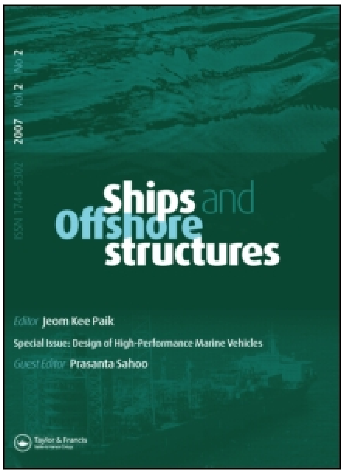

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Maintenance/repair and production-oriented life cycle cost/earning model for ship structural optimisation during conceptual design stage

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The aim of this paper is to investigate the effect of the change in structural weight due to optimisation experiments on life cycle cost and earning elements using the life cycle cost/earning model, which was developed for structure optimisation. The relation between structural variables and relevant cost/earning elements are explored and discussed in detail. The developed model is restricted to the relevant life cycle cost and earning elements, namely production cost, periodic maintenance cost, fuel oil cost, operational earning and dismantling earning. Therefore it is important to emphasise here that the cost/earning figure calculated through the developed methodology will not be a full life cycle cost/earning value for a subject vessel, but will be the relevant life cycle cost/earning value. As one of the main focuses of this paper is the maintenance/repair issue, the data was collected from a number of ship operators and was solely used for the purpose of regression analysis. An illustrative example for a chemical tanker is provided to show the applicability of the proposed approach.

Keywords: production, periodic maintenance/repair, life cycle cost/earning, net present value, regression analysis, scantling optimisation

Introduction

This research was initiated with the idea of developing a methodology/framework to be able to assess the life cycle cost/earning of production and maintenance/repair with respect to the structural optimisation variables, mainly scantlings and its derivative lightweight, to be used during the conceptual ship design stage. It is a fact that changes in scantlings might have a big cost impact on production and maintenance/repair because of increasing/decreasing steel weight. In general, lighter weight and smaller plate thickness may possibly mean more extensive steel replacement unless a proper hull maintenance strategy is adopted. This can also lead to longer dry-docking times and thereby increasing costs in terms of the cost of dry-docking and the cost of the ship being unavailable for use. However, heavier lightship also means heavier displacement and hence a higher fuel cost or smaller deadweight capacity, and hence lower operational income. It is important to know and assess this impact at the earliest phase of a ship's life cycle for many reasons such as evaluation and comparison of alternative designs, identification of main cost drivers and maintenance planning, etc. Assessing production cost is a straightforward calculation and a well-studied area in literature (Ross 2004; Ross and Aasen 2005; Bole 2006, 2007; Miroyannis 2006; Keulen et al. 2007). However, assessing the maintenance/repair cost of a ship during the design stage requires a life cycle prediction in terms of the amount of steel to be replaced and the amount of time the ship is unavailable in the dry-dock. Therefore, history and past data relating to a ship type become vital and critical.

Ships as a part of the marine transportation system are crucial assets of the supply chain. Availability of these assets is extremely important, as downtime of ships is costly both due to income loss of a ship and due to the knock-down effect on the rest of the transportation system. Availability of ships depends on the effectiveness of the preventive maintenance system. Observations in the current state of ship operation can be listed as:

- High life cycle costs, particularly maintenance costs; maintenance activities can account for as much as 25–35% of an operator's direct operating costs and have remained at this level for many years. Furthermore, with the increase in oil prices, the budgets have gone up by an additional 25% more (plus world inflation) in the last 6 years and therefore operators try to cut the operational cost by other means including maintenance cost.

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- Ships that are not maintained or monitored properly pose a risk to the environment as well as to the cargo and people on board.
- In the case of corrective maintenance implemented, it usually leads to expensive repairs, significant loss of time/off hire periods and a decrease in the ship's credibility. However, preventive maintenance may create an 'over-maintained' policy, in which the ship's components/items are replaced before the end of their operational life, thus leading to the accumulation of unnecessary and expensive spare parts/inventories.
- Expenses related to frequent inspections (including spare parts, attendance from company's personnel and classification society's surveyors and temporary or permanent measures implemented) might constitute a big portion of the total maintenance expenditure. When repair works/spare parts are needed on board the vessel, they have to be planned well in advance as the ship sails in different geographical locations, thus with significant functional/access restrictions.
- Seafarers are occupied with various tasks to fulfil, both from operational and maintenance points of view, while the ship is trading in busy – and in some cases, short – distance routes. Consequently, there is no onboard resource (technical and human) management system to deal with these types of activities. Nowadays, the time spent on board the ship by the crew is reduced and the compilation of the crewmembers changes more often than before. Consequently, there is a need for a standard, well-understood approach to the maintenance followed.
- Moreover, the lately implemented on-line maintenance reports from the ship to the onshore headquarters of a shipping company/operator requires well-trained personnel and the application of user-friendly software platforms. Data gathering, censoring and dissemination require an amount of human and technical resources that are difficult to manage and operate simultaneously. It is a common fact that accumulating data are stored without being converted into accessible information, which in practice renders them useless.
- Ship managers/operators still try to find an effective way to combine the rich practical knowledge acquired in the actual marine field with the technological advances stemming from the relevant information technology sector. It should be noted that the key point is to identify the essential information and decide which maintenance attitude is the most efficient to follow.
- Further delays occur from a shortage in efficient communication between the ship's owner/manager, the shipyard and the supplier so as to plan the repair and maintenance process. In this case, ships may have to wait in the repair shipyard alongside the quay or in the anchorage before any inspections are performed.
- Operators clearly indicate that the availability of the ship is extremely important for sustainable/robust transportation services.

Although there is no standard taxonomy for life cycle cost (LCC), breakdown in the maritime industry and its relevant literature, the following will be used in this study, which is adopted from Stopford (1997). It should be noted that in the present study, the focus is on tanker ships (see illustrative examples, Tables 2 and 3) and some of the formulas, such as steel replacement due to repair, are valid for tankers only:

Acquisition costs

- Design
- Production

Ownership costs

- Operating costs
  - Personnel
  - Routine maintenance and repair (which does not make ships unavailable)
  - Insurance
  - Stores, lubricants and supplies
  - Administration or management
- Periodic maintenance (which makes ships unavailable)
- Voyage costs
  - Fuel
  - Canal dues
  - Port charges
- Cargo handling costs

Earning breakdown

- Operational earning
- Dismantling earning

In the LCC calculation of this study, consideration will be given only to relevant costs and earnings, which are directly or indirectly affected by the design options being considered with respect to structural variables. The following explanations are for that purpose.

Among the cost/earning elements given above, the following are considerably affected by the changes in structural variables, either scantlings or lightweight:

- Production cost
- Periodic maintenance cost
- Fuel oil cost
- Operational earning
- Earning of dismantling

The relation between each element and the aggregative cost model is given in detail in the third part of this article. It is apparent that more steel weight means more production cost in terms of material and labour costs, and also more dismantling earning. Similarly, less steel weight indicates less fuel consumption and vice versa. The assumptions made for maintenance/repair are given below.

Maintenance and repair

According to Watson (1998): 'budgets for maintenance will generally include sums for work on the hull and superstructure, cargo spaces and systems, the main and auxiliary machinery, the electrical installation and safety equipment plus survey fees'.

Maintenance activities of a ship can be classified into two main categories: The first category (routine maintenance and repair) consists of regular or routine checks and services that can be performed every day without disturbing the ship's operations; the second category (periodic maintenance) is the major maintenance that requires dry-docking and makes the ship unavailable or off-hire. The second category will be considered in the development of the maintenance cost/earning model. Therefore data collection activity was focused on this area.

It would be important to give the seminal descriptions of these two maintenance types as stated in Stopford (1997):

- 'Routine maintenance and repair includes maintaining the main engine and auxiliary equipment, painting the superstructure and carrying out steel renewals in such places which can be safely accessed' (i.e. small brackets/stiffeners on hatch coaming stays around cargo hold openings of bulk carriers).
- 'Periodic maintenance costs are incurred when the ship is dry-docked for major repairs, usually at the time of its special survey. In older ships this may involve considerable expenditure, so shipping companies often include a "dry-docking provision" in their operating costs. Since this is a provision rather than a cash item it is better treated separately from operating costs'.

The reader is also referred to Yamamoto and Ikegami 1996, Qin and Cui 2002, 2003, Garbatov et al. 2005, Paik et al. 2006 and Paik and Thayamballi 2008 for common causes/effects of corrosion and the most widely used corrosion rate prediction models.

This paper presents the development of a life cycle cost/earning model, which is production and maintenance/repair oriented, to be used in ship structure optimisation during conceptual design stage.

The rest of the paper is organised as follows. The second part of this article explains the data collection activity. In the third part, the development of a relevant life cycle cost/earning model to be used within the structural optimisation is introduced and the details of this new technique are given. In the fourth part, an illustrative example is given for a Chemical Tanker. Finally, the deliverable concludes the work with future recommendations.

Data collection

The aim of this part of the article is to present the data collection during the visits to various shipping/managing companies regarding their past repair activities for the ships that were unavailable due to their dry-docking period. This was carried out in two ways. At first, a detailed questionnaire was prepared concerning the survey for the unavailability and repair of ships. The objectives were to gather failure and repair data, which could be expressed in either a quantitatively or qualitatively format. The second way was also through the previously mentioned contacts in order to collect data regarding the repairs and unavailability of the ships during their dry-docking activities. In the second method there was no specific questionnaire involved but just collection of existing reports and data.

The data structure provided by the operators would mention the failures that render the ship unavailable, their repair activities and the unavailability period over the ship's operating time and other pertinent issues. More specifically, initial data gathering included: the main dimensions and characteristics of the vessel(s) that were selected for the survey, description of the failure and repair data, maintenance and repair practices followed by each operator (i.e. maintenance/repair policy implemented, diagnostic tools used, specialised software in place, etc).

