Probability Cost-Benefit Analysis for Ship Structural Design

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ABSTRACT: The objective is to design and optimise the midship section of a multi-purpose ship based on a probability cost-benefit analysis. From the rules of the Classification Society and the *MARS2000* software, the midship section is designed to comply with the minimum requirements. Structural strength is determined against buckling and yielding. Ultimate strength calculations include plates and stiffeners. The FORM is employed to identify, assess, and analyse the risk behaviour of the structure in reducing the probability of failure, Ultimate Limit State, about progressive collapse. The estimate of the initial costs of the construction investment associated with the costs of materials, manufacturing, and labour of this type of ship is estimated through CAPEX. Structural optimisation consists of minimising the construction cost and predefined target reliability. The analysis of the risk behaviour will be analysed concerning the impact of economic issues, such as the fluctuation of raw materials prices.

1 INTRODUCTION

The initial stage of the design of a marine structure or a ship consists of the iterative process of decision making, considering certain aspects that must be considered, such as the type of service, cargo transported, velocity, etc., to determine the ideal structural configuration. One of the main steps of the project is the structural analysis, whose objective is to design and determine an efficient and optimised structure.

The International Maritime Organization (IMO) developed rules and regulations that regulated the ship's design to maintain safety in the maritime sector. In 1969, IMO gave responsibility for applying maritime safety rules and standards to the International Association of Classification Societies (IACS). The classification of the ship following the regulations imposed by the classification societies does not consider the economic viability of the ship.

Due to increased competition in maritime transport, it is necessary to design and optimise more efficient structures with a reasonable level of reliability for a lower construction cost, and consequently lower structural weight, and not only comply with the minimum values required by the standards of classification societies.

2 SHIP STRUCTURAL DESIGN

The main objective of the ship's structural design is to generate information needed to build a ship within the requirements of class rules and customers, which is a complex and interactive process. The ship design goes through a series of evolutionary stages converging to a single point, and the most traditional method is spiral design (Evans, 1959). The optimisation of a structure or project differs between the initial stages of the project.

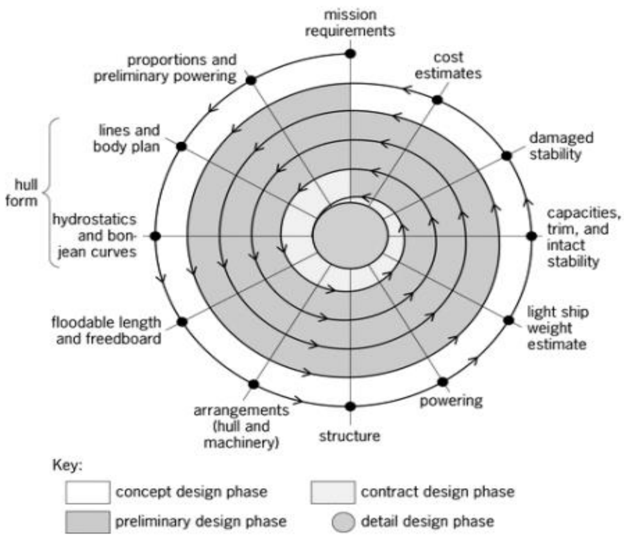

Figure 1. Ship design spiral (Evans, 1959).

Harlander (1960) began the first studies of optimisation of ships and maritime structures, performing calculations by hand. In the following years, Evans et al. (1963) and Nowacki et al. (1970) developed computer-aided design and optimisation algorithms. In the 1980s, Hughes (1980, 1988) developed essential steps in optimising structures.

Seo et al. (2003), Rigo et al. (2003), Khajehpour et al. (2003), Parsons et al. (2004), Klanac et al. (2004) and Cho et al. (2006) developed the techniques of design and optimisation.

The structural design of the ship consists of two distinct phases:

- Preliminary Project.
- Detail Design.

The preliminary project determines the position and spacing of ordinary stiffeners and primary supporting members. The detailed design determines the geometry, local reinforcement, connections, and notches until satisfactory scantling fulfils the project criteria.

2.1 *Case study*

The present study intends to design the midship section of a multi-purpose ship equipped for carriage containers, with additional service *GRABLOADING*, i.e., ships with holds tank tops specially reinforced for loading/unloading cargoes using buckets or grabs (BV), whose main dimensions are in *Table 1*.

