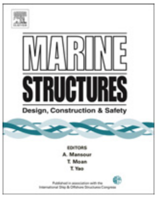
Marine Structures 32 (2013) 1–17

Contents lists available at SciVerse ScienceDirect

Marine Structures

journal homepage: www.elsevier.com/locate/marstruc



Study on alternative approaches to corrosion protection of ballast tanks using an economic model

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ARTICLE INFO

Article history:
Received 31 October 2012
Accepted 22 February 2013

Keywords:
Ballast tank
Total cost of ballast tanks
Corrosion
Corrosion resistant steel
Coating
Sensitivity analysis

ABSTRACT

One of the most relevant problems in ship construction and maintenance nowadays is corrosion in ballast tanks of modern merchant vessels. On the one hand, there is a general consensus that the economic lifespan of such a vessel depends, to a large degree, upon the corrosion state of its ballast tanks, while on the other hand these ballast tanks, located between the outer hull and the cargo tanks, makes routine inspection and maintenance a difficult task.

Today, ship's ballast tanks are usually constructed in steel and protected with an epoxy coating backed up by sacrificial zinc anodes. Such a construction has been applied without significant alterations for many years. The objective of this economic study is to compare this construction method with some potential alternatives. The considered alternatives are: (1) an increase in structural scantlings, eliminating the necessity to replace corroded at a cost of real cargo carrying capacity of the ship, (2) application of the novel and more durable $TSCF_{25}$ coating (3), the use of corrosion resistant steel in ship construction and (4) a standard $PSPC_{15}$ coating combined with lifetime lasting aluminum sacrificial anodes. A cost model was used to evaluate these alternative options

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http://dx.doi.org/10.1016/j.marstruc.2013.02.003

together with sensitivity analysis. It is concluded that the durable coating and the use of lifetime lasting aluminum anodes are bound to improve the actual basic tank concept. Corrosion resistant steel becomes attractive when the steel price becomes competitive.

1. Introduction

1.1. The problem of ballast tank corrosion

The degradation of metallic surfaces due to atmospheric corrosion is a well known problem for many steel structures such as bridges, storage tanks and pipelines. Bringing seawater into this equation causes an even more aggressive environment and an increased corrosion effect. Nevertheless, merchant vessels, carry cargo all over the seven seas, are mostly built of steel. In the absence of cargo, or when the ship is only partly loaded, a vessel carries seawater in her ballast tanks to ensure maneuverability and to control draft, stress and stability. As necessary as they are for the operation of a ship, though, the fact that ballast tanks are prone to corrosion poses an important challenge for ship owners.

Corrosion is expensive. For the U.S. economy alone, the 1998 cost of corrosion amounted to $275.7 billion/year [1,2]. These economic losses were provoked by production interruptions, incidents and repairs. For the U.S. marine shipping industry, the annual corrosion-related costs were estimated at $ 2.7 billion. This cost is associated with new construction ($1.12 billion), maintenance and repairs ($ 810 million) [3], and corrosion-related downtime ($ 785 million [1,2];). Corrosion can become a safety issue in ships. Statistics show that 90% of ship failures were attributed to corrosion [4].

Corrosion is a major cause of marine structural failures. Corrosion results in loss of structural strength at local and global levels, and leads to fatigue failure and stress corrosion cracking. Some recent marine incidents with tankers have been directly linked to accelerated corrosion [7]. Localized corrosion is often found on ship structures. The areas most susceptible to corrosion are the ballast tanks due to the intense contact with seawater, humidity, and the chloride-rich environment, even when empty. Because of the double hull configuration required by the Oil Pollution Act of 1990 [6,8,9], ballast tanks are difficult to maintain. The access to ballast tanks is limited, the environment is unfriendly, the light is scarce, large parts are hard to reach. The cost of inside maintenance is high, partly because the working conditions are troublesome. In short, double hull ballast tanks act as the Achilles' heel of the ship.

The introduction of the double hull tankers in the nineteen nineties resulted in longitudinal stiffeners being placed in the ballast tanks [7]. This configuration aggravates the corrosion problem. The quantity of corrosion in ballast tanks is therefore a major factor for ending the economic life of a ship that will send her to the scrap yard [10].

Today, ship's ballast tanks are constructed in carbon steel and protected with an epoxy coating and sacrificial zinc anodes at some locations. These serve to reduce and in some instances effectively defer corrosion and mitigate corrosion consequences [5]. Such a construction has been applied without significant changes for decades. The goal of this study is to compare this traditional approach with some potential alternatives through an analysis of the total cost, restricted to construction, exploitation and maintenance of the ballast tanks, hereinafter called total cost of ballast tanks (TCB). As such, the impact of any structural investments can be investigated in the conceptual stage of the vessel. Important elements in such an analysis are the selection of appropriate construction, equipment and protection material.

1.2. Research objective

The objective of this study is to construct a cost-based model outlining some aspects in the construction of a double hull ship to achieve minimal corrosion effects during the economic lifetime of the ship (25 years).

Based on this model, five different options of ballast tank construction (cases I–V in Table 1) are compared, within the currently available techniques and materials, in order to obtain cost reductions. Selection of options I–IV occurred on the basis of Safinah [11], option V is based on experience and information we obtained while working on this article [12]. The equations are applied to a typical Panamax tanker, a ship constructed according to the size limits for ships traveling through the Panama Canal [13].

Case I is the typical tank as constructed today in ordinary grade A steel, 14 mm thickness, coated with a standard $PSPC_{15}$ coating [14] and equipped with zinc sacrificial anodes. Such a tank remains intact for approximately 5 years [15,16]; then the coating starts to degrade and corrosion appears requiring eventually steel replacement and paint restoration at a certain point of time. The anodes have to be replaced every 5 years.

In case II, the core element is corrosion allowance. The corrosion allowance is the maximum steel thickness loss allowed by the classification society, meaning that in the lifespan of a ship a certain quantity of corrosion is tolerable without endangering the structural integrity of the ship. As a rule of thumb, steel will be replaced, in dry dock, when its thickness has been reduced to 80% of the initial value. The present corrosion allowances of even the most conservative classification societies are marginally adequate for a 20-year design life vessel [17]. Hence, case II has been chosen to provide for an additional corrosion allowance of 3 mm, As in case I, a standard $PSPC_{15}$ coating is applied, and the anodes have to be replaced every 5 years.

