based on the information provided by shipyard.

For the operation phase, the 2016 fuel consumption figures were provided by the ship operator.

The maintenance phase will consider both the effect of steel degradation and regular coating. With a higher steel corrosion allowance and the same degradation rate, the hull repair period will be increased. Corrosion allowance is an extra thickens added to the wall to compensate the loss of the steel plate.

For the scrapping phase, the removal of coatings and recycling of the steel are taken into account. At the end of the ship's life, blasting and washing are required to remove the paint from ship hull. The quantity of recyclable steel will depend on the repair period: e.g. for a 10 year repair period and 30 year life span, the steel will be degrading during the last ten years of the ship's life. For a 7 year repair period, the renewed steel will only have degraded for the last 2 years of the ship's life increasing the amount of recyclable steel. The steel degradation rate is taken as 3% per year for a 0.02 m thick steel plate.

After estimating the costs and profits from all activities in the four life phases of the ship, the total costs can be derived and for the five coating cases.

3.5 Results and discussion

In addition to the environmental impact, the total cost (CAPEX and OPEX) of the ship is a critical factor affecting the ship owners' decisions on design specification and maintenance strategies. Since costs during the four life cycle phases are different, shipyards and ship owners can decide particular options that suit their interests. In the next section the estimated costs for the five re-coating cases are combined with the emission costs.

3.5.1 *Conversion of environmental impact into costs*

According to the carbon credit policy in the UK, one tonne of CO_2 emission is regarded equivalent to \$29 (Maibach et al., 2008). The GWP and carbon credits for three cases are shown in Table 3. The difference in GWPs between Cases 1 (re-coating annually) and 2 (re-coating every two years) is estimated at 7×10^5 kg/CO_2e, whereas the difference of GWPs between Cases 1 and 3 (re-coating every three years) is about 1.4×10^6 kg/CO_2e. When the estimated GWPs for different cases are converted to costs, the results show that the increase in emission credits for Case 2 is \$20,300 and for Case 3 is \$40,600 compared to Case 1.

Table 3. The GWPs and carbon credits of different cases

Case number	GWP (kg/CO_2 e)	Carbon Credits (\$)
Case 1	1.40×10^7	406,000
Case 2	1.47×10^7	426,300
Case 3	1.54×10^7	446,600

3.5.2 *Optimal maintenance strategy*

With regards to steel renewal, Table 3 suggests that increasing steel plate thickness by 3% the maintenance interval can be increased by one year. Different maintenance strategies lead to different costs for construction and maintenance phases in which the process of steel production and purchase are involved.

Figure 5 presents the relationship between the patching intervals and life cycle cost. Although longer the maintenance intervals require more steel during the construction phase, the total life cycle cost does not follow an expected trend, instead it changes in a random manner. Nevertheless, the results presented in Table 3 indicate that the hull maintenance carried out every ten years would result in the minimal life cycle cost. For this optimal maintenance interval, the required steel thickness is 23 mm with the estimate of 130 tonnes of steel weight which is 4 tonnes more than for the five-year maintenance interval.

Table 3 Life Cycle Cost and steel thickness changes with steel renewal intervals

Interval (year)	**Thickness (mm)**	**Thickness Increment (%)**	**Cost ($)**	**Steel Weight (tonne)**
5	20.0	0	210,190	126.38
6	20.6	3	209,071	127.10
7	21.2	6	213,384	127.85
8	21.8	9	209,254	128.64
9	22.4	12	212,431	129.39
10	23.0	15	205,510	130.16
11	23.6	18	207,814	130.90
12	24.2	21	210,019	131.65
13	24.8	24	212,133	132.41

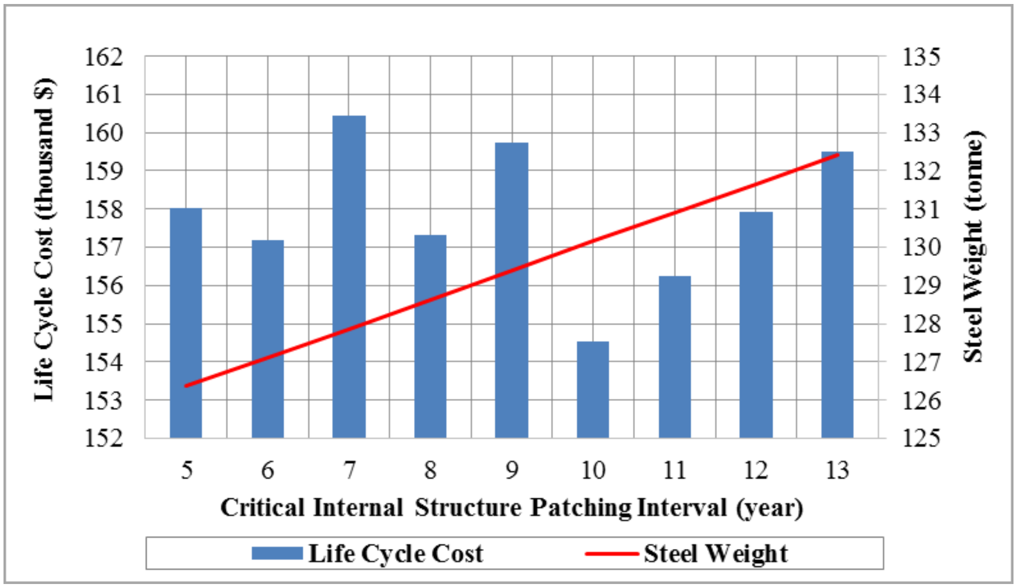

Figure 5 LCA cost and hull weight changes with steel renewal intervals

3.5.3 Optimal re-coating strategy

Although the total investment in coating materials and activities might reduce the less frequent re-coating interval, the increment in the fuel consumption caused by such inappropriate management may lead to a significant increase in operation costs.