Table 1.Main dimensions on the vessel considered.

Rule Length, L [m]	115.07
Moulded Breadth, B [m]	20.00
Depth, D [m]	10.40
Moulded Draught, T [m]	8.30
Block Coefficient, C_B [-]	0.72
Maximum Service Speed, V_s [knots]	14.00
Deadweight, DWT [t]	9 800
Effective Propulsive Power, P_w [kW]	5 400
Number of Crew Members, NE [Pax]	20
Number of Superstructure Decks, NJ [-]	6

Considering the typical structural configuration of a multi-purpose ship, the midship section is designed according to the rules of the classification society BV: NR 467 Rules for Classifications of Steel Ships, July 2019 edition, according to the following chapters:

- Structure design principle.
- Hull girder loads.
- Ship motions and accelerations.
- Sea Pressure.
- Internal sea pressures and forces.
- Hull girder strength.
- Hull scantlings.
- Buckling.
- Ultimate Strength.

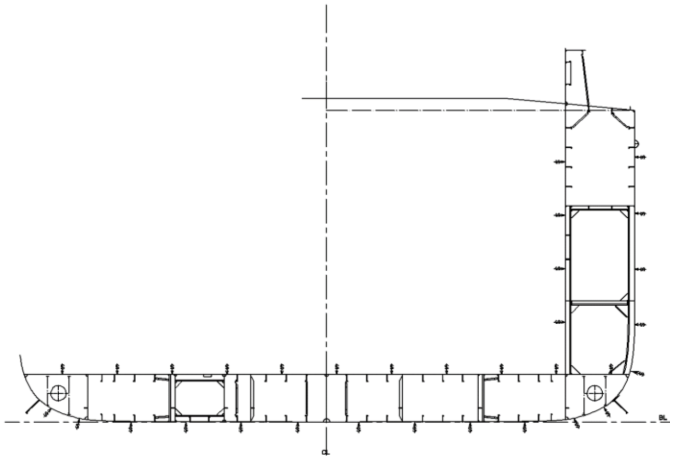

Figure 2. Midship section configuration.

2.2 *Structure design principle*

Since the midship section is not symmetrical in the bottom structure, it is necessary to consider the plates and profiles of the entire section. To understand and analyse the section study more efficiently, it was decided to divide it into panels. The section was divided into nine panels code defined by the MARS 2000 software: keel, bottom, inner bottom, double bottom girder, bilge, side shell, inner hull, double hull girder, and strength deck.

Figure 3. Division of section by panels.

Assuming the structural configuration (*Figure 2)*, the width of plates and the spacing of ordinary stiffeners, it is necessary to determine the longitudinal girder span. Normally, it is considered that the longitudinal girder span is four to five times the standard frame spacing. Due to the weight distribution of the vessel and the high cargo capacity to which the vessel is subject, in this case, it is assumed that:

$$l = 2.S \tag{1}$$

where S is the standard frame spacing.

Ordinary-strength steel was selected for the bottom structure and elements of the structure closest to the neutral axis. The choice of high-tensile steel for the structural elements distant from the neutral axis, in this case, the deck area, is due to the significant stresses they are subjected to.

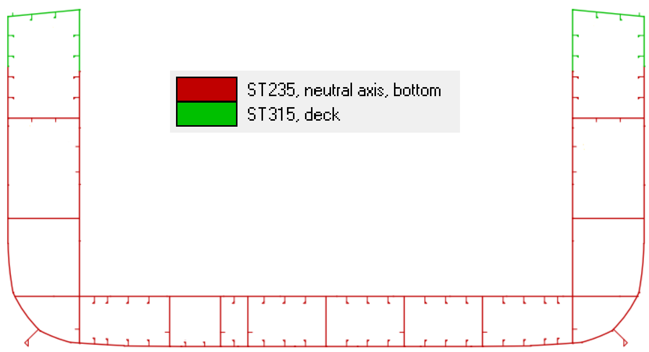

Figure 4. Type of material for each element of the structure.

2.3 *Hull girder loads*

The moments imposed on the ship can be divided into two components: the moments created due to the shape of the ship's weights arrangement (still water bending moments) and moments created by waves (wave bending moment).