The following data structure was proposed for the operators to provide the data concerning failures that make the ship unavailable for operations and their repair activities over the ship's operating period. It should be emphasised that the following data needed to be provided for the failure (causing unavailability of ship) and its corresponding repair work. Besides, a guideline report was prepared and sent to the shipping operators so as to facilitate the ship's data collection.

After the initial version of the data-gathering report, a second one was distributed to the operators so as to facilitate the whole procedure even more. It contained a more practically orientated course of action so as to maximise the efficiency of data collection bearing in mind the limited amount of time that a ship operator might afford during the usual everyday workload. In total, data from 100 different ships were collected including oil, product and chemical tankers, LPGs, bulk carriers, general cargo ships, RoRo and RoPax and passenger vessels. From all these ships, 145 different repair events and 225 unavailability events were also collected. In the present study, only the data relevant to tanker ships are considered for the analysis (see Tables 2 and 3 in Appendix 1, which present the part of the collected data relevant for tanker ships).

The main aim of this work was to know about:

- Costs of preventive/predictive maintenance activities focusing on the reports/data/information of:
  - Annual surveys, particularly for RoPax.
  - Intermediate surveys (generally taking place every 2.5 years).
  - Special surveys (generally taking place every 5 years).
- Costs of corrective maintenance or repair activities.
- Based on the above information:
  - Amount of the steel replaced and its main cause (corrosion, etc.) and the relevant zone of the ship.
  - Costs of unavailability because of those off-service times.
- Proportion of hull structure related costs to machinery-related costs.

What follows is a description of some examples in terms of more practical use.

- Initial quotation lists (concerning work to be carried out during the dry docking period from both shipyard's and sub-contractors' side, sand/water blasting, coating, etc).
- Any additional quotation list deriving from unscheduled on-site repair works.
- Data gathered from subsequent dry docking periods (time between special and intermediate survey, every 2½ years).
- Final repair booklets (including sketches of repaired areas with their exact location, dimensions and material used/grade of steel).
- Cause of the defects occurring, which lead to steel renewals (i.e. cracks/fractures, deformation/buckling, corrosion patterns).
- Time (days) in dry-dock/floating dock and shipyard's quay.
- Any supplementary maintenance or repair jobs carried out by the crew on board the vessel under examination (i.e. cleaning of ballast tanks from mud deposits, de-scaling of loose rust, minor repairs, recoating of small areas, etc).
- Existing maintenance strategies of the operators.
- Number of days in actual operation per year and trading area of the vessel.
- Type of chartering contract (i.e. spot market, time chartered and for how long).

It should be mentioned that data collection is not an easy task to perform. During this period it was experienced that it is not only the unavailability and confidentiality of such data that renders them difficult to get but also ship owners/operators may keep folders with huge amounts of information; it is also critical to communicate to them the exact information that you are looking for in practical terms.

Life cycle maintenance/repair cost/earning model

The aim of this part is to establish a generalised production and maintenance/repair oriented life cycle cost/earning (GLCMC) model to be used within a structural optimisation platform. This model will not only focus on maintenance/repair related aspects but also will consider a few ownership and acquisition costs, and thereby the following models will be developed:

- Model 1: production cost.
- Model 2: cost of periodic maintenance.
- Model 3: cost of fuel oil for main engine(s).
- Model 4: operational earning or revenue.
- Model 5: dismantling earning.

Life cycle maintenance cost for a subject vessel to be evaluated equals the sum of the following cost and earning elements:

- Production cost
- Periodic maintenance cost
- Fuel oil cost and
- Earning (operational and dismantling)

The relation between the above-mentioned models, life cycle cost/earning elements and structure optimisation variables is shown in Figure 1.

Model 1: Production cost

This part presents the modelling of the production cost, as implemented in the basic cost module (BCM) of LBR5 optimisation tool. The LBR5 software is an integrated package to perform cost and weight optimisation of stiffened ship structures, allowing (Rigo 2001, 2003; Toderan et al. 2007):

- a 3-D analysis of the general behaviour of the structure;
- to include all the relevant limit states of the structure (service limit states and ultimate limit states) in an analysis of the structure based on the general solid-mechanics;
- an optimisation of the scantlings (profile sizes, dimensions and spacing);
- to include the unit construction costs and the production sequences in the optimisation process

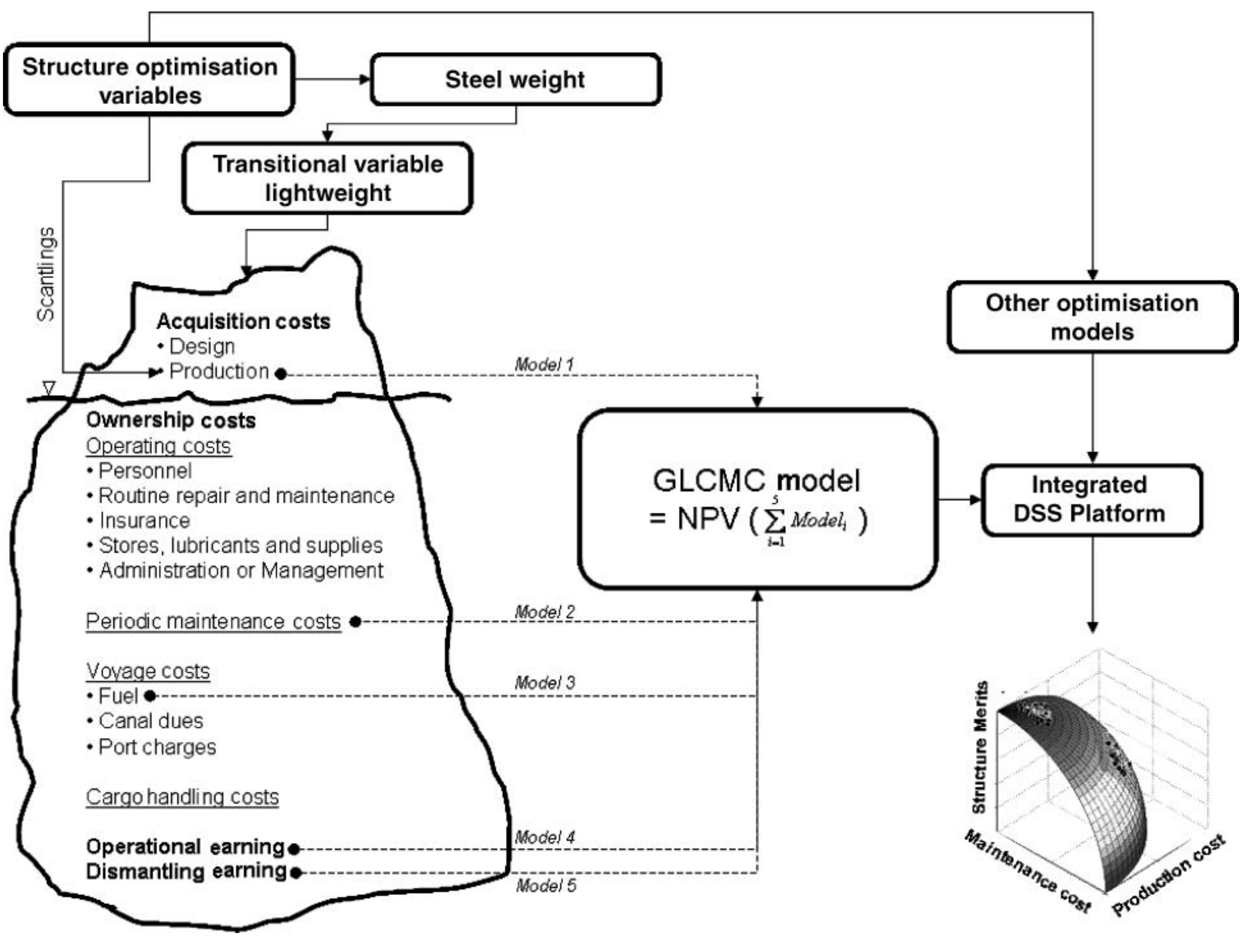


Figure 1. GLCMC model and life cycle cost/earning elements within a ship design optimisation platform.

(through a production-oriented cost objective function).

The total production cost given by Model 1 will be the sum of the following three components:

$$F_C = F_{MAT} + F_{CONS} + F_{LAB} \quad (1)$$

where

F_C	=	the total production cost, €
F_{MAT}	=	the cost of materials, €
F_{CONS}	=	the cost of consumables, €
F_{LAB}	=	the cost of labour, €

The cost of materials

The cost of materials means the steel acquisition cost. For a stiffened panel, this cost is directly derived from the structural weight using the following formula:

$$F_{MAT} = \gamma L B \left[C_1 \delta + C_2 \frac{(hd + wt)_X}{\Delta_X}[1 + DW_2] + C_3 \frac{(hd + wt)_Y}{\Delta_Y}[1 + DW_3] \right] \quad (2)$$

where

F_{MAT}	=	the cost of materials – for a stiffened panel, €
γ	=	steel specific weight, N/m^2
L	=	stiffened panel length, M
B	=	stiffened panel width, M
δ	=	stiffened panel plate thickness, M
h	=	web height, M
d	=	web thickness, M
w	=	flange width, M
t	=	flange thickness, M
Δ_X	=	longitudinal stiffeners spacing, M
Δ_Y	=	transversal frames spacing, M

X = index of longitudinal stiffeners
Y = index of transversal frames
C_1 = cost/kg of a plate with δ thickness (for instance 0.9 €/kg), €/kg
C_2 = cost/kg of longitudinal stiffeners, €/kg
C_3 = cost/kg of transversal frames, €/kg
DW_2 = corrective factor of longitudinal stiffeners weight due to the extra weight induced by brackets for local stiffening (for instance 0.1 for a 10% increase)
DW_3 = corrective factor for the weight of transversal frames due to the extra weight induced by brackets for local stiffening

The values of the parameters C_1, C_2, C_3, should be calculated using the formulas:

$$C_1 = C_1^{o}[1 + \Delta C_1(\delta - E_0)10^3],$$
$$C_2 = C_2^{o}[1 + \Delta C_2(d_X - E_{0X})10^3] \quad (3)$$
$$C_3 = C_3^{o}[1 + \Delta C_3(d_Y - E_{0Y})10^3]$$

where (indicative values are given in Rigo 2001, 2003).