In case III, ships receive the currently experimental $TSCF_{25}$ coating on top of 14 mm grade A steel. This coating system is postulated to have a lifetime expectancy of 25 years, the economic lifetime of the ship, by a better preparation of the substrate, improved application conditions and an increased coating thickness [18,19]. Consequently, there is no more need for steel replacement, and coating repair needs are reduced. Since the surface attacked by corrosion is reduced, so will be the consumption of the sacrificial anodes. The anodes will be replaced only once every 10 years.

For case IV, the tanks are constructed in corrosion resistant steel (CRS) and painted with an esthetical white coating as per IMO $PSPC_{15}$ [14]. Coating repair remains necessary, although reduced. Anodes become redundant and are not used.

The case V tanks are again constructed in ordinary grade A steel and protected with a standard $PSPC_{15}$ epoxy coating. Cathodic protection is obtained by aluminum sacrificial anodes of sufficient mass to last 25 years, the full economic lifespan of the selected model.

2. Methodology

To assess the different possibilities a total cost of ballast tanks model is developed. In a next step, uncertainties are taken into account by a sensitivity analysis, including Monte Carlo sensitivity analysis. For each of the equations, Table 2 gives the applicable variables.

2.1. TCB (total cost of ballast tanks)

The TCB equals the initial investment plus the operating costs through 25 years minus the residual value when the ship is sold for scrap and with DR as discount rate.

Table 1
Summary of the five cases in the analysis in terms of construction, equipment and maintenance criteria.

	Case I	Case II	Case III	Case IV	Case V
Steel	Grade A	Grade A	Grade A	Corrosion resistant	Grade A
Paint system	IMO $PSPC_{15}$	IMO $PSPC_{15}$	$TSCF_{25}$	1 coat white epoxy	IMO $PSPC_{15}$
Thickness	320 μm	320 μm	350 μm	160 μm	320 μm
Paint quality	Pure epoxy	Pure epoxy	Pure epoxy	Pure epoxy	Pure epoxy
Anodes	Yes (Zn)	Yes (Zn)	Yes (Zn)	No	Yes (Al)
Replacement of the anodes	Every 5 years	Every 5 years	Every 10 years	NA	Every 25 years
Coating repair	Yes	Yes	Yes	Yes	Yes
Increased scantlings	No	Yes	No	No	No
Steel replacement	Yes	NA	NA	NA	Yes

Table 2
TCB variables per model and per equation.

	Case I	Case II	Case III	Case IV	Case V
2.1.1 Initial investment-steel cost-Eqs. (3) and (4)					
Surface area	AREA	AREA	AREA	AREA	AREA
Thickness	PT	PT + CA	PT	PT	PT
Density	DENS	DENS	DENS	DENS	DENS
Cost new building steel	CAN	CAN	CAN	CNCRS	CAN
2.1.1 Initial investment-coating cost-Eq. (5)					
Initial coating cost per m^2	$PSPC_{15}$	$PSPC_{15}$	$TSCF_{25}$	CCRS	$PSPC_{15}$
2.1.1 Initial investment-anode cost-Eq. (6)					
Number of anodes	ZA	ZA	ZA	\	AA
Initial installation cost per anode	IZA	IZA	IZA	\	IAA
2.1.2.1 Steel renewal cost-Eq. (9)					
Lightweight	LWT_T	\	\	\	LWT_T
Cost of steel repair per ton	RAS	\	\	\	RAS
2.1.2.2 Coating repair cost-Eq. (11)					
Surface	AREA	AREA	AREA/2	AREA/4	AREA
Cost of recoating per square meter	RPSPC	RPSPC	RTSCF	RCCRS	RPSPC
2.1.2.3 Anode replacement cost-Eq. (12)					
Number of anodes	ZA	ZA	ZA	\	AA
Installation cost per anode	IZA	IZA	IZA	\	IAA
2.1.2.4 Cost of unavailability due to dry dock-Eq. (14)					
Factor f	1	2	4	4	1
Lightweight	LWT_T	LWT_{TII}	LWT_T	LWT_T	LWT_T
Time charter equivalent	TC	TC	TC	TC	TC
Cost of dry dock per day	CDD	CDD	CDD	CDD	CDD
2.1.3 Residual value-Eq. (16)					
Lightweight	LWT_T	LWT_{TII}	LWT_T	LWT_T	LWT_T
Value of scrap iron	SCI	SCI	SCI	SCRS	SCI

$$\mathrm{TCB} = \text{Initial investment} + \sum_{1}^{25} \frac{\text{exploitation cost}}{(1+\mathrm{DR})^{n}} - \frac{\text{residual value}}{(1+\mathrm{DR})^{25}} \tag{1}$$

2.1.1. *Initial investment*

The initial investment for each of the cases can be calculated as follows:

$$\text{Initial investment} = \text{steel cost} + \text{coating cost} + \text{anode cost} \tag{2}$$

$$\text{Steel cost} = \text{lightweight(Eq. 4)} \times \text{cost of steel} \tag{3}$$

$$\text{Lightweight} = \text{surface area} \times \text{thickness} \times \text{density} \tag{4}$$

$$\text{Coating cost} = \text{surface area} \times \text{initial coating cost per m}^2 \tag{5}$$

$$\text{Anode cost} = \text{number of anodes} \times \text{initial installation cost per anode} \tag{6}$$

2.1.2. *Exploitation cost*

The calculation of the exploitation cost takes five elements into account: steel renewal cost, coating repair cost, the cost to replace the anodes, the cost of unavailability of the ship due to dry dock and (for case II ships) the loss of cargo carrying capacity due to an increased lightweight.

2.1.2.1. Steel renewal cost. Effective ship maintenance can only be carried out during dry docks. A ship has to visit dry docks two times every five years, during one of which steel and coating repair jobs are performed. A rough estimate of the steel renewal cost has been derived from data obtained from a population of 18 ships (Fig. 1), taken from three separate shipping companies who are willing to share their information on past maintenance repairs. These ships were maintained in a normal way and repairs had been carried out during every previous dry dock visit. The quantity of steel replaced during dry dock resulting from damage by corrosion, cracks and deformation but excluding accidents can be represented by the following regression [20]:

$$\frac{\mathrm{ASR}}{\mathrm{LWT}} = 0.031e^{0.2982t} \text{ or } \mathrm{ASR} = \mathrm{LWT} \times 0.031e^{0.2982t} \tag{7}$$

with ASR representing the quantity of steel replaced per dry dock and t the age of the ship.