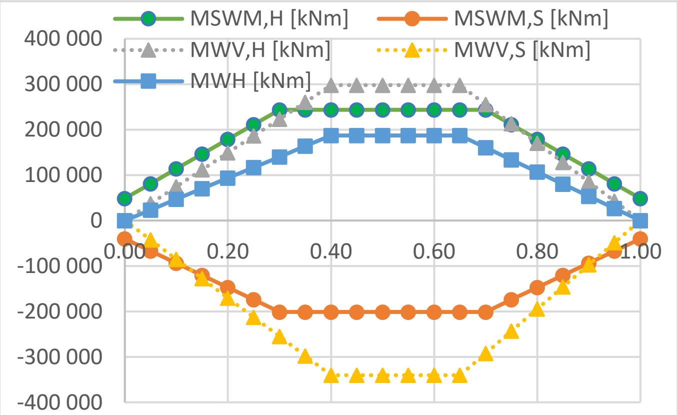

Figure 5. Classification Societies Rules, still water bending moment, M_{SW} [kN.m.]; wave bending moment, M_W [kN.m].

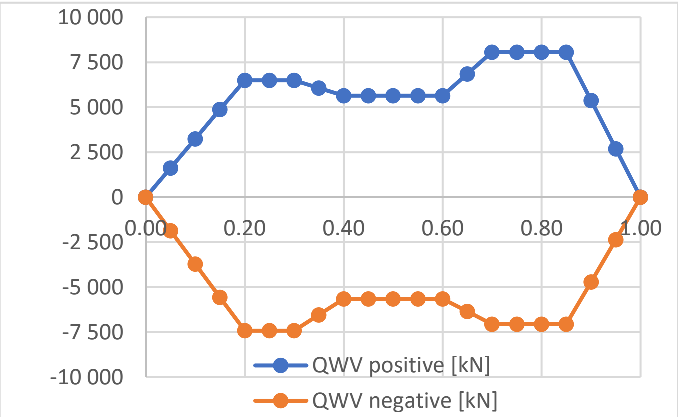

Figure 6. Classification Societies Rules, Vertical Wave Shear Force, Q_{WV} [kN].

2.4 *Load cases*

The load cases used for structural element analysis are:

- Load cases "a" and "b".
- Load cases "c" and "d".

Load cases "a" and "b" refer to the ship in upright conditions, i.e., at rest or having surge, heave, and pitch motions. Load cases "c" and "d" refer to the ship in inclined conditions, i.e., sway, roll and yaw motions.

2.5 *Hull scantlings*

2.5.1 *Plating*

It is considered that the elementary plate panel is the smallest unstiffened part of plating. The loading point considered for calculating lateral pressure and hull girder stresses are at the lower edge of the elementary plate panel or the point of minimum y-value among those of the elementary plate panel considered, in the case of horizontal plating (BV rules).

The net thickness of the plate panel subjected to in-plane normal stresses acting on the shorter side is to be not less than the value obtained, in mm, from the following formula:

$$t = 14.9.C_a.C_r.S.\sqrt{\gamma_R.\gamma_m.\frac{\gamma_{S2}.p_S+\gamma_{W2}.p_W}{\lambda_L.R_y}} \geq t_{min} \quad (2)$$

where: p_S is the still water pressure and p_w is the wave pressure, *s* is the shorter side of plating, and l is the longer side of plating, C_a is the aspect ratio of the plate panel, C_r is the coefficient of curvature and R_y is the minimum yield stress.

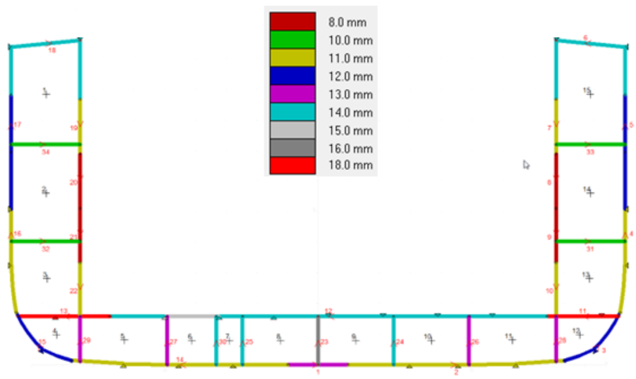

Figure 7. Plate panel final thickness according to the rules of Classification Society BV.