δ = stiffened panel plate thickness – actual, M
d_X = longitudinal stiffeners web thickness – actual, M
d_Y = transversal frames web thickness – actual, M
E_0 = reference thickness for plate cost assessment, M
E_{0X} = reference web thickness for longitudinal stiffeners, M
E_{0Y} = reference web thickness for transversal frames, M
C_1° = cost/kg of a plate with E_0 thickness, €/kg
C_2° = cost/kg of longitudinal stiffeners with E_{0X} web thickness, €/kg
C_3° = cost/kg of transversal frames with E_{0Y} web thickness, €/kg
ΔC_1 = variation of C_1 per mm, 1/mm
ΔC_2 = variation of C_2 per mm, 1/mm
ΔC_3 = variation of C_3 per mm, 1/mm

The cost of consumables

The cost of consumables means the cost of welding except the labour cost and it is composed by the cost of energy, gas, electrodes and provision for equipment depreciation. The cost of consumables for a stiffened panel will be calculated as follows:

$$F_{CONS} = L \times B \times \left(\left[\frac{2-\alpha_X}{\Delta_X}\right] \times C_{8X} + \left[\frac{2-\alpha_Y}{\Delta_Y}\right] \times C_{8Y}\right) \quad (4)$$

where

F_{CONS} = the cost of consumables – for a stiffened panel, €
L = stiffened panel length, M
B = stiffened panel width, M
Δ_X = longitudinal stiffeners spacing, M
Δ_Y = transversal frames spacing, M
X = index of longitudinal stiffeners
Y = index of transversal frames
α_X = binary coefficient related to stiffeners manufacturing
α_Y = binary coefficient related to frames manufacturing
C_{8X} = cost/metre of the consumables related to longitudinal stiffeners welding, €/m
C_{8Y} = cost/metre of the consumables related to transversal frames welding, €/m

Note: The welding length is assumed to be same as the stiffener spacing and this is included in the equation.

The values of the parameters C_{8X} and C_{8Y} should be calculated as follows:

$$C_{8X} = C_{8X}^{0}\,[1 + \Delta C_{8X}\,(d_X - E_{0X})\,10^3]$$
$$C_{8Y} = C_{8X}^{0}[1 + \Delta C_{8Y}(d_Y - E_{0Y})\,10^3] \quad (5)$$

where

d_X = longitudinal stiffeners web thickness – actual, M
d_Y = transversal frames web thickness – actual, M
$E_{0X,}$ = reference web thickness for longitudinal stiffeners, M
E_{0Y} = reference web thickness for transversal frames, M
C_{8X}° = cost/metre of consumables for longitudinal stiffeners with E_{0X} web thickness, €/m
C_{8Y}° = cost/metre of consumables for transversal frames with E_{0Y} web thickness, €/m
ΔC_{8X} = variation of C_{8X} per mm, 1/mm
ΔC_{8Y} = variation of C_{8Y} per mm, 1/mm.

The labour cost

The labour cost is related to the workload for welding and welding surface preparation. For a stiffed panel, the labour will be estimated as follows:

$$F_{LAB} = \eta \times\ k \times\ C_1^{o} \times\ \text{WLoad} \quad (6)$$

where

F_{LAB} = the labour cost – for a stiffened panel, €

η = efficiency parameter for the considered production plant ($0 =< \eta \leqslant 1$, usually taken as 1)
k = plate weight equivalent to a man hour of the considered shipyard, kg/man hour
C_1° = cost/kg of a plate with E_0 thickness (see above – cost of materials), €/kg
WLoad = workload required for the fabrication of the stiffened panel, man hour

The amount of workload should be calculated with the formula:

$$\mathrm{WLoad} = L \times B \begin{bmatrix} \frac{1}{\Delta_X} \times P_4 + \frac{1}{\Delta_Y} \times P_5 \\ + \frac{1}{\Delta_X \times \Delta_Y}(P_6 + \beta_X \times \beta_Y \times P_7) \\ + \frac{1}{\Delta_X} \times P_{9X} + \frac{1}{\Delta_Y} \times P_{9Y} \\ + P_{10} \end{bmatrix} \quad (7)$$

where

WLoad = workload required for the fabrication of the stiffened panel, man hour
L = stiffened panel length, M
B = stiffened panel width, M
Δ_X = longitudinal stiffeners spacing, M
Δ_Y = transversal frames spacing, M
P_4 = workload per metre for the welding of longitudinal stiffeners web on the plate (preparation included), man hour/m
P_5 = workload per metre for the welding of transversal frames web on the plate (preparation included), man hour/m
P_6 = workload required for the welding and preparation of one intersection between longitudinal stiffeners and transversal frames, man hour/intersection
P_7 = workload required for fixing the brackets at one intersection between longitudinal stiffeners and transversal frames, man hour/intersection
P_{9X} = workload required to build 1 metre of longitudinal stiffener – assembly of web – flange (preparation + welding), man hour/m
P_{9Y} = workload required to build 1 metre of transversal frame – assembly of web – flange (preparation + welding), man hour/m
P_{10} = workload required for the preparation of 1 m^2 of plate (cutting, positioning), man hour/m^2
β_X = ratio between the amount of intersections requiring longitudinal brackets and the total amount of intersections
β_Y = ratio between the amount of intersections requiring transversal brackets and the total amount of intersections

The values of the unitary cost parameters involved in the Equation (7) should be calculated as follows:

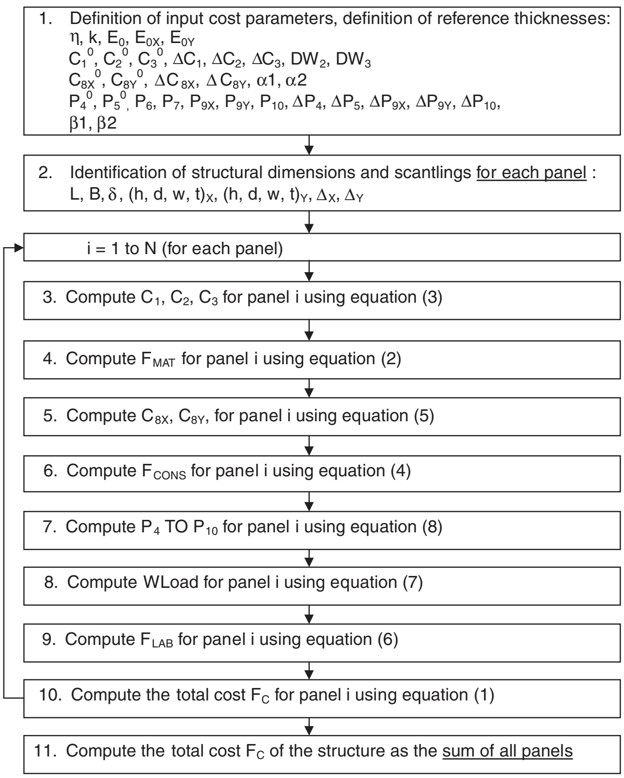
$$\begin{aligned} P_4 &= P_4^0[1 + (d_\mathrm{X} - E_\mathrm{OX}) \times 10^3 \times \Delta P_4] \\ P_5 &= P_5^0[1 + (d_\mathrm{Y} - E_\mathrm{OY}) \times 10^3 \times \Delta P_5] \\ P_{9\mathrm{X}} &= P_{9\mathrm{X}}^0[1 + (d_\mathrm{X} - E_\mathrm{OX}) \times 10^3 \times \Delta P_{9\mathrm{X}}]\,[0, 1] \\ P_{9\mathrm{Y}} &= P_{9\mathrm{Y}}^0[1 + (d_\mathrm{Y} - E_\mathrm{OY}) \times 10^3 \times \Delta P_{9\mathrm{Y}}] \\ P_{10} &= P_{10}^0[1 + (\delta - E_\mathrm{o}) \times 10^3 \times \Delta P_{10}] \end{aligned} \quad (8)$$

where

δ = stiffened panel plate thickness – actual, M
d_X = longitudinal stiffeners web thickness – actual, M
d_Y = transversal frames web thickness – actual, M
E_0 = reference thickness for plate cost assessment, M
E_{0X} = reference web thickness for longitudinal stiffeners, M
E_{0Y} = reference web thickness for transversal frames, M
P_4° = workload per metre for the welding of longitudinal stiffeners web (E_{0X} thickness) on the plate man hour/m
P_5° = workload per metre for the welding of transversal frames web (E_{0Y} thickness) on the plate (preparation included), man hour/m
P_{9X}° = workload required to build 1 metre of longitudinal stiffener – assembly of web (E_{0X} thickness) – flange (preparation + welding), man hour/m
P_{9Y}° = workload required to build 1 m of transversal frame – assembly of web (E_{0Y} thickness) – flange (preparation + welding) man hour/m
P_{10}° = workload required for the preparation of 1 m^2 of plate with E_0 thickness, man hour/m^2
ΔP_4 = variation of P_4 per mm, 1/mm
ΔP_5 = variation of P_5 per mm, 1/mm
ΔP_{9X} = variation of P_{9X} per mm, 1/mm
ΔP_{9Y} = variation of P_{9Y} per mm, 1/mm
ΔP_{10} = variation of P_{10} per mm, 1/mm

Model 1: Stepwise description of production cost model

Before the start of the production cost calculation, the considered structure should be divided into several flat stiffened panels, as required by LBR5 mesh. Considering that the total number of stiffened panels is N, the calculation will follow the following steps:



Model 2: Cost of periodic maintenance

Based on the definition of periodic maintenance given in the first part of this article, Model 2 will include the following items:

- The cost of steel replacement and coating and
- The cost of unavailability because of a subject vessel's downtime

The cost of steel replacement for tankers

According to the shipyards and operators, steel replacement is very rare before 10 years of age. Steel replacement usually takes place every 2.5 years following the intermediate and special surveys. Nevertheless, in most cases the steel replacement occurs every 5 years during the dry-docking period of the vessel.