In this model, an important amount of scatter shows up for ships older than 15 years. Next to our in situ experience in the ballast tanks of more than 150 ships, this type of scatter turns out to be rather common among older ships, and the difference in the condition of the ballast tanks of two similar ships

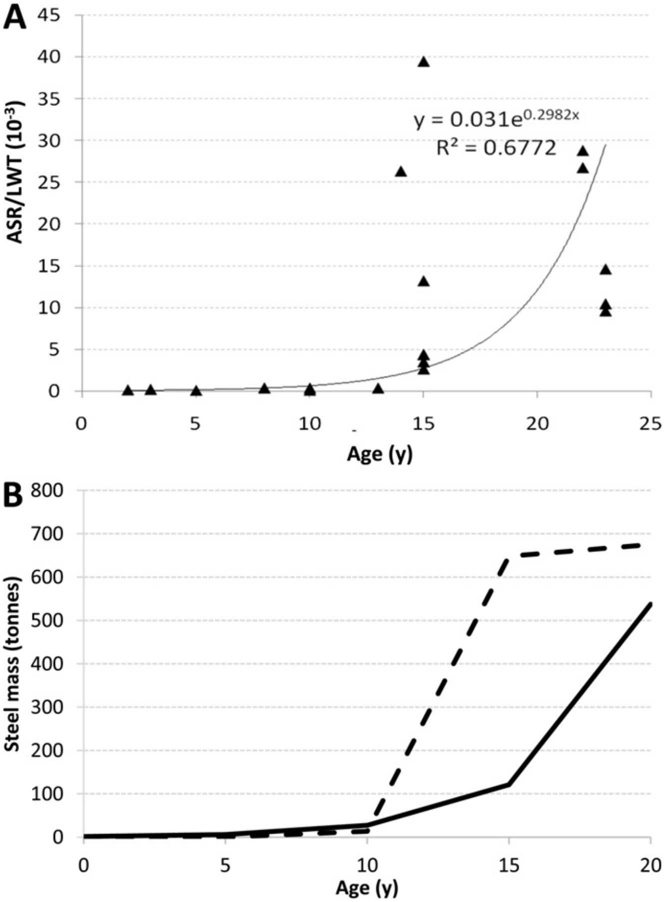


Fig. 1. A. Quantity of steel in terms of the quantity of steel replaced per dry dock, per unit lightweight of the ship, in function of the age of the ship (Aloui, 2010). B. Comparison of the predicted steel replacement in according eq. (7) with the observed replacements by Løseth et al. (1994). Full line: own model (Eq. (7)) upsized to a VLCC of 300.000 DWT Dashed line: Data taken from Løseth et al. (1994), for a double hull VLCC, with the effect of maintenance taken into account.

of the same age could be strikingly huge. This compares with the observations of Paik and Kim [21], the distribution of corrosion wastage statistics for any structural member is highly scattered at any corrosion exposure time and changes with time. Indeed, the condition of a ballast tank is not only age-dependent but other important factors are involved such as substrate preparation, application conditions, mechanical damages, maintenance and many more. Moreover, when these observations are compared to other, previously published time dependent corrosion models [22–28], a similarly high variability can be noted for older ships.

However, data collected by Løseth et al. [29] can be used for a validation of eq. (7) (Fig. 1). As it turns out, these data show an comparably large variation for steel renewal per dry dock for fifteen-year-old vessels, ranging from 6 to 1700 tons. To this end, it is necessary to reduce the total quantity of steel work per dry dock to the steel replacement exclusively imposed by corrosion. Steel repair work can be a consequence of deformations, corrosion and cracks. In the context of this research we are only interested in steel repair work inflicted by corrosion. A polynomial regression (Fig. 2) of the data obtained by Kawano & Hirakata [30] offers the following expression for the fraction of ASR/LWT caused exclusively by corrosion in function of the time, represented by $C1$ ($R^2 = 0.911$):

$$C1 = -0.0325t^3 + 1.1299t^2 - 4.465t + 1.1866 \tag{8}$$

Multiplication of eq. (7) and eq. (8) leads to the quantity of corroded steel to be replaced per dry dock. Fig. 1 compares the results of this model with the observed steel replacements from [31]. An overall comparison of these data and eq. (7) shows that there is hardly any difference, except in ships above an age of 20 years, which, as is stated further on, are not considered here either. Hence, eq. (7) offers an acceptable description for corrosion-driven steel replacement in function of the age of a ship.

Finally, steel renewal cost can be calculated as follows:

$$\begin{aligned}\text{Steel renewal cost} = {} & 0.031e^{0.2982t} \times \text{lightweight} \times \left(-0.0325t^3 + 1.1299t^2 - 4.465t + 1.1866\right) \\ & \times \text{cost of steel repair per ton}\end{aligned} \tag{9}$$

2.1.2.2. *Coating repair cost.* With regard to coating repair, the data presented in Verstraelen et al. [15,16] offers a means to determine the percentage of the surface to be recoated, through the following equation:

$$\text{CI} = 1.6817t - 7.1449 \tag{10}$$

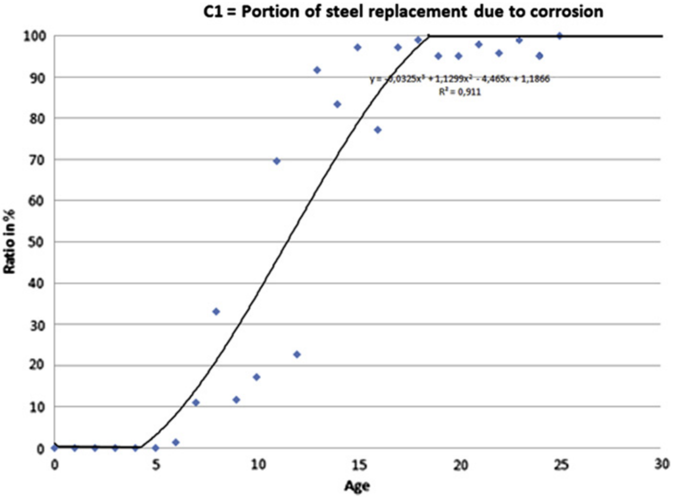


Fig. 2. C1 in function of the age of the ship (graphical presentation of numerical data presented by Kawano & Hirakata 2003).