2.5.2 *Ordinary stiffeners*

The minimum net shear sectional area A_{Sh}, in cm^2 And the net section modulus W, in cm^3 for ordinary longitudinal stiffener subjected to lateral pressure are to be not less obtained from the following formulae:

$$A_{Sh} = 10.\gamma_R.\gamma_m.\beta_S.\frac{\gamma_{S2}.p_s+\gamma_{W2}.p_W}{R_y}.\left(1-\frac{S}{2.l}\right).S.l \quad (3)$$

$$W = \gamma_R . \gamma_m . \beta_b . \frac{\gamma_{S2} . p_s + \gamma_{W2} . p_W}{m(R_y - \gamma_R . \gamma_m . \sigma_{x1})} . \left(1 - \frac{S}{2 . l}\right) . S . l^2 . 10^3 \quad (4)$$

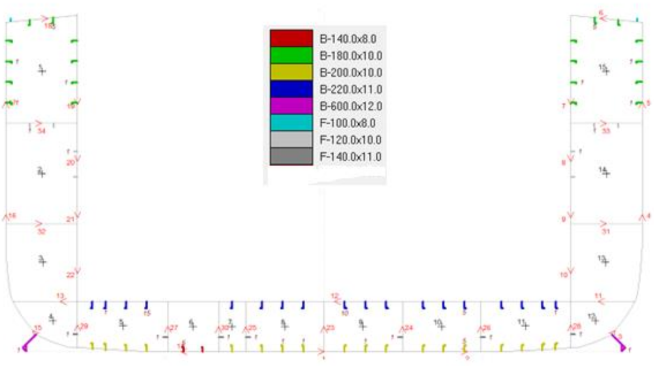

Figure 8. Final Longitudinal Ordinary Stiffeners, according to the rules of Classification Society BV.

2.6 *Buckling*

The structural elements of the ship are subject to the following loads and their combinations: axial, bending, shear, cyclic and dynamic. One of the main failure modes of these elements is their buckling and their structural instability.

The common causes of plate buckling of ship structures are:

- High compressive and residual stresses.
- High shear stresses.
- Combined stresses.
- Lack of flexural rigidity.
- Lack of stiffening.
- Extensive and improper use of High Tensile Steel (HTS).
- Excessive material wastage due to general and local corrosion.

The general modes of failure of stiffened panels are:

- Lateral buckling of stiffeners.
- Torsional buckling of stiffeners.
- Flexural buckling of stiffeners.
- Flexural buckling for plate stiffener combination.
- Buckling of plate panel between stiffeners.

2.6.1 *Plating*

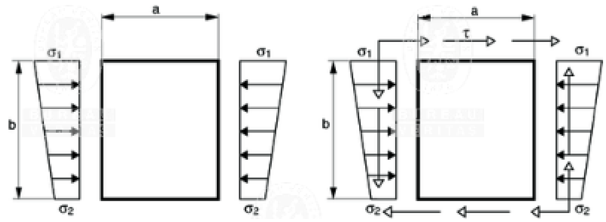

Figure 9. Buckling for plate panel subjected to compression and bending, with or without shear (BV rules).

The combined critical stress for plate panels subjected to compression, bending and shear is to be obtained from the following formulae:

$$F \leq 1 \, for \, \frac{\sigma_{comb}}{F} \leq \frac{R_{eH}}{2\gamma_R \gamma_m} \quad (5)$$

$$F \leq \frac{4\sigma_{comb}}{\frac{R_{eH}}{\gamma_R \gamma_m}} \left(1 - \frac{\sigma_{comb}}{\frac{R_{eH}}{\gamma_R \gamma_m}}\right) for \, \frac{\sigma_{comb}}{F} > \frac{R_{eH}}{2\gamma_R \gamma_m} \quad (6)$$

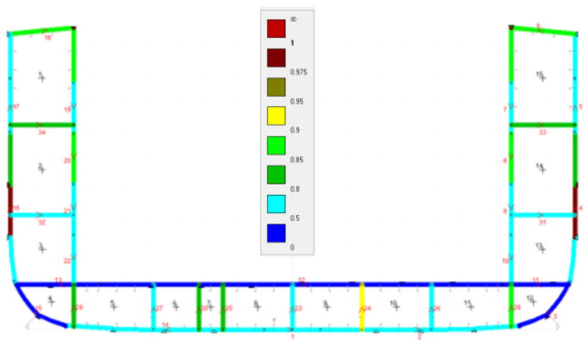

Figure 10. Buckling Normal Stress for plane panel, according to the Classification Society BV.