Prediction of the amount of deteriorated steel to be replaced following intermediate and special surveys has to be known in order to calculate the cost of steel replacement. For that purpose, the repair data was collected from operators for mainly cargo vessels and tankers. Then regression analyses were carried out using this data. Because of the difficulty of obtaining full life-cycle repair data for a particular ship, an anonymous index (ARS/Lightweight) is introduced to be used in regression analysis. This index is represented as the amount of replaced steel divided by lightweight for a particular year.

Common practice regarding calculating cost of steel replacement is given in unit price per kg (Prstrp) depending on the location of the yard where the replacement has taken place. For example, in China, this figure is US\$1.6–1.7 per kg regardless of the ship's zone[1], €–6 per kg in Greece, \$3–4 per kg in Turkey, all including labour and material costs and excluding coating costs. In general, these steel processing prices include material, workmanship, lighting, ventilation and hanging staging but exclude staging, tank cleaning, testing the tanks and access work. Coating is also a separate job.

The cost of steel replacement, COSR for tankers is calculated by using the following formula:

$$\mathrm{COSR} = (\mathrm{ARS})_{\mathrm{CONF}} \times 1000 \times \mathrm{Pr}_{\mathrm{strp}}. \qquad (9)$$

Based on the data of tankers, ARS is calculated by using the following regression formulas:

$$(\mathrm{ARS})_{\mathrm{CONF}} = \mathrm{Lightweight} \times 0.0306 \times (e)^{0.2772 \times (\mathrm{age})} / 1000 \qquad (10)$$

where

COSR	=	the cost of steel replacement, €
Lightweight	=	lightweight of the ship, tonnes
$\mathrm{ARS}_{\mathrm{CONF}}$	=	the amount of replaced steel (using the confidence interval analysis/most likely regression formula-see following explanation), tonnes
$\mathrm{Pr}_{\mathrm{strp}}$	=	the unit price of steel replacement, € /kg

The derivation of formulas (10) is explained below.

Confidence level oriented approximation for tankers (Clements 1991)

The population of steel replacement for tankers used in this stream includes 16 points and is given in Figure 2. The population of unavailability used in this stream includes 32 points and is given in Figure 3.

The regression model used here creates an exponential line of specific, predicted steel replacement amounts based on years. For example, it is predicted that year 15 would produce 20 tonnes (for a lightweight of 10,000 tonnes) of

[1]Excluding the cases where the total steel amount to be replaced is relatively small. In such circumstances, the price per kg may be around \$US3–4.

##	x	y	y' = mean	(y-y')	(y-y')2	y'+ CI	y'-CI
1	10	0.3062	0.489	-0.18	0.033	9.361	0.000
2	13	0.3062	1.124	-0.82	0.668	9.995	0.000
3	2	0.0846	0.053	0.03	0.001	0.000	0.000
4	3	0.1551	0.070	0.08	0.007	0.000	0.000
5	5	0.0306	0.122	-0.09	0.008	0.000	0.000
6	8	0.3191	0.281	0.04	0.001	9.153	0.000
7	10	0.0367	0.489	-0.45	0.205	9.361	0.000
8	23	10.4023	17.961	-7.56	57.129	26.832	9.089
9	23	9.5622	17.961	-8.40	70.534	26.832	9.089
10	23	14.5846	17.961	-3.38	11.398	26.832	9.089
11	15	4.3219	1.956	2.37	5.598	10.828	0.000
12	15	4.3219	1.956	2.37	5.598	10.828	0.000
13	15	2.5907	1.956	0.63	0.403	10.828	0.000
14	15	3.4483	1.956	1.49	2.227	10.828	0.000
15	12	3.5641	0.852	2.71	7.358	9.723	0.000
16	15	13.1660	1.956	11.21	125.667	10.828	0.000
		sum	67.14	0.06	286.84		
		average	4.196	0.004	17.93		
		st error	4.53				
	95% C.I.	8.872					

Figure 2. The population (inc. 16 points) of steel replacement.

##	Age	Unavailability time (days)	y'	y-y'	(y-y')2	y'+ CI	y'-CI
1	3	24	18.88	5.12	26.22	37.29	0.47
2	4	13	20.38	-7.38	54.45	38.79	1.97
3	5	42	21.88	20.12	404.87	40.29	3.47
4	8	25	26.38	-1.38	1.89	44.79	7.97
5	10	37	29.38	7.63	58.14	47.79	10.96
6	13	31	33.87	-2.87	8.25	52.28	15.46
7	15	44	36.87	7.13	50.82	55.28	18.46
8	18	51	41.37	9.63	92.75	59.78	22.96
9	3	18	18.88	-0.88	0.77	37.29	0.47
10	6	17	23.38	-6.38	40.68	41.79	4.97
11	8	25	26.38	-1.38	1.89	44.79	7.97
12	10	21	29.38	-8.38	70.14	47.79	10.96
13	13	30	33.87	-3.87	15.00	52.28	15.46
14	10	20	29.38	-9.38	87.89	47.79	10.96
15	2	16	17.38	-1.38	1.91	35.79	-1.03
16	1	14	15.88	-1.88	3.54	34.29	-2.53
17	3	14	18.88	-4.88	23.81	37.29	0.47
18	3	23	18.88	4.12	16.98	37.29	0.47
19	3	16	18.88	-2.88	8.29	37.29	0.47
20	5	18	21.88	-3.88	15.04	40.29	3.47
21	8	41	26.38	14.62	213.85	44.79	7.97
22	10	16	29.38	-13.38	178.89	47.79	10.96
23	10	20	29.38	-9.38	87.89	47.79	10.96
24	23	34	48.87	-14.87	220.99	67.28	30.46
25	22	50	47.37	2.63	6.93	65.78	28.96
26	23	33	48.87	-15.87	251.73	67.28	30.46
27	22	67	47.37	19.63	385.47	65.78	28.96
28	23	43	48.87	-5.87	34.41	67.28	30.46
29	15	37	36.87	0.13	0.02	55.28	18.46
30	15	43	36.87	6.13	37.56	55.28	18.46
31	15	52	36.87	15.13	228.87	55.28	18.46
32	15	41	36.87	4.13	17.04	55.28	18.46
	sum				2,647.00		
	Average	31	30.50	0.001			
		st error	9.39				
	95% C.I.	18.411					

Figure 3. The population (inc. 32 points) of unavailability.

steel replacement. However, it is known that in practice the actual amount of steel replacement will not be exactly this number but one that is fairly close.

Determining a range for the actual steel replacement figure is done the same way as forming interval estimates. We assume that the predicted value is the average. Then a standard deviation for the prediction and form interval estimates (error shifts) around the mean will be calculated. The standard deviation for regression is called the standard error of the estimate. The formula used is:

$$\text{Sxy} = \sqrt{\frac{\sum (Y - Y')^2}{n - 2}}$$

where
Sxy, standard error of the estimate
Y, actual value obtained in our original data
Y', predicted value
n, number of data pairs in our original data

This standard error is treated just like a standard deviation. If an estimate around a mean is to be formed, a confidence interval based on the Z-values of the area under a normal curve will be used. For example, plus and minus one standard deviation around the mean would represent a 68% chance that the actual steel replacement figure would fall inside the defined range.

The procedure for calculating a standard error of the estimate is fairly simple. First list the original data. Against this data list the predicted values for each factor X value (Age). For example, the first X value listed is 10 years. Using the regression formula from the previous step ($\text{Y(ARS/LWT)} = 0.0306\text{e}^{0.2772\times(\text{age})}$) we calculate the predicted value, also called the Y-prime (Y').

$$Y' = 0.0306\ \text{e}^{0.2772(10)} = 0.489$$

This is repeated for each of the X (age) values listed and then the predicted values are subtracted from the actual Y value. This is the amount of deviation between prediction and the actual data. By summing the square of these deviations, you can obtain the information needed to complete the formula for the standard error of the estimate.

Before the standard error of the regression is calculated, the average of the (Y–Y') column should be checked. This represents the average deviation from the line of regression following normally distributed discrete values. If the regression model has made a good fit, this value should be very close to zero. In other words, the deviation from overestimates equals those for underestimates. The population including 16 points for steel replacement and relevant X(age), Y (the amount of steel replacement), Y', (Y–Y'), $(Y–Y')^2$ values are given in Figure 2. For the population of 16 points,

$$\Sigma(Y - Y') = 0.06 \text{ and}$$
$$0.06 / 16 \text{ data pairs} = 0.004$$

Indeed, this is very close to zero. This indicates that the average predictions are on target. The calculation of the standard error of the estimate indicates how much variation there is in the model.

$$\text{Sxy} = \sqrt{\frac{286.84}{16 - 2}}.$$

To calculate the range of prediction error, a confidence interval should be selected such as:

$$\pm 1.96 \text{ Sxy} = 95\% \text{ confidence}$$
$$\pm 2.58 \text{ Sxy} = 99\% \text{ confidence}$$

In this work, an interval estimate 95% confidence will be formed. Specifically, we will look at the estimate for 10 years. The regression formula predicted an average steel replacement/LWT of 0.489. The interval estimate would be

$$10 \text{ years} = Y' \pm 1.96\,\text{Sxy}$$

or

$$10 \text{ years} = 0.489 \pm (1.96 \times 4.53)$$

You have 95% confidence in this estimate.

Based on the errors calculated above, high and low regressions were established (Figure 4). High regression includes the points whose values are in the ($y' +$ CI) column. Low regression includes the points whose values are in the ($y' -$ CI) column where CI represents confidence interval.