With the corrosion index CI representing the surface of the coating damaged by corrosion in % and function of the time [15,16]. This formula shows that a coating remains nearly intact during approximately the first 5 years. Afterwards the paint degrades in a nearly linear way with approximately 1.7% surface per year.

$$\text{Coating repair cost} = \text{Surface} \times (1.6817t - 7.1449) \times \text{cost of recoating per square meter} \tag{11}$$

At this moment $TSCF_{25}$ is seldom applied and certainly not generally accepted by the shipping world as being the ultimate solution for the corrosion problem in ballast tanks (Damen Shipyard, 2011, pers. comm.). Consequently, statistical data on the effective lifetime of this coating are still lacking. The result of this study rests upon the basic assumption that the $TSCF_{25}$ lives up the promised characteristics. When applying a $TSCF_{25}$ (case III) instead of $PSPC_{15}$ the surface to be recoated and number of dry-days to do this are diminished with 40% following the predicted lifetime of the coating system. For corrosion resistant steel (case IV) a similar reasoning is followed seen the nature of the substrate.

2.1.2.3. Anode replacement cost. Anodes should normally be replaced every 5 years. However, due to the expected good performance of the $TSCF_{25}$ coating (case III), it can be surmised that replacement is only required once every 10 years. Tanks built in corrosion resistant steel (case IV) do not require any anodes at all. Case V ships are equipped with aluminum sacrificial anodes lasting the economic lifespan of the ship. Anodes replacement is not considered.

$$\text{Anode replacement cost} = \text{number of anodes} \times \text{installation cost per anode} \tag{12}$$

2.1.2.4. Cost of unavailability of the ship due to dry dock. Time in dry dock as a consequence of corrosion is the sum of the time needed to replace the steel plus the time needed to restore the coating and replace the anodes.

The steel replacement time equals Eq. (7) × Eq. (8) divided by the yard capacity in t/day. Research (data obtained from 20 ship repair yards worldwide) revealed a huge variation in capacity ranging from 2 to 40 tons of steel per day. An average of 16.7 t/day was calculated and rounded to 20 t/day.

The calculation of the coating maintenance and repair time in dry dock is complicated since a lot of variables are involved. Maintenance is normally done at sea or in port by the crew while repair work in ballast tanks does not necessarily require the vessel to enter dry dock, all the work can be done afloat at a repair base or at sea using a riding squad.

$$\sum_{t=1}^{5}(1.6817(5t) - 7.1449) \tag{13}$$

the algebraic sum of the outcome of (eq. (10)) after 5, 10, 15, 20 and 25 years indicates that 90.4% of the coating is repaired during the complete lifecycle of the ship.

It would take typically two months dry dock to recoat the ballast tanks completely (Kattan, Safinah Ltd., pers. comm). Moreover, the coating of a ship accounts for 12–25% (average 18.5%) of the total man hours for the construction, with approximately 50% of the coated surface being inside the ballast tanks [32].

Applied to a Panamax tanker, which takes around 21 mh/cgt (manhour per compensated gross tonnage) to be built (Lloyds shipping economist, 2006), or, with a cgt of 21,000 [33], around 441,000 mh for the total construction and 41,000 mh to (re)coat the ballast tanks. With 3 teams of 10 men working each 3 shifts of 10 h per day, this complete recoating is finished in 45 working days, which corresponds to the amount of time devoted to it in practice (Kattan, Safinah Ltd., pers. comm). These 45 days will be divided following the appearance of corrosion as represented by eq. (10) and over the major 5-year dry dock periods, as represented in Table 3. Finally, the time in excess of a standard dry dock of 6 days [31, Antwerp Ship Repair, 2012, pers. comm.] is allocated to the corrosion problem.

Table 3
Number of days needed for recoating in function of ship's age.

Moment of dry dock (years)	Number of days recoating (DRC)
5	0
10	3
15	9
20	14
25	19[a]
Total	45

[a] Will not be taken into account since the ship is sold for scrap at that time.

Dry dock time can then be calculated according to eq. (14):

$$\text{Dry dock time} = \left[\frac{[0.031\, e^{0.2982t} \times \text{lightweight} \times (-0.0325t^3 + 1.1299t^2 - 4.465t + 1.1866)]}{20} + \text{DRC}\right] - 6 \tag{14}$$

The equivalent cost then comes down to:

$$\text{Dry dock cost} = [\text{Dry dock time} \times (\text{Time Charter Equivalent} + \text{cost of dry dock per day})] \tag{15}$$

When applying a $TSCF_{25}$ (case III) instead of $PSPC_{15}$ the number of days is diminished with 40% following the predicted lifetime of the coating system. When using corrosion resistant (case IV) steel a similar reasoning is followed seen the nature of the substrate. In case II, III and IV no dry dock time is provided for corroded steel replacement based on the fundamental assumptions of these alternative ways of construction.

2.1.2.5. Loss or gain of cargo carrying capacity due to an increased or decreased lightweight. A final exploitation cost, calculated in eq. (16), is the loss of income (LI) due to an increased LWT as a consequence of the increase of the corrosion allowance. This cost is only applicable to option II. Increasing the corrosion allowance increases the lightweight of the ship while the cargo carrying capacity is diminished with the same amount. As this loss is only applicable during loaded voyages, the tanker is here supposed to be loaded 50% of the time [34].

$$\text{LI} = \frac{(\text{TC} \times 365\ \text{ays})}{\text{total load}} \times (\text{LWT}_{\text{TII}} - \text{LWT}_{\text{T}}) \times 0.5 \tag{16}$$

For a preliminary assessment of the parameters linked to the use of corrosion resistant steel (CRS), an experimental steel type was obtained (the characterization of which will be the focus of a future manuscript). A preliminary result indicates that this alloy corrodes 30% slower than grade A ship construction steel. Additionally, a lightweight gain of 5% had to be factored in, based on a reduction of the corrosion allowance and the difference in density.

2.1.3. Residual value

After 25 years of service the ship is sold at the value of the scrap iron. As it is improbable that the higher concentrations of valuable alloys will influence the scrapping price, the same price can also be used for the tanks constructed in CRS (case IV). Residual value can then be calculated as follows:

$$\text{Residual value} = \text{lightweight} \times \text{value of the scrap iron} \tag{17}$$

2.2. Sensitivity analysis and Monte Carlo simulation

2.2.1. Sensitivity analysis

To determine how the optimal solution, the minimum cost of the ballast tanks, is affected by multiple parameters a sensitivity analysis was carried out. Each of the parameters was varied and the variance of the real TCB analyzed.

2.2.2. Monte Carlo Simulation

To examine how the TCB varies when the value of uncertain assumptions are modified, a Monte Carlo simulation was performed using the software program Crystal Ball (Oracle). When performing a Monte Carlo sensitivity analysis, probability distributions are specified for uncertain values of model input parameters. Then multiple trials are executed, taking each time a random draw from the distribution for each parameter. For each trial, the output is calculated for each set of specified values. When all the trials have been executed, a probability distribution of the model output is obtained [35].