2.6.2 *Ordinary Stiffeners*

The critical buckling stress for compression and bending is to be obtained in N/mm^2, from the following formulae:

$$\sigma_c = \sigma_E \, for \, \sigma_E \leq \frac{R_{eH}, S}{2} \quad (7)$$

$$\sigma_c = R_{eH} \left(1 - \frac{R_{eH,S}}{4\sigma_E}\right) for \, \sigma_E > \frac{R_{eH}, S}{2} \quad (8)$$

where:

$$\sigma_E = Min(\sigma_{E1}, \sigma_{E2}, \sigma_{E3}) \quad (9)$$

The critical buckling stress of the ordinary stiffeners is to be checked according to the following formula:

$$\frac{\sigma_c}{\gamma_R \gamma_m} \geq |\sigma_b| \quad (10)$$

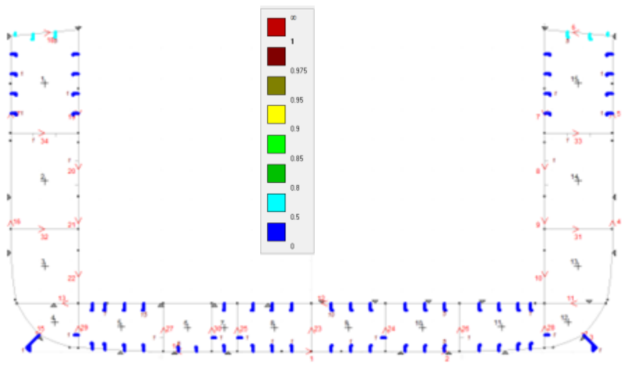

Figure 11. Buckling Normal Stress for longitudinal stiffeners, according to the Classification Society BV.

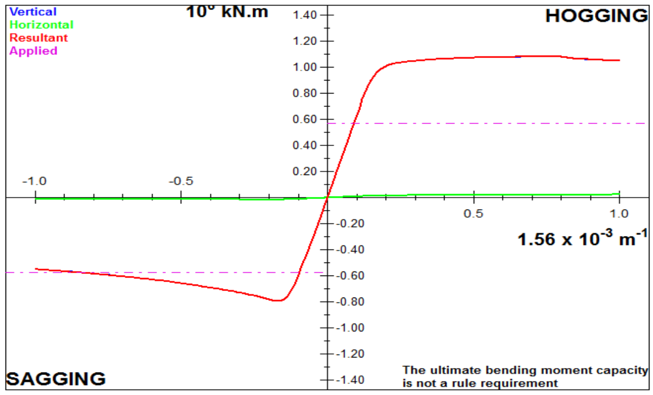

Figure 12. Ultimate strength of the structure (MARS 2000 software).

2.7 *Ultimate girder strength*

MARS 2000 allows the study of ship strength in the plastic domain and predicts the loads that lead to its collapse. The software adopts the Smith method to analyse the ultimate strength of the hull girder between two adjacent frames.

The midship section is divided into structure elements: stiffener attaching plating element and hard corner element, acting independently in their failure modes. Using the Smith method (Smith, 1977), the curvature momentum curve is obtained using an incremental-iterative approach. For each iteration, the bending moment acting on the hull girder transverse section increases due to the imposed curvature. Each structural member has an axial strain due to the angle of rotation of the hull girder transverse section about its horizontal neutral axis. The structural elements above the neutral axis are shortened, while the structural elements below the neutral axis are lengthened in the sagging conditions. The location of the neutral axis and the cross-section of the ship are calculated based on the failure mode of each structural element as the external moment is applied. The tensile structural elements present a single mode of elastic-plastic failure, while in compression, they present the mode of buckling or yielding (Da-wei & Gui-jie (2018)).

The pink dashed line shows the minimum bending moment the hull girder needs to support before reaching the yield point (*BV rules).* It can also be observed that the higher bending moments occur in the hogging condition.

As can be seen, the bending moments experienced by the structure during a cycle are higher during hogging and lower during sagging. If we consider that the critical situation occurs on the deck because it is the farthest point of the neutral axis. If it occurs in compression, it is concluded that the worst possible situation for the structure occurs during sagging.