The major assumption here is that the values for the low regression during the first 15 years are assumed to be reasonably low (well-maintained vessel).

The same procedure is also applied to the approximation of unavailability under a 95% confidence interval. Figure 5 shows the regressions for unavailability.

The cost of coating

This cost item includes the coating (COA), which is carried out for the replaced steel during dry-docking. This cost, COA, is calculated as:

$$\text{COA} = \text{TAC} \times \text{Pr}_{\text{COA}} \tag{11}$$

where

COA = the cost of coating, €
TAC = the total area of coating, m^2

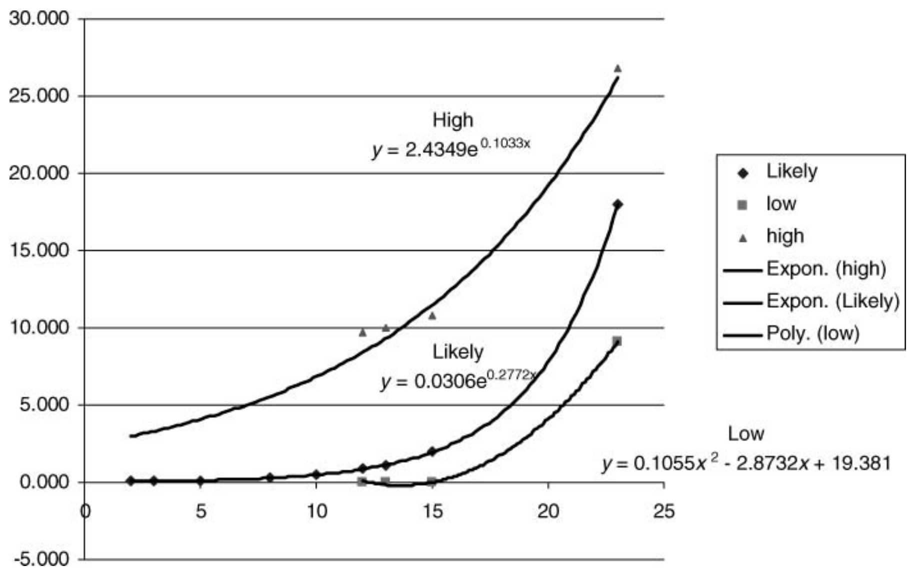


Figure 4. Regressions for tankers with respect to 'steel replacement vs. age' (for 95% confidence).

Pr_{COA} = the unit price of coating per m^2, including material and labour, € /m^2.

TAC can be calculated using the following regression.

$$\text{TAC} = (\text{ARS})\ \text{CONF} \times 1000\ /\ (8 \times \text{Average thickness}). \tag{12}$$

The new steel materials, which will be used in the repairs of the hull structure, are already coated with a protective layer of primer coating. After the new plates/stiffeners are fitted and welded, there may be a full coating application on one side depending on the area and the requirements of the ship owner/operator. Here, it is assumed that coating is carried out on one side but if required it can be adapted easily.

The cost of unavailability

The main assumption here is that the unavailable days considered in this study are the days spent during dry-docking, D_{dock}, assuming

$$D_{\text{sea}}(= D_{\text{sea - ld}} + D_{\text{sea - bal}} + D_{\text{port}}) + D_{\text{dock}} = 365.$$

where

D_{dock} = number of days in shipyard

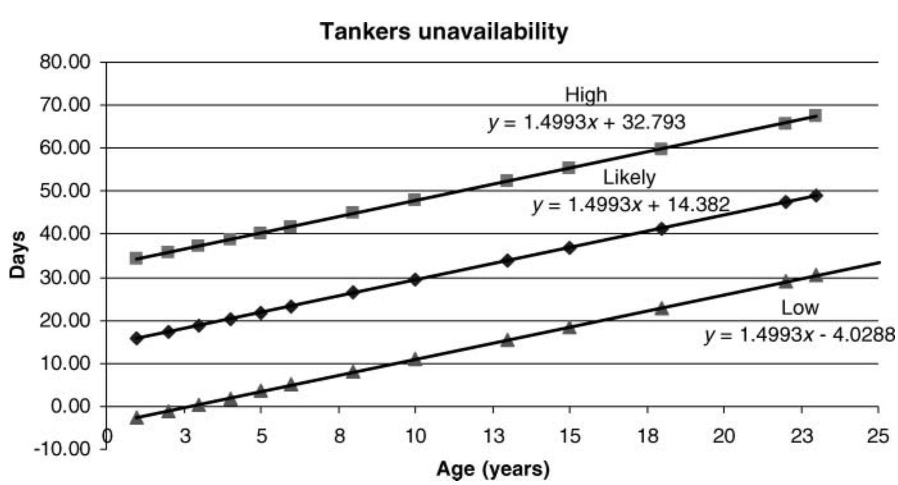


Figure 5. Regressions for tankers with respect to 'unavailability vs. age' (for 95% confidence).

D_{port} = number of days in port
$D_{sea - ld}$ = number of days on sea in loaded condition
$D_{sea - bal}$ = number of days on sea in ballast condition

Lost service (or operation) is a function of downtimes of a subject ship, which are the times spent during dry-docking.

The following formula is used for calculating the cost of unavailability (CUNA) per year:

$$\mathrm{CUNA} = D_{\mathrm{dock}} \times C_{\mathrm{DDT}} \tag{13}$$

where

C_{DDT} = cost of one-day downtime because of the unavailability of the subject vessel
D_{dock} = the number of downtime days spent during dry-docking

Based on the data of tankers, D_{dock} is calculated by using the following regression formula:

$$D_{\mathrm{dock}} = 1.4993X + 14.382 \tag{14}$$

For regression analysis, a database containing the values of the dependent (downtime and replaced steel tonnage) and independent (age) variables for a set of observations was used. Each observation would contain three numbers: unavailability, replaced steel tonnage and age, collected from various ship operators. Finally, the total cost of periodic maintenance is equal to the sum of the cost of steel replacement, the cost of coating and the cost of unavailability as shown below:

$$\mathrm{CODO} = \mathrm{COSR} + \mathrm{COA} + \mathrm{CUNA}$$

where

CODO = the cost of periodic maintenance (or the cost of dry-docking)
COSR = the cost of steel replacement, €
COA = the cost of coating, €
CUNA = the cost of unavailability, €

For i-th design of experiment of the subject vessel within the optimisation loop, stepwise description for the cost of periodic maintenance is given as follows:

1. $\mathrm{Lightweight}_i$
2. Calculate $(\mathrm{COSR}_i)_t$ @ t $\{t = 5, 7.5, 10, 12.5, 15, \ldots, 25\}$ by using Equation (9)
3. Calculate $(\mathrm{COA}_i)_t$ @ t $\{t = 5, 7.5, 10, 12.5, 15, \ldots, 25\}$ by using Equation (11)
4. Calculate $(\mathrm{CUNA}_i)_t$ @ t $\{t = 5, 7.5, 10, 12.5, 15, \ldots, 25\}$ by using Equation (13)
5. Calculate the cost of dry-docking $((\mathrm{CODO}_i)_t)$ at current prices
6. If relevant, escalate the current cost of dry-docking at assumed inflation rate(s)
7. Discount the (escalated) CODO, as shown in the Appendix, to find the present worth
8. Sum-up discounted costs to establish the net present value.

Model 3: Cost of fuel oil

This model is developed based on the following assumptions and relations:

In this case the DWT is kept constant and variations with lightweight of the ship are examined: If lightweight increases, in order to keep the same DWT, displacement will also increase. Accordingly, draught, resistance, required main engine power and daily fuel oil consumption would also increase. The opposite occurs if LWT decreases. Then, in order to keep the same DWT, displacement must decrease. Accordingly, draught, resistance required, main engine power and daily fuel oil consumption would also decrease. These are described below as:

DWT constant	Displacement	Draught	Resistance	Power of main engine(s)	Daily fuel oil consumption
If LWT increases, then:	Increase	Increase	Increase	Increase	Increase
If LWT decreases, then:	Decrease	Decrease	Decrease	Decrease	Decrease

Annual cost of fuel (ACOF) for main engine(s), is calculated by using the following equations:

$$\mathrm{ACOF} = D_{\mathrm{sea}} \times \mathrm{DFC} \times \mathrm{Pr}_{\mathrm{fuel}} \times N_{\mathrm{main}} \times \mathrm{Oil}_{\mathrm{corr}} \tag{15}$$

$$\mathrm{DFC} = P_{\max} \times \mathrm{SFOC}_{\mathrm{main}} \times 10^{-6} \times F_{\mathrm{mean}} \times 10^{-2} \times 24 \tag{16}$$

where

ACOF = annual cost of fuel for main engine(s), €
D_{sea} = days at sea
DFC = daily fuel consumption, tonnes
Pr_{fuel} = fuel price, €/tonne
N_{main} = number of main engines
Oil_{corr} = correction ratio for lubrication oil and diesel oil, 1.15
P_{max} = maximum power of main engine, kW
SFOC_{main} = specific fuel oil consumption of main engine, g/kW h
F_{mean} = reduction factor average speed (percentage of maximum speed), %
C = admiralty coefficient, $\mathrm{t}^{2/3}\mathrm{kn}^3/\mathrm{kW}$
δ = variation

Admiralty coefficient (C) can be used to establish the link between lightweight and fuel cost. The admiralty coefficient is assumed to be constant for similar ships with similar Froude numbers, i.e. ships that have almost the same C_B, C_P, F_n, etc.

$$C = \frac{\Delta^{2/3}\ V^3}{P_B}$$

where P_B is the break power (in kW), V is the speed (in knots) and Δ is displacement (in tonnes).