Figure 6 Annual fuel oil consumption changes with re-coating interval

Error! Reference source not found. shows the relationship between annual fuel consumption and coating interval, which was estimated based on data provided by the case ship operator (Caledonian MacBrayne). Figure 7 represents the change in life cycle costs in relation to the increase in the coating interval. When the coating interval increases from yearly to bi-yearly, the total cost increases by $60,588. Similarly, if the coating interval is increased to every three years, the cost will be increased by $116,895compared with the annual re-coating interval.

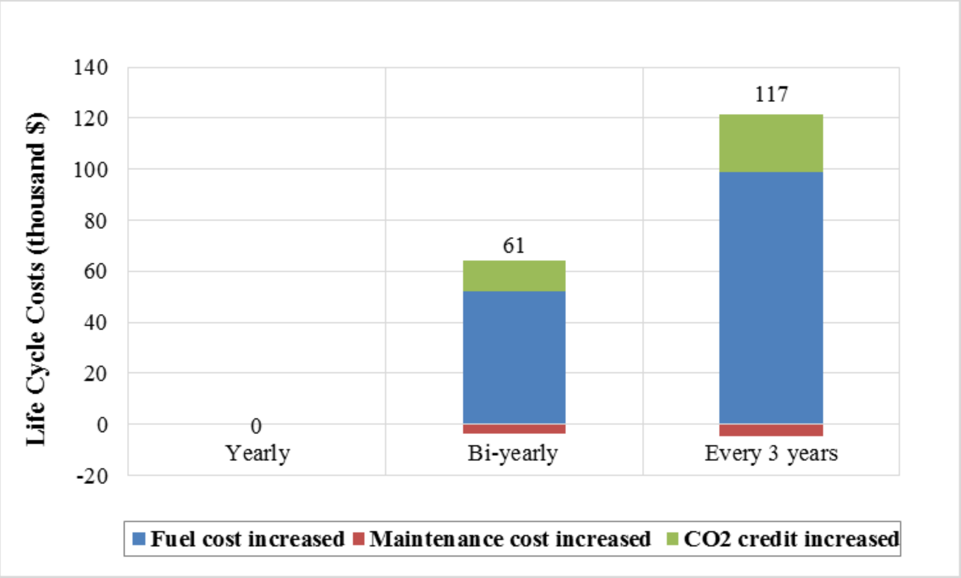

Figure 7 Costs increased under different re-coating intervals

3.5.4 Fleet consideration

The results of the LCA, LCCA and environmental analysis show that that the total cost is reduced by applying optimal hull and coating maintenance intervals. It may be useful extending the concept of the optimal hull maintenance from a single ship to a fleet of ships which has the potential of reducing fleet ownership costs significantly. This study also shows how the selection of an optimized maintenance strategy, with its lower emission and fuel consumption, impacts favorably on the carbon reduction policy. Currently the operator follows a five year re-coating interval. Based on this study, it is recommended to reduce the re-coating interval to yearly leading to reduced fuel consumption and emissions.

4 Conclusions

This paper investigated the life cycle cost and environmental impact due to various decision-making during different ship phases on hull maintenance for a short-route ferry. The LCA models established using GaBi dealt with various ship activities associated with the four life phases of the ship, including steel processing and machinery installations in the shipyard; operation of the engine and batteries on board; maintenance of ship hull (both structure and coating) and scrapping of hull materials and machineries. Based on the data and information provided by the construction shipyard and the ship operator, a case study for a hybrid ferry has been carried out using the established LCA model in order to determine the ship's environmental impact. The life cycle cost of the ship is estimated and based on the relationship between phases, the optimal interval for steel patching/renewal and re-coating have been determined.

The case study showed that the optimal interval for the steel renewal is 10 years. With respect to re-coating intervals, it was evidenced that more frequent re-coating leads to a lower life cycle cost. The findings also provided an insight into the correlation between cost/environmental effects of the ship hull maintenance strategies, placing an emphasis on the fact that an optimal hull maintenance plan is vital to reducing the ship cost and emissions.

The research findings illustrate the economic and environmental benefits to CalMac, by changing from their current annual partial re-coating practice to an annual full re-coating strategy.

This paper presented the process of LCA applied to a short route hybrid ferry in order to investigate the sensitivity of different construction and maintenance choices on the life cycle cost and environmental impact of the ship. It is believed that this process has illustrated the advantages of applying LCA methods in the marine industry.

5 Acknowledgement

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