3 STRUCTURAL RELIABILITY ASSESSMENT

3.1 *Ultimate limit state design*

The collapse of the structure due to the loss of structural stiffness and strength, related to the loss of equilibrium, attainment of the maximum capacity of the resistance by yielding, rupture or fracture and the instability resulting from the buckling or plastic collapse of plating, stiffened panels, and support members, is defined as the ultimate limit state function (ULS). The limit state function of the reliability assessment of the structure is based on the ultimate strength of the ship hull defined as (Guedes Soares et al., 1996):

$$g = \tilde{x}_u.\widetilde{M}_u - (\tilde{x}_{sw}.\widetilde{M}_{sw} - \tilde{x}_w.\tilde{x}_s.\widetilde{M}_w) \qquad (11)$$

where $\widetilde{M}_u$ is the ultimate bending moment; $\widetilde{M}_{sw}$ is the still water bending moment fitted to a Normal distribution. (Guedes Soares & Moan, 1988; Guedes Soares, 1990); $\widetilde{M}_w$ is the wave-induced bending moment fitted to the Gumbel distribution; $\tilde{x}_u$ is uncertainty model on ultimate strength; $\tilde{x}_{sw}$ is uncertainty model prediction on still water bending moment; $\tilde{x}_w$ is the error in the wave-induced bending moment due to linear seakeeping analysis and $\tilde{x}_s$ is nonlinearities in sagging. The uncertainty coefficients ($\tilde{x}_{sw}, \tilde{x}_w, \tilde{x}_s$), are fitted to a Normal distribution of the mean value of 1.00 and standard deviation of 0.1. The model uncertainty on ultimate strength ($\tilde{x}_u$) is fitted to a Normal distribution of the mean value of 1.05 and a standard deviation of 0.1. Using the *MARS 2000* software calculates the value of the confidence level of 5% of the ultimate bending moment, $M_u^{5\%} = M_u^C$. It is fitted to a lognormal probability density function, with the variance σ_{Mu} and mean value μ_{Mu}. It is assumed that covariance (*COV*) is equal to 0.08.

$$f_{Mu} = \frac{1}{M_u \sigma_{Mu} \sqrt{2\pi}} e^{-\frac{ln(M_u)-\mu_{Mu}}{2\sigma_{Mu}^2}} \qquad (12)$$

3.1.1 *Reliability of the midship hull structure*

The reliability index of the midship hull structure for the net and gross designs can be related assuming that at the end of the service life of the ship ($\tau_s = 25\ years$), when the structure of the ship is already corroded, i.e. there is no corrosion margin determined by the classification society rules *BV* defined in the previous chapter, concerning net ship hull structural design and the gross structural design is considered when non-corroded ship structure up to the moment when the corrosion protection fails. It is analysed that the structure of the midship section is subject to general corrosion, where its degradation occurs for all structural elements over the years. Garbatov et al., (2007), defined the mean value [d^{cd}(t)] and standard deviation St Dev [d^{cd}(t)] of the corrosion depth as a function of time. Guedes Soares & Garbatov (1999) developed the time-dependent non-linear corrosion degradation model and the time-variant reliability index ($\beta(t)$), where $t \in [0, \tau_S]$ is defined as:

$$\beta(t) = \beta_{gross} - (\beta_{gross} - \beta_{net}) \times (1 - e^{-\frac{t-\tau_c}{\tau_t}}), t > \tau_c \quad (13)$$

$$\beta(t) = \beta_{gross}, t < \tau_c \quad (14)$$

where τ_c = *6.50 years* is the coating life and τ_t = *11 years* is the transition life.

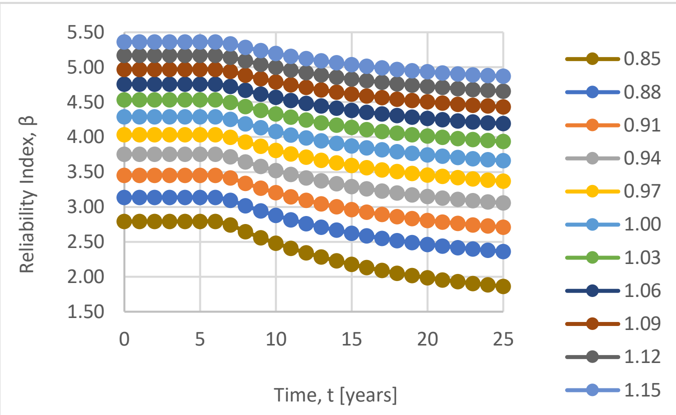

Figure 13. Time variant reliability index $\beta(t)$, corrosion degradation model for design modification factor (DMF).