For i-th design of experiment of the subject vessel within the optimisation loop, stepwise description for the annual cost of fuel oil is given as follows:

1. Lightweight_i
2. δ Lightweight = $\text{Lightweight}_i -$ Original Lightweight (either positive or negative)
3. i = Original + δ Lightweight
4. $(P_B)_i = (\Delta_i^{2/3} \times V^3)/C$
5. Calculate $(\text{DFC})_i$ by using Equation (16)
6. Calculate annual cost of fuel for main engine(s), ACOF, by using Equation (15)
7. If relevant, escalate ACOF at assumed inflation rate(s)
8. Discount the (escalated) ACOF as shown in Tables 2 and 3 to find the present worth
9. Sum up discounted costs to establish the net present value.

Model 4: Operational earning

In this case the displacement of the ship is kept constant and the effect of change in lightweight of the ship is examined. When LWT, increases DWT will decrease, in order to keep the same displacement. Accordingly, Operational Earning will also decrease. The opposite occurs if LWT decreases. Then, in order to keep the same Displacement, DWT must increase and accordingly, Operational Earning will also increase:

Displacement constant	**DWT**	**Operational Earning**
If LWT increases, then:	decrease	decrease
If LWT decreases, then:	increase	increase

A model needs to be developed to be able to assess the variation in earning due to the change in lightweight and deadweight, preferably expressed in revenue per annum.

According to Stopford (1997) the basic revenue calculation involves two steps: first, determining how much cargo the vessel can carry in the financial period, measured in whatever units are appropriate (tonnes, tonne miles, cubic metres, etc.), and, second, establishing what price or freight rate the owner will receive per unit transported. In more technical terms, the revenue per annum can be viewed as the product of the ship's productivity, measured in tonne miles of cargo transported per annum, and the freight rate per tonne mile, thus,

$$R_{\text{tm}} = P_{\text{tm}} \quad \text{FR}_{\text{tm}} \tag{17}$$

where

R_{tm} = revenue per annum
P_{tm} = Productivity in tonne miles of cargo per annum
FR_{tm} = freight rate per tonne mile of cargo transported
t = time period
m = ship type

The analysis of productivity can be carried further by subdividing into its component parts as follows:

$$P_{\text{tm}} = 24 \times S_{\text{tm}} \times (D_{\text{sea - ld}})_{\text{tm}} \times \text{DWU}_{\text{tm}} \tag{18}$$

where

S_{tm} = average operating speed per hour
$D_{\text{sea - ld}}$ = loaded days at sea per annum
DWU_{tm} = deadweight utilisation.

For i-th design of experiment of the subject vessel within the optimisation loop, stepwise description for operational earning is given as follows:

- Lightweight_i
- δLightweight = $\text{Lightweight}_i -$ Original Lightweight (positive or negative)
- DWT_i = Original DWT + δLightweight
- Calculate $(P_{\text{tm}})_i$ by using Equation (18)
- Calculate revenue per annum $(R_{\text{tm}})_i$ by using Equation (17)
- If relevant, escalate the annual operational earning value at assumed inflation rate(s)
- Discount the (escalated) operational earning as shown in Tables 2 and 3 to find the present worth
- Sum up discounted costs to establish the net present value.

Model 5: Earning of dismantling

The dismantling revenue, EDIS, will be the function of the lightweight of the subject vessel, and will be calculated as:

$$\text{EDIS} = \text{Pr}_{\text{dist}} \times \text{Lightweight}_i \tag{19}$$

where
EDIS = the earning of dismantling, €
Pr_{dist} = the unit price of dismantling per tonne, €/tonne

The whole procedure given above is shown in Figure 6 schematically.

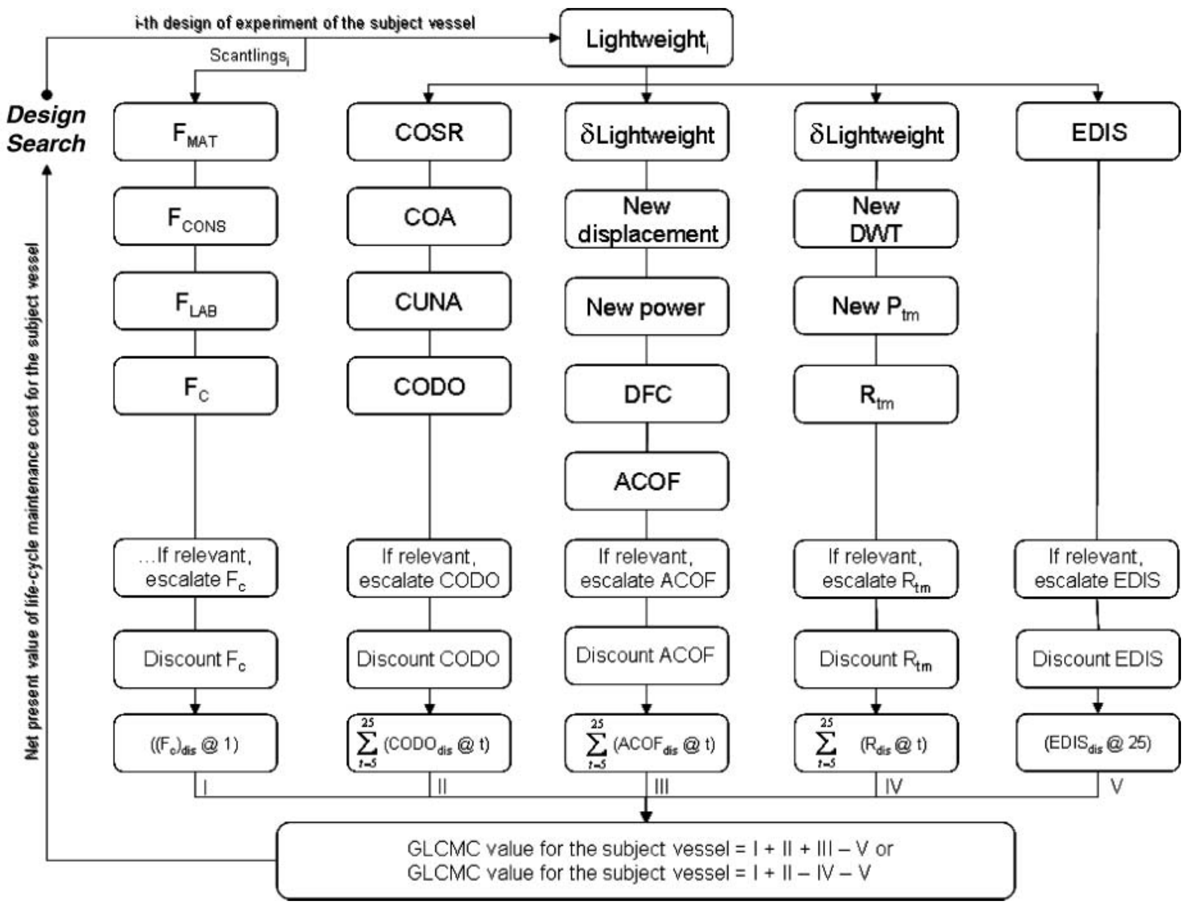


Figure 6. The stepwise procedure for GLCMC.

Illustrative example: Chemical tanker

In order to show the applicability of the proposed methodology, an illustrative example using a chemical tanker is given in this part. In this example, variation in lightweight of the ship will be taken into account and its effect on relevant operational cost and earning will be investigated using the models 2, 3, 4 and 5. Model 1 (production cost) will not be investigated in this particular example. Model 1 will be developed in the future work. It should be noted that there are illustrative examples and applications of model 1 for a Floating Storage and Offloading (FSO) unit with a capacity of 370,000 tonnes (Rigo 2001) and a medium size LNG carrier (Rigo 2003). The main particulars of the example chemical tanker are:

$L_{oa} = 182$ m
B (moulded) = 29.4 m
D (depth) = 13 m
d(draft) = 10.03 m
Lightweight = 9500 tonnes
Displacement = 41,500 tonnes
DWT = 32,000 tonnes
Design speed = 15 knots
Power of main engine is 11,000 kW
Number of main engine = 1

In order to be able to follow the whole process, the calculations for the particular year 5 and new lightweight value of 10,000 tonnes are provided below in detail.

It is assumed that escalation and discount rates are different and they are 3% (prices escalate 3% per year) and 8% over a period of 25 years, respectively.

Model 2 related

$\text{ARS} = 0.1582\,(e^{0.1787\times(5)})\times 10{,}000/1000 = 3.9$ tonnes
$\text{Pr}_{\text{strp}} = 5$€/kg
COSR @ current prices = 5 × 3.9 × 1000 = 19,328€
Escalated COSR = $19{,}328 \times (1+0.03)^5 = 22{,}406$€
Discounted COSR = $22{,}406/(1+0.08)^5 = 15{,}249$€
$\text{TAC} = 3.9 \times 1{,}000/(8 \times 17) = 28.4\ \text{m}^2$
$\text{Pr}_{\text{COA}} = 5$€/m^2

It should be noted that the cost of coating refers only to the full coating of the replaced steel and not that of the entire ship during the dry-docking period. Moreover, it is assumed that the replaced steel is a flat panel of the bottom plate with a specific thickness (17 mm in this case) and that the coating process refers to all different layers applied on the outer surface of the plate. Labour cost as well as the paint supply is included in the coating cost. In general, repair shipyard sites provide very low coating prices per m^2 as they take into account the entire repair specification of the ship.