By applying the Monte Carlo Simulation technique, not consequences but risks are compared and hence, more information is obtained as compared to when a conventional, static model is used. When probability distributions for several defined assumptions are specified, uncertainties are incorporated in the model. Moreover, the results of the model not only incorporate the uncertainties of the input parameters, they also give us their importance [36].

3. Case study

3.1. Model selection

The model selected for this study is a Panamax tanker. The maximum length overall (LOA-the total length of a ship's hull from the foremost to the aftermost points) of the ship is determined by the usable length of the locks being 304.8 m. The maximum draft (12.04 m in tropical fresh water) is limited by the shallowest depth at the south sill of the Pedro Miguel locks and the maximum air draft of 57.91 m (at any state of the tide) is defined by the clearance under the Bridge of the America's at Balboa. The maximum width over outer surface of the shell plating is 32.31 m. The deadweight of a Panamax ship varies between 50,000 and 80,000 Mt (DWT-total weight of cargo, crew, stores, ballast and bunkers on board a ship). Panamax ships can be considered as a good representation of the medium size merchant ship, representing approximately 48% of the world fleet [37].

More specifically, the calculations presented here are based on an average Panamax tanker of approximately 75,000 Mt DWT, an LOA of 228 m, and a beam of 32.2 m. As the sole interest of this study concerns the ballast tanks, all assessments are limited to the size and weight of the ballast tanks only. Starting point is the surface of the ballast tanks set at 51,000 m^2 [34]. Furthermore, the ship is supposed to have been built in China and to have dry dock inspections and repairs in Bahrain, due to the availability of recent, suitable and complete data. The economic life of the ship is set at 25 years. Afterwards the ship is sold for scrap iron.

3.2. Calculations

Table 4 lists the parameters used in the basic economic model as developed in Section 2. To this end, the parameters are sub-divided into 3 categories, viz. the values used to calculate (a) the lightweight of the tanks, (b) the initial investments and (c) the exploitation costs. For each parameter the acronym, a short description, the standard value and unit, source and formula and the type are indicated in the table.

Three types of variables can be distinguished. The first type gives parameters with a fixed value [F], determined by the selected generic Panamax tanker and constant in all further simulations. The second type shows the uncertain parameters [U]. During Monte Carlo analysis, these parameters will be allowed to vary according certain probability distributions between minimum and maximum values (see Table 5). The third type describes the parameters which are dependent [D] upon one or more other parameters of either other type.

The cost of steel renewal, coating repair, the replacement of anodes and the rental cost of the dry dock have been based on the price list of Bahrain ASRY dry docks of 2008 (http://www.asry.net). More recent prices were available from other dry dock facilities, but the set of Bahrain was the only complete list for the purposes of this study.

Fig. 3 shows the outcome of the basic economic model for each of the 5 cases based on the parameters given in Table 4. The numbers represent real values, adjusted for an inflation of 2% and discount rate of 4% (see 3.2.1).

Table 4
Parameters used in the economic model.

Acronym	Parameter	Value	Source & formula	Type[a]
Parameters used to calculate the lightweight of the tanks				
AREA	Surface of the ballast tanks	51,000 m^2	[34]	F
DWT	Deadweight	75.000 t		F
DENS	Density steel	7.8 t/m^3	[48]	F
PT	Plate thickness	14 mm	Own assumptions	F
CA	Corrosion allowance	3 mm	IACS CSR	F
WA	Weight anodes Zn & Al	22 kg	Assumption	F
LWT_T	Lightweight Tank I, III & IV	5569.2 t	See 2.1	F
LWT_TII	Lightweight Tank II	6762.6 t	See 2.1	F
Parameters used to calculate the initial investment				
PSPC_{15}	Initial coating PSPC_{15}	40 €/m^2	[49]	U
TSCF_{25}	Initial coating TSCF_{25}	63 €/m^2	IHC, pers. comm. $\text{TSCF}_{25} = \text{PSPC}_{15} \times 1.575$	D
CCRS	Initial coating CRS	35 €/m^2	Own estimation $\text{CCRS} = \text{PSPC}_{15} \times 0.875$	D
PZ	Price zinc	4 €/kg	[50]	U
PA	Price Aluminum	8 €/kg	[50]	U
ZA	Number of zinc anodes	325	[34]	F
IZA	Initial installation zinc anodes	116 €/anode	IZA = (WA × PZ) + 28 €/piece	D
AA	Number of aluminum anodes	477	Own calculation	F
IAA	Initial installation aluminum anodes	204 €/anode	IAA = (WA × PA) + 28 €/piece	D
AS	Grade A steel purchase price	900 €/t	ArcelorMittal, 2009,	U
RACRS	Ratio CRS versus grade A	1.3	30% > grade A; POSCO, pers. comm.	U
CRS	CRS steel purchase price	1170 €/t	CRS = AS × RACRS	D
CAN	New building in grade A	3150 €/t	CAN = AS × 3.5	D
CNCRS	New building in grade CRS	4095 €/t	CNCRS = CRS × 3.5	D
$	Dollar exchange rate	1$ = 0.68473 €	As per 26/04/2011	F
Parameters used to calculate the operating costs				
RAS	Repair grade A steel	7020 €/t	RAS = AS × 7.8	D
RPSPC	Repair PSPC_{15}	61.35 €/m^2	Terkels (ASR) & Hoogenboom (Hempel), pers. comm. $\text{RPSPC} = \text{PSPC}_{15} \times 1.5338$	D
RTSCF	Repair TSCF_{25}	96.62 €/m^2	Own estimation $\text{RTSCF} = \text{PSPC}_{15} \times 2.4156$	D
RCCRS	Repair coating CRS	53.8 €/m^2	Own estimation $\text{RCCRS} = \text{PSPC}_{15} \times 1.345$	D
SCI	Scrap per t grade A steel	585 €/t	SCI = AS × 0.65	D
SCRS	Scrap per t CRS steel	585 €/t	SCRS = AS × 0.65	D
CDD	Rental dry dock	2885 €/day	[51] (LXBX0.5$/dag)	U
TC	Time Charter Equivalent Panamax tanker	15,514 €/day	[52]	U
IR	Inflation rate	2%	[37]	
DR	Discount rate	4%	[42,43] & pers. comm. Notteboom	U
DRC	Days Re Coating	See 1.2.1.4	Own estimation	

[a] F are parameters with a fixed value determined by the selected model, U are the parameters with a variable value (see Table 5) and D are parameters that are function other parameter(s). (see source & formula column).