The design modification factor (*DMF*) (Guia, J. et al. 2018) represents the modification of the midship section structure, keeping the structure closest to the neutral axis constant (inner side and side shell) by changing the structure farthest from the neutral axis (bottom, double bottom, and deck structure). The modification of the midship structure was achieved by increasing and decreasing the thickness of the plate panel in equal measure, keeping the spacing, number and type of stiffeners constant.

Table 2. Design Modification Factor (DMF) corresponding to the modification of the midship structure

Thickness Variation [mm]	*Net area of cross section [m²]*	*DMF*	*Gross area of cross section [m²]*	*DMF*
-5	1.08	0.81	1.32	0.85
-4	1.15	0.86	1.36	0.88
-3	1.19	0.89	1.40	0.91
-2	1.24	0.93	1.46	0.94
-1	1.29	0.97	1.50	0.97
0	1.33	1.00	1.55	1.00
+1	1.38	1.03	1.59	1.03
+2	1.42	1.07	1.64	1.06
+3	1.47	1.10	1.68	1.09
+4	1.51	1.14	1.73	1.12
+5	1.56	1.17	1.78	1.15

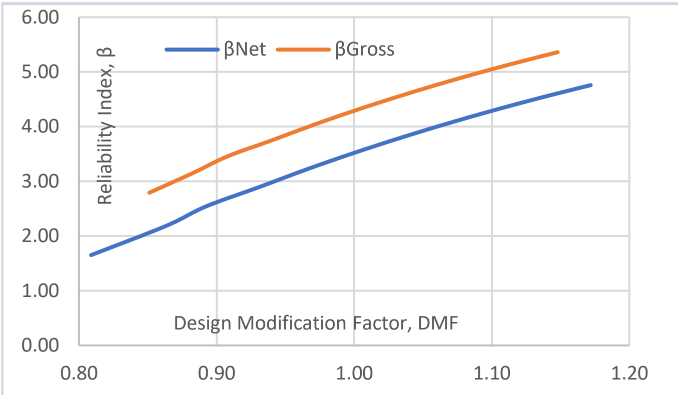

Figure 14. Reliability index β for net and gross scantling according to the modification factor (DMF).

4 INVESTMENT COST ESTIMATION

The Life Cycle Cost (LCC) of the ship is defined as the total cost of all the different phases of life of the ship and its equipment: conception, design, acquisition, operation, maintenance, upgrade, and decommissioning. It is determined by the sum of cost estimates from the beginning to the end of their life cycle. It is usually used in the design process of all engineering systems, including ships (Damyanliev et al., 2017, Garbatov & Georgiev, 2017, Garbatov et al., 2017) and offshore structures. The costs related to the different phases of the ship's life cycle are divided into three different groups: capital costs (CAPEX), operational cost (OPEX) and decommissioning cost (DECEX).

4.1 *Lightship Estimation*

The lightship weight is defined by the weight of the hull structures, deck equipment and machinery, loading and handling devices, navigation equipment, electrical equipment, furniture and fittings, main and auxiliary engine, pipelines, engine spares and liquids in machinery. In the initial stage of the project, the lightship weight is subdivided into three components: hull structure weight, equipment and outfitting weight and machinery weight.

$$LW = W_A + W_B + W_C \ [tonnes] \tag{15}$$

where W_A is the weight of the ship hull, W_B is the weight of equipment and outfitting and W_C is the weight of the propulsion machinery system.

The initial estimate of the structural weight of the vessel can be obtained by regression equations based on a statistical analysis of existing vessels (Benford, 1967, Cudina et al., 2010).

$$W_A = W_1 \ [tonnes] \tag{16}$$

$$W_B = W_2 + W_3 + W_5 + W_6 + W_7 \ [tonnes] \tag{17}$$

$$W_C = W_4 \ [tonnes] \tag{18}$$

where W_1 is the weight of the ship hull, W_2 is the weight of ship equipment, W_3 is the weight of accommodation, W_4 is the weight of the propulsion machinery, W_5 is the weight of the ship's systems, W_6 is the weight of electrical equipment and control system and W_7 is the weight of general ship equipment and arrangement are regression equations used for the estimation of the lightship weight calculation are developed by Damyanliev (2001, 2002) and used in a concept project (Damyanliev et al., 2017), the recalibrated equations is based on the actual data of five multi-purpose ships of similar dimensions, recently built.