COA @ current prices = 28.4 × 5 = 142.1€
Escalated COA = 142.1 × $(1 + 0.03)^5$ = 164.8€
Discounted COA = 164.8/$(1 + 0.08)^5$ = 112.1€
D_{dock} = 1.4993 × 5 + 14.382 =∼21 days
CDDT = Annual revenue (see subsequent revenue calculations below)/D_{sea}− l d (loaded days at sea)
D_{sea}− l d = (2/3) × (D_{sea})
D_{sea} = 365 −D_{dock} = 365 − 21 = 344 days
CDDT = 375,648€
CUNA @ current prices = 43,680 × 21 = 7,849,878€
Escalated CUNA = 7,849,878 × $(1 + 0.03)^5$ = 9,100,161€
Discounted CUNA = 9,100,161/$(1 + 0.08)^5$ = 6,193,416€

Model 3 related

Original PB = 11,000 kW
Admiralty coefficient = $(41{,}500)^{2/3} \times 15^3/11{,}000 = 368$
New power $P_{max} = (41{,}500 + 500)^{2/3} \times 15^3/368 = 11{,}088$ kW
$SFOC_{main}$ = 125 g/kW h
F_{mean} = 90
DFC = 11,088 × 125 × 90 × 24 × 10^{-8} = 29.9 tonnes
D_{sea} = 365 −D_{dock} = 365 − 21 = 344 days
Pr_{fuel} = 419€/tonne
N_{main} = 1
Oil_{corr} = 1.15
ACOF @ current prices = 29.9 × 344 × 419 × 1 × 1.15 = 4,968,119€
Escalated ACOF = 4,968,119 × $(1 + 0.03)^5$ = 5,759,412€
Discounted ACOF = 5,759,412/$(1 + 0.08)^5$ = 3,919,759€

Model 4 related

S_{tm} = 14 knots
D_{sea}-l d = (3/4) × (D_{sea}) = (3/4) × 344 = 258 days
DWU_{tm} = 0.8
P_{tm} = 24 × 14 × 258 × 0.8 × 32,500 = 2,254,563,515 tonne miles of cargo per annum
F_{rtm} = 0.043€ per tonne mile for molasses cargo
R_{tm} @ current prices = 2,254,563,515 × 0.043 = 96,946,231€
Escalated R_{tm} = 96,946,231 × $(1+0.03)^5$ = 112,387,252€
Discounted R_{tm} = 112,387,252/$(1+0.08)^5$ = 76,488,876€

Model 5 related

Because of dismantling, EDIS is attributed to the particular year 25. Then
Pr_{dist} = 451.61€/tonne
EDIS @ current prices = 451.61 × 10,000 (new lightweight) = 4,516,129€
Escalated EDIS = 4,516,129 × $(1+ 0.03)^{25}$ = 9,455,771€
Discounted EDIS = 9,455,771/$(1 + 0.08)^{25}$ = 1,380,712€

Table 1 is the summary of the calculations carried out for cost and earning with respect to the change in lightweight, bearing in mind that the fourth experiment is the base design. It can be concluded for this illustrative example that changes in cost and earning are marginal with respect to the significant change in lightweight.

For this sensitivity analysis the following three options will be considered:

Options	**Steel replacement**	**Unavailability**
The worst case	High	High
The most likely case	Likely	Likely
The best case	Low	Low

where high represents 'not well maintained vessel' and low represents 'well maintained vessel'. The following experiments are for the lightweight values of 10,500 tonnes and 8,500 tonnes as shown in Figure 7.

Where scenario 1 is relevant life cycle cost and scenario 2 is relevant life cycle earning, it can be easily concluded that if a vessel is not maintained well (worst case), cost increase can be more than 100% compared to the best case (well-maintained vessel). Similarly, the same can be concluded for the earning element, which decreases almost by 35%.

Table 1. The results of the scenario analysis for confidence interval oriented approximation.

	Lightweight (in tonnes)	% δ	Scenario 1 M2 + M3 – M5 (DWT is constant)	% δ	Scenario 2 M2 – M4 – M5 (Δ is constant)	% δ
1.	8500	−10.53%	79,522,514	−0.41%	−369,396,089	0.58%
2.	9000	−5.26%	79,685,660	−0.20%	−368,336,711	0.29%
3.	9250	−2.63%	79,766,962	−0.10%	−367,807,022	0.14%
4.	9500	0.00%	79,848,086	0.00%	−367,277,333	0.00%
5.	9750	2.63%	79,929,033	0.10%	−366,747,645	−0.14%
6.	10000	5.26%	80,009,804	0.20%	−366,217,956	−0.29%
7.	10500	10.53%	80,170,825	0.40%	−365,158,578	−0.58%

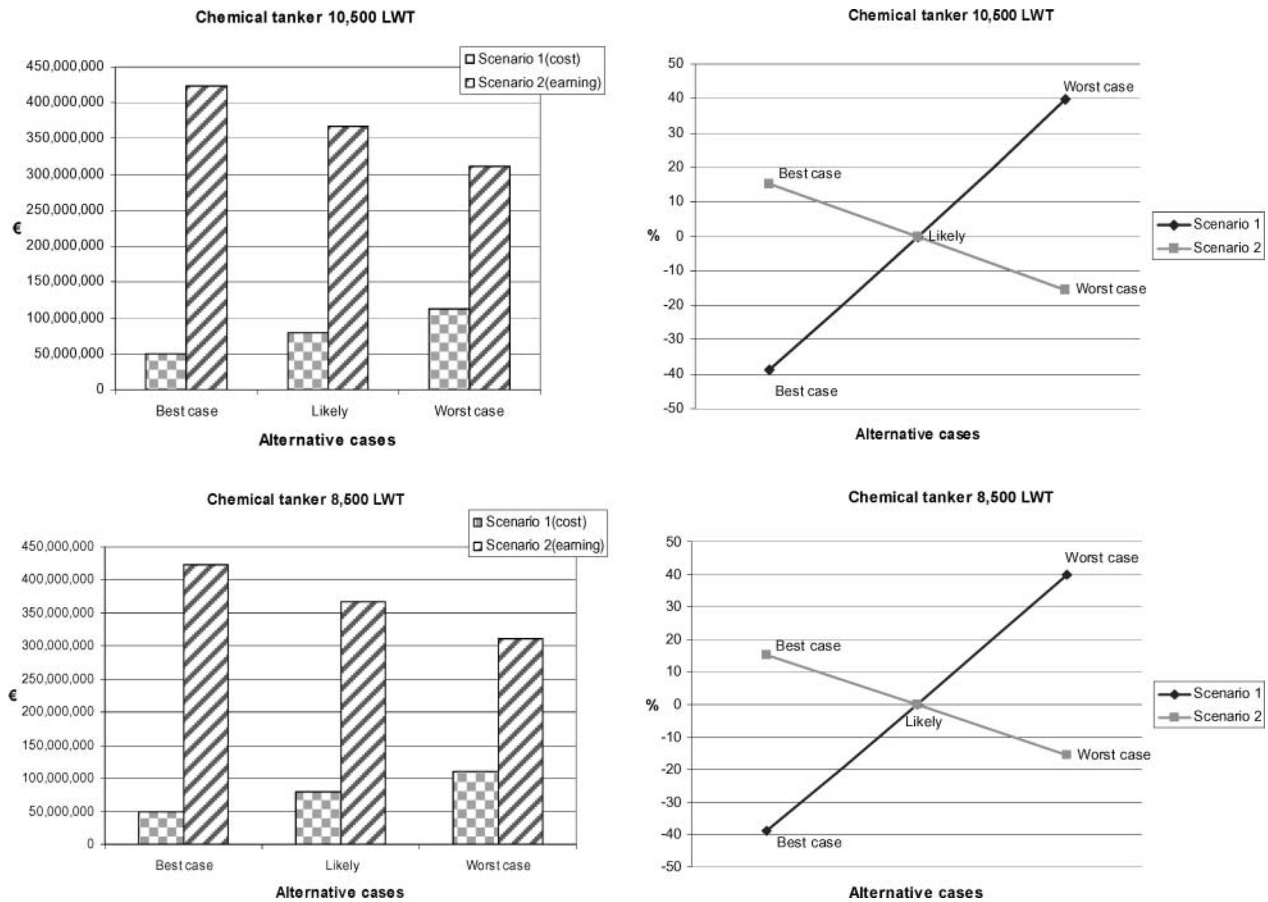


Figure 7. Sensitivity analysis with respect to lightweight with constant DWT.

Figure 8 shows the cost and earning assessments for the best, the most likely and the worst options with respect to 8,500 and 10,500 LWT.

Conclusions and future research

This section summarises the achievements and shortcomings of the research carried out in this study as well as pointing the way for further research in this area. From the work carried out in this study, the following can be concluded:

- The developed life cycle maintenance/repair cost model is robust enough to be used within a design search platform. The model can be utilised to find maintenance/repair related cost/earning values for the subject vessels with respect to design of experiments throughout the structure optimisation.
- The developed method can efficiently help designers, ship owners and production engineers to make rationale decisions during early design phases.
- Although the model is able to calculate generalised life-cycle maintenance cost/earning, it can also be used for what if scenario analyses with respect to other parameters of the model, such as unit price of steel replacement per kg, price of fuel oil and so on.
- This model can further be improved with the inclusion of other life cycle cost elements to identify the (significant) cost drivers.

The main shortcoming of the proposed methodology is that the regression analyses heavily rely on the operators' data, which can be greatly improved with the availability of additional maintenance/repair data.

This research provided a theoretical and practical foundation for carrying out further research and development of more mature maintenance/repair cost modelling systems. Some of the improvements that may enhance the proposed methodology include the following:

- To employ advanced inference and/or reasoning systems that are to perform reasoning under vagueness environments; where maintenance/repair data is difficult to obtain and expert knowledge expressed in verbal settings is present
- To make use of neural networks for better predictions of annually replaced steel and unavailability times.