3.2.1. Financial parameters used throughout the calculations

3.2.1.1. Inflation adjustment factor. The result of the model, the sensitivity analysis and the Monte Carlo simulation are real cost. An inflation adjustment factor $(1+P)^{-t}$ was applied. P is the inflation per year and t is the age of the tank. Based on the Harmonized Indices of Consumer Prices (HICP) as published by Eurostat [37] for the European Union for the period December 1997 till June 2012, P was assumed to vary between 0.9 and 3.8 with an average value of 2% [38].

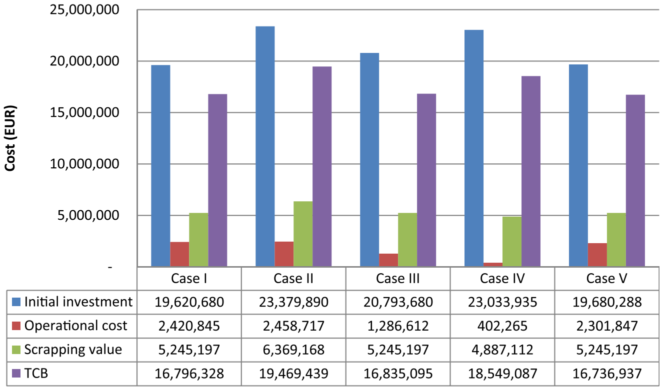
Table 5
Minimum, maximum and most possible value of the uncertain parameters used during the Monte Carlo analysis together with the probability distribution.

Uncertain parameter	Symbol	Min.	Most possible value	Max.	Model	Unit
Initial cost PSPC coating	$PSPC_{15}$	40	45	60	Normal	€/m^2
Grade A steel (basic price)	AS	900	1000	1500	Normal	€/t
Ratio CRS versus grade A	RACRS	1.2	1.3	1.5	Normal	
Drydock/day	CDD	2597	2885	3174	Normal	€/day
Time charter equivalent	TC	13,963	15,514	17,065	Normal	€/day
Price zinc	PZ	4	5	6	Normal	€/kg
Price aluminum	PA	8	10	12	Normal	€/kg
Inflation rate	IR	0.9	2	3.8	Normal	%

3.2.1.2. Steel price. The steel price is rising steeper than the 2% per annum taken into account by the general inflation rate (see 3.2.1.1). This increase in price is caused firstly by the increasing scarcity of raw materials, especially given the growing demand in China. Moreover, the fabrication of ship construction steel is energy consuming and energy is getting ever more expensive. An increase of 8.6% per year was observed for hot rolled steel for the Asian market in a period from August 2005 till April 2011 [39]. Hence, an increase of 6% was incorporated in the model. However, a changing price of grade A means that the price of corrosion resistant steel, steel repair work and scrap are supposed to vary in parallel.

3.2.1.3. Discount rate. Generally, low discount rates favor projects with the highest total benefits while high SDRs rates favor projects where the benefits are front-end loaded. Based on the European Commission [40] (social cost-benefit 2% and private investments 15%) a discount rate of 4% was chosen.

This figure is backed up by an analysis of similar, maritime, investments. Eijgenraam et al., mention in their directives for CBA that the real discount rate should equal average interest rate for risk-free long term loans on the capital market [41]. The figure they put forward is 4% per annum. Pearce et al. also prefer to use a standard discount real discount rate of 4% based on social time preference [42,43]. And the cost and benefits analysis of major harbor projects in Flanders and the Netherlands, such as Maasvlakte 2, uses a 4% discount rate as well (Notteboom, pers. comm.). A sensitivity analysis of the impact of the discount rate (data not shown) indicates that, although absolute values in the outcome of the calculations change, there is no effect on the differences between the different cases that are analyzed in this text.



	Case I	Case II	Case III	Case IV	Case V
🟦 Initial investment	19,620,680	23,379,890	20,793,680	23,033,935	19,680,288
🟥 Operational cost	2,420,845	2,458,717	1,286,612	402,265	2,301,847
🟩 Scrapping value	5,245,197	6,369,168	5,245,197	4,887,112	5,245,197
🟪 TCB	16,796,328	19,469,439	16,835,095	18,549,087	16,736,937

Fig. 3. Results of the basic model with inflation of 2% and discount rate of 4% per year.

4. Results and discussion

4.1. Model results

Comparison of the TCB results in Fig. 3 shows that cases I, III, and V were very competitive, whereas, in case II, expanded scantlings might well offer adequate protection against corrosion, but are counterbalanced by the high penalty of an increased loss of cargo carrying capacity. This conclusion is confirmed by Psarros [44] and Eliasson [25] who state that it is possible to build ships with thick steel without corrosion protection which would have enough strength left to during its designed service life. However, it is generally agreed today that this is no longer a cost efficient way to build and operate ships.

The outcome of cases III, V and even IV increases the number of choices available to the ship owner. A few years ago the classic combination of grade A steel protected with a $PSPC_{15}$ system coating and backed up with sacrificial anodes, would not have been questioned. This study shows that today it is may be worthwhile to take alternatives III, IV or V into consideration. A sensitivity and Monte Carlo analysis is therefore well placed to shed more light on which parameters are most influential.

4.2. Sensitivity analysis

The parameters with substantial impact on TCB are the steel and coating price. Other parameters have a negligible importance.

Table 6 represents the impact of a change in steel price and coating cost on the real value of the TCB and the relative ranking of the cases. The values used in the original basic economic model are in cells with grey shading. Cases are ranked from left to right with ascending TCB value. The difference between I, III and V remains small and nearly unaffected by them. It is inevitable that the price of raw materials, such as ship construction steel, grade A as well as CRS, will rise in the future. The increased scantling method and the construction in CRS will lose ground compared to the cases were the protection of the tanks is based on coating and sacrificial anodes.

Table 7 represents the influence of cost of CRS to grade A steel and cost of $PSPC_{15}$ to $TCSF_{25}$ and the discount on the relative ranking of the cases. It is not surprising that when CRS becomes more expensive compared to grade A steel, the position of case IV becomes less favorable. Additionally, the impact of the relation between the cost of $TSCF_{25}$ and $PSPC_{15}$ is not sufficiently important to influence the relative position of the cases significantly. Only when the price of the $TSCF_{25}$ system drops, case III becomes attractive. The second part of Table 7 shows the influence of the cost of coating. When application of a coating becomes cheaper, the use of sophisticated coating systems (case III) becomes favored compared to the standard $PSPC_{15}$ coating.

Table 6
Influence of steel price and coating cost on TCB.