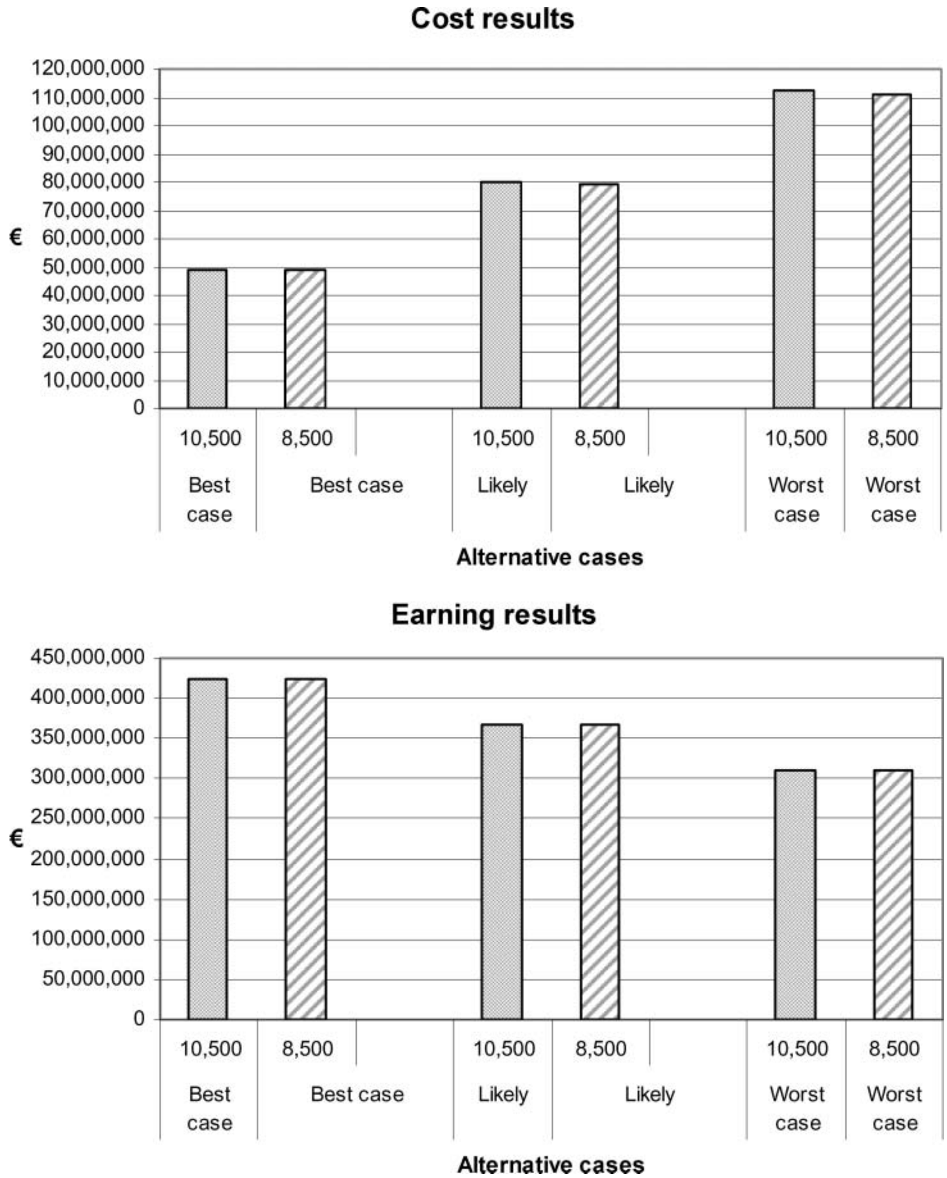


Figure 8. Sensitivity analysis with respect to the maintenance strategy with constant DWT.

- To create ship specific regression models and databases with the availability of additional maintenance/repair data.
- To extend the existing model to take account of maintenance/repair strategy of a ship owner.
- To carry out the same analysis for fluctuations in the freight rate estimations (which will affect the operational earning).

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Appendix 1: Data

In Tables 2 and 3, the data gathered and used for the illustrative example regarding the tanker vessels are presented. Table 2 shows the detailed table including the unavailability and repair events. It should be noted that during the data-gathering procedure some of the steel repair events were not recovered due to shipping operators' lack of proper data archiving.

Table 3 presents a more detailed decomposition of the areas of the hull structure repaired during the dry-docking of some of the oil tankers used at this data collection. Main areas repaired are the deck plate (mostly due to pitting corrosion), side ballast tanks due to general corrosion affected surfaces (especially in the upper part of transverse bulkheads) and webs. Also, the fore and aft peak tanks due to general corrosion patterns affecting the transverse bulkheads, the stringer plates and the transversal web frames. Other areas in the exposed deck surfaces included the poop deck area, the superstructure decks and the forecastle deck, mostly due to pitting corrosion problems. It is also worthwhile mentioning that there is a slight variation between the as-built and the actually renewed steel weight (new original) due to the unavailability of original scantlings at the dry-docking places (shipyards in the Far East).

Appendix 2: Financial basics – The net present method

LCC analysis consists of defining the LCC of each element and reducing each element cost to a common basis. It is important to compare alternatives on a common baseline. This Appendix discusses the methods of reducing the LCC to a common basis using present worth calculations.

In LCC analysis, escalation and discount rates must be considered. The most widely used method of LCC analysis uses the net present worth method. In this method, costs are estimated in current euros, escalated to the time when they would be spent, and then corrected to a present worth using a discount rate. When the inflation and discount rates are equal, LCC can be computed as current euros, totalled for the ship life and compared. When the escalation and discount rate are different, the escalation and present worth calculations must be performed.

To estimate the impact of discounting and escalating, the following common equations (A.1) and (A.2) may be applied.

Escalating takes account of the change in price levels over time.

$$\mathrm{EF} = (1 + E_1) \times (1 + E_2) \times \cdots \times (1 + E_t) \tag{A.1}$$

where
EF is the escalation factor in year t
E_t is the escalation rate in t-th year.

As maintenance/repair actions are distributed over long time periods (e.g. 25–40 years), the effect of time on money must be considered. The cost of each action must be converted to an equivalent value at a reference instant. This can be achieved through the discount rate, r. The equivalent cost today, C_0^*, of spending a certain amount of money, C_t^*, at a given time t in the future, can be expressed by the present value of cost, given as:

$$C_0^* = \frac{C_t^*}{(1 + r)^t} \tag{A.2}$$

where
r: discount rate
t: the specific year in the life-cycle costing period
C_t^*: Net cost in year t, this can be assumed equal for all years.

The discount rate of money is difficult to predict, since it depends on the economical conditions during then lifetime of a subject vessel.

Table 2. Detailed table including the unavailability and repair events for the tanker vessels.

##	Ship type	Survey period	Age	Unavailability time (days)	LWT (tonnes)	Steel repair (kgs)
1.	Pr. Tanker	Annual	3	24	10, 670	
2.	Pr. Tanker	Annual	4	13	10, 670	
3.	Pr. Tanker	1st Sp.	5	42	10, 670	
4.	Pr. Tanker	1st Int.	8	25	10, 670	
5.	Pr. Tanker	2nd Sp.	10	37	10, 670	
6.	Pr. Tanker	2nd Int.	13	31	10, 670	
7.	Pr. Tanker	3rd Sp.	15	44	10, 670	
8.	Pr. Tanker	3rd Int.	18	51	10, 670	
9.	Pr. Tanker	4th Sp.	19	7	10, 670	
10.	Tanker	Annual	3	18	16, 327	
11.	Tanker	1st Sp.	6	17	16, 327	
12.	Tanker	1st Int.	8	25	16, 327	
13.	Tanker	2nd Sp.	10	21	16, 327	5, 000
14.	Tanker	2nd Int.	13	30	16, 327	5, 000
15.	Tanker	2nd Sp.	10	20	15, 629	
16.	Tanker	Annual	2	16	23, 650	2, 000
17.	Tanker	Annual	1	14	19, 346	
18.	Tanker	Dry-dock	3	14	19, 346	3, 000
19.	Tanker	Dry-dock	3	23	21, 066	
20.	Tanker	Annual	1	11	16, 327	
21.	Tanker	Annual	3	16	16, 327	
22.	Tanker	1st Sp.	5	18	16, 327	500
23.	Tanker	1st Int.	8	41	16, 327	5, 210
24.	Tanker	Dry-dock	9	5	16, 327	
25.	Tanker	Dry-dock	10	16	16, 327	
26.	Tanker	2nd Sp	10	20	16, 327	600
27.	Tanker	4th Int.	23	34	13, 939	145, 000
28.	Tanker	4th Int.	22	50	14, 251	381, 000
29.	Tanker	4th Int.	23	33	14, 118	135, 000
30.	Tanker	4th Int.	22	67	13, 889	400, 000
31.	Tanker	4th Int.	23	43	13, 850	202, 000
32.	Pr. Tanker	3rd Sp	15	37	11, 569	50, 000
33.	Pr. Tanker	3rd Sp	15	43	11, 569	50, 000
34.	Pr. Tanker	3rd Sp	15	52	11, 580	30, 000
35.	Pr. Tanker	3rd Sp	15	41	11, 600	40, 000
36.	Tanker	3rd Sp	15	180	22, 786	900, 000
37.	Tanker	3rd Sp	15	68	22, 786	300, 000
38.	Tanker	3rd Sp	15	149	22, 786	2, 000, 000
39.	Tanker	3rd Sp	14	167	22, 786	600, 000
40.	Ch. Tanker	Dry-dock	31	6	2, 875	20, 670
41.	Tanker	Dry-dock	12	10	923	259

Table 3. Oil tanker ship repair data per area examined.

	Generic hull structure repair estimation table oil tanker ships									
	T1		T2		T3		T4		T5	
Area examined/ship	As-built	New original	As-built	New original	As-built	New original	As-built	New original	As-built	New original
Deck plate	68	68	189	196	69	73	176	177	112	113
Side-ballast tanks	47	48	114	116	37	38	162	164	54	56
Cargo tanks	4	4	20	21	0	0	0	0	0	0
Fore peak tank	8	8	14	14	4	5	22	22	10	1
Forecastle deck	2	2	6	6	3	3	7	7	5	5
Poop deck	6	6	14	15	7	8	17	17	9	9
Superstructure decks	3	3	5	5	3	3	5	5	4	4
A peak tank	6	6	8	8	5	5	8	8	5	5
Total (tonnes)	144	145	370	381	128	135	397	400	199	5

Notes:
1. Total estimation of steel renewals are rounded up to the nest whole number (in tonnes).
2. As built: renewal based on as built thickness.
3. New original: renewal based on new original thickness.