TCB in €					
Steel price					
−50%	Case V 10,168,501	Case I 10,227,892	Case IV 10,368,176	Case III 10,686,203	Case II 12,002,928
−25%	Case V 13,452,719	Case I 13,512,110	Case III 13,760,649	Case IV 14,458,632	Case II 15,736,183
900 EURO/ton*	Case V 16,736,937	Case I 16,796,328	Case III 16,835,095	Case IV 18,549,087	Case II 19,469,439
+25%	Case III 19,909,540	Case V 20,021,155	Case I 20,080,546	Case IV 22,639,543	Case II 23,202,694
+50%	Case III 22,983,986	Case V 23,305,373	Case I 23,364,764	Case IV 26,729,999	Case II 26,935,949
+100%	Case III 29,132,877	Case V 29,873,809	Case I 29,933,200	Case II 34,402,460	Case IV 34,910,910
Cost of coating					
−50%	Case III 14,628,568	Case V 15,081,953	Case I 15,141,344	Case IV 17,322,494	Case II 17,814,455
−25%	Case III 15,731,832	Case V 15,909,445	Case I 15,968,836	Case IV 17,935,791	Case II 18,641,947
$PSPC_{15}$ 40 EURO/m^2*	Case V 16,736,937	Case I 16,796,328	Case III 16,835,095	Case IV 18,549,087	Case II 19,469,439
+25%	Case V 17,564,429	Case I 17,623,820	Case III 17,938,358	Case IV 19,162,384	Case II 20,296,930
+50%	Case V 18,391,921	Case I 18,451,312	Case III 19,041,621	Case IV 19,775,681	Case II 21,124,422

*Row refers to values used in the basic model.

Table 7
Influence of the price ratios of CRS to grade A steel and $TSCF_{25}$ to $PSPC_{15}$ on TCB.

TCB in €					
Ratio cost CRS to grade A steel					
1	**Case IV 13,645,487**	Case V 16,736,937	Case I 16,796,328	Case III 16,835,095	Case II 19,469,439
1.1	**Case IV 15,280,021**	Case V 16,736,937	Case I 16,796,328	Case III 16,835,095	Case II 19,469,439
1.2	Case V 16,736,937	Case I 16,796,328	Case III 16,835,095	**Case IV** 16,914,554	Case II 19,469,439
1.3*	Case V 16,736,937	Case I 16,796,328	Case III 16,835,095	**Case IV 18,549,087**	Case II 19,469,439
1.4	Case V 16,736,937	Case I 16,796,328	Case III 16,835,095	Case II 19,469,439	**Case IV 20,183,621**
1.5	Case V 16,736,937	Case I 16,796,328	Case III 16,835,095	Case II 19,469,439	**Case IV 21,818,154**
Ratio cost $TSCF_{25}$ to $PSPC_{15}$					
1.4	**Case III 16,478,095**	Case V 16,736,937	Case I 16,796,328	Case IV 18,549,087	Case II 19,469,439
1.575*	Case V 16,736,937	Case I 16,796,328	**Case III 16,835,095**	Case IV 18,549,087	Case II 19,469,439
1.6	Case V 16,736,937	Case I 16,796,328	**Case III 16,886,095**	Case IV 18,549,087	Case II 19,469,439
1.8	Case V 16,736,937	Case I 16,796,328	**Case III 17,294,095**	Case IV 18,549,087	Case II 19,469,439

*Row refers to values used in the basic model.

5. Monte Carlo analysis

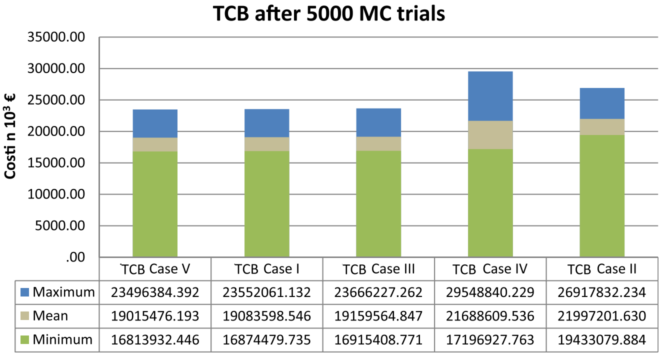
5.1. Input parameters

As indicated in paragraph 3.2 the parameters used in the Monte Carlo analysis are divided into three categories. The fixed parameters are model dependent, the dependent parameters are a function of one or more other values and the uncertain parameters are allowed to vary according to a certain probability distribution. For all of the uncertain parameters a triangular distribution was selected. Minimum and maximum values and most probable value are listed in Table 5.

5.2. Results of the Monte Carlo analysis

The bar graphs in Fig. 4 show the median value of the real Total Cost of Ballast tanks (TCB) after 5000 trials. Statistical data and sensitivity analysis are shown in Tables 8 and 9. Table 8 gives the complete statistical outcome of the Monte Carlo analysis after 5.000 trials as per Crystal Ball software; Table 9 gives the contribution to the variance of certain assumptions. These assumptions are given in the first column and correspond to the uncertain parameters as described in Table 5.

When Fig. 3 (outcome of the basic economic model) and Fig. 4 (results of the Monte Carlo simulation) are compared we observe an increase in absolute values of the TCB's while the ranking of the cases remains the same. The considered parameters (Table 5) were an increase in the cost of steel, coating, aluminum and zinc over the 25 years to come. If the range and distribution model of these variables are assumed correctly this is reflected by a rise of the mean value of the TCB's with an average of 20% without a change in the relative relation of the cases.



	TCB Case V	TCB Case I	TCB Case III	TCB Case IV	TCB Case II
🟦 Maximum	23496384.392	23552061.132	23666227.262	29548840.229	26917832.234
▨ Mean	19015476.193	19083598.546	19159564.847	21688609.536	21997201.630
🟩 Minimum	16813932.446	16874479.735	16915408.771	17196927.763	19433079.884

Fig. 4. Monte Carlo analysis results after 5000 trials.

Table 8
Statistical outcome of the Monte Carlo analysis after 5000 trials.

Statistics	TCB case I	TCB case II	TCB case III	TCB case IV	TCB case V
Trials	5000	5000	5000	5000	5000
Mean	19,083,599	21,997,202	19,159,565	21,688,610	19,015,476
Median	18,974,364	21,876,340	19,059,431	21,548,482	18,906,595
Mode	–	–	–	–	–
Standard Deviation	1,103,677	1,250,232	1,064,975	1,963,763	1,103,431
Variance	1,218,102, 868,859	1,563,080, 502,415	1,134,172, 277,275	3,856,365, 805,060	1,217,559, 756,106
Skewness	0	0	0	0	0
Kurtosis	3	3	3	3	3
Coeff. of Variability	0	0	0	0	0
Minimum	16,874,480	19,433,080	16,915,409	17,196,928	16,813,932
Maximum	23,552,061	26,917,832	23,666,227	29,548,840	23,496,384
Range Width	6,677,581	7,484,752	6,750,818	12,351,912	6,682,452
Mean Std. Error	15,608	17,681	15,061	27,772	15,605

The values shown in Table 9 are the percentages variance or uncertainty in the target forecast due to the respective assumptions. Items with a positive contribution have a positive value; this reflects a direct relationship between the item and the TCB. Items with a negative value have an inverse relationship.

Only three assumptions are worth mentioning. The influence of the steel price is decisive for all cases. 20% of the variance of the TCB of Case III is due to the cost of $TSCF_{25}$ and the TCB of case IV is mainly affected by the price of CRS.

6. Discussion

The increased scantling technique (case II), can be classified as economically not healthy, based on the reference model and supported by the sensitivity analysis and the Monte Carlo simulation. Expanded scantlings offer adequate protection against corrosion but the penalty of an increased lightweight and consequently the loss of cargo carrying capacity is simply too important. This conclusion is a confirmation of J. Eliasson's [45] statement, it is possible to build ships with such thick steel that even with free corrosion taking place the ship would have enough strength left to perform its designed service life but that It is generally agreed today that this is no longer a cost efficient way to build and operate ships.

Construction methods I, III and V are matched and the correct choice will be dependent upon a lot of parameters, the most important being the steel price and the coating cost. The use of corrosion resistant steel (option IV) becomes attractive if the cost of CRS comes down till maximum 1.1 times the cost of ordinary grade A steel.

Case I, the way we are actually constructing ballast tanks is not the worst of solutions though that there is still a lot of room for improvement.

Table 9
Sensitivity data of the Monte Carlo analysis.

Assumptions	TCB case I	TCB case II	TCB case III	TCB case IV	TCB case V
Drydock/day	0	0	0	0	0
Grade A basis	94.1	94.7	88.8	44.3	94.2
Initiele cost $PSPC_{15}$ or $TSCF_{25}$	5.5	4.3	10.9	1.1	5.5
Price aluminum anodes in €/kg	0	0	0	0	0
Price anodes in €/kg	0	0	0	0.00	0
Relation grade A – CRS	0.1	0.1	0.1	54.6	0.1
Time Charter equivalent	0	0.6	0	0	0
Inflation rate	0.2	0.3	0.2	0	0.2
Total	99.9	100	100	100	100

The average degradation rate of the coating used in the economic model is probably high. 1.7% surface degradation per year is based on our database of 140 ships ranging from 0 to more than 40 years of age. A follow-up study to determine a sound corrosion rate is needed with a focus on PSPC ships without considering older non-PSPC ships.

The average durability of $PSPC_{15}$ coating can be increased substantially if sufficient attention is given to surface preparation and application conditions.

Case V is a logical evolution of case I. The sacrificial Zn anodes have been replaced by aluminum anodes and the weight has been increased to last the full economic lifespan of the ship.

Zinc has been in use as a sacrificial anode for longer than aluminum and is considered the traditional anode material. However, aluminum has several outstanding advantages as a sacrificial anode material and is fast becoming the material of choice [46].

The replacement of zinc by aluminum is ecological beneficial. The negative impact of zinc on the marine environment is well known and documented while this is not the case for aluminum. Aluminum is not considered a pollutant.

However, there are also some drawbacks regarding the use of aluminum as sacrificial material in ballast tanks adjacent to tanks for liquid cargo with flash point $<60\,^{\circ}$C. According to DNV Rules for Ships such tanks are considered dangerous areas. Aluminum alloyed anodes are to be so located that a kinetic energy of $\leq$275 J is developed in case of their falling down. That means that an aluminum anode weighing for instance 10 kg must be located lower than 2.8 m from the tank bottom or stringer deck.

In a forgoing study [3] we demonstrated that sacrificial anodes are only beneficial if they are installed and maintained in a correct way. Practical experience after many tank surveys indicated that this is not very often the case.

Economically, Case III, the use of a superior paint, seems promising yet. What such an improved paint system should look like is still far from clear. Our field research indicates mechanical damage and cracking, besides application shortcomings, as primary cause of corrosion. A protective coating can be made more resistant to deformations by the addition of fibers. Natural or synthetic fibers will be used to mechanically reinforce formulations increasing fatigue properties, strength, and flexibility improving corrosion resistance and increasing the service life of coating.

Also, the performance of $TSCF_{25}$, used in this study, is questioned by some shipyards. A Dutch shipyard (which requested to stay anonymous) mentioned as follows: "The wish to reduce and eventually completely eliminate, the maintenance in ballast tanks is fully understandable. I am not aware of any independent scientific proof that the complete removal of the shop primer, the reduction of the allowable quantity of dust, a lowering of the maximal chloride pollution from 50 to 30 mg/m2, the increase of the layer thickness from 320 to 350 (90/10) micron and 3 full coats instead of 2 will result in an increase of lifespan of 67%."

Case IV studies the use of corrosion resistant materials instead of grade A steel. It is assumed here that CRS will live up to the promised characteristics. At this moment these steel varieties are in an experimental phase and the exact features still remain to be established. Also, the exact retail price is unknown at present. The estimations used in this study are indicative and only based on the value of the composing alloy elements. It is almost certainly that when the demand for this product increases, the retail price will follow.

The data used in this model are an approximation of reality. They provide a platform to compare the different cases and should not be considered as true costs. Differences exist and prices vary in function of geographical location, time and availability. Since the basic commodities are becoming scarcer, the steel price will keep on rising. The CRS obtains its qualities by adding, amongst others, chromium and molybdenum, both becoming increasingly scarce. These arguments are favoring the use of improved coating systems. However, the coating cost is very sensitive. A little change in the cost of $TSCF_{25}$ is capable of reversing the economical ranking of the hypothetical cases.

7. Conclusion

At this moment the best way to protect ballast tanks is by applying a standard $PSPC_{15}$ coating on a perfectly prepared substrate and under good application conditions. Lifetime lasting aluminum anodes could then be used as a backup system, if they are well distributed across the ballast tank and properly maintained.

In addition, the most promising line of research seems to be dealing with the development of an improved paint system with increased resistance to impact damage.

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