4.2 *CAPEX Estimation*

The MARAD system (Maritime Administration, used by the USA administration) is used to subdivide group-specific ship systems and their associated costs. The systems groups are based on the different components in the construction of the ship's life cycle, and their costs are included in the construction project.

The initial capital cost estimate CAPEX for constructing multi-purpose ships is based on several design parameters such as main dimensions, deadweight tonnage (DWT), weight, propulsive power, etc. By a regressions analysis, it is possible to estimate the CAPEX using a mathematical relationship between the input parameters (L, B, D, C_b, P_W, etc.) and the cost of construction (Garbatov, et al., 2017). Construction costs are divided into four components: material, labour, overheads, and profits. It is assumed that the estimated hourly labour cost is 10 € / hour, and the price of steel is k_A= 580€/ton, and the price of the equipment is k_B= 1500€/ton.

$$CAPEX = [1 + P_R].[1 + O].[\sum C_i + \sum C_{mi}] \tag{19}$$

where P_R is the profit of the shipyard (consider 5%), O is the overhead cost (consider 25%), C_i is the material cost, and C_{mi} is the cost of the man-hours, for *i* = A is for the hull, *i* = B is for the equipment and outfitting, and *i* = C is for the machinery.

5 COST-BENEFIT ANALYSIS

During the service life of a ship, its structure is subject to corrosion degradation, occurring structural failures due to the progressive structural collapse of the ship's hull. To control the risk associated with the structural collapse of the ship's hull, accounting for its uncertainties based on an identified failure scenario, which may occur during its service life, risk analysis is measured as the product of the likelihood of structural failure and its consequences.

$$Risk\ (t) = \sum_j P_{f,j}\ (P[g(X_{1,j}|t) \le 0])\ C_{f,j}(X_{2,j}|t) \tag{20}$$

where $P_{f,j}(P[g(X_{1,j}|t) \le 0])$ is the probability of the failure, $C_{f,j}(X_2|t)$ is the consequence of the cost of failure, X_1 and X_2 are the vectors of parameters involved in the probability of failure and consequence analyses that occur during the service life of the ship($t \in [0,\tau_S]$).

Risk management aims to reduce the risk to an acceptable level, by optimising the purpose and functionality of the ship's hull structural system design and evaluating alternative options for decision making. The method used to define the level of acceptable risk is through the target reliability level that minimises the total cost of the consequence of the design of the structural system, where the various failure modes result in economic, environmental, human losses and other consequences.

The cost-benefit analysis is defined as (Garbatov et al., 2018):

$$Ctotal(t^n|DMF,\beta) = C_{Pf}\ (t^n|DMF,\beta) + C_{me}(DMF,\beta) \tag{21}$$

where $C_{Pf}\ (t^n|DMF,\beta)$ is the cost associated with the structural failure over the service life (τ_S) of the ship and $C_{me}(DMF,\beta)$ Implementing a structural safety measure accounts for the DMF, including the cost of materials and labour. That is, the midship section hull structure is being redesigned.

5.1 *Cost associated with the structural failure*

The cost associated with the structural failure over the service life (τ_S) of the ship is estimated as a function of DMF, reliability index (β) and time (t_j) as (Garbatov et al., 2018):

$$C_{pf}(t^n|DMF\ ,\beta) = \sum_j^n P_f\ (t_j|DMF,\beta).[C_S(t_j|DMF,\beta) + C_C + C_d + C_v]e^{-\gamma t_j} \tag{22}$$

where $P_f(t_j|DMF,\beta)$ is the probability of failure, $C_S(t_j|DMF,\beta)$ is the cost of the ship in the year $t_j \in [0,\tau_S]$, C_C is the cost associated with the loss of the cargo, C_d is the cost associated with the accidental spill, C_v is the cost associated with the loss of human life, and γ = 5% is the assumed value of the discount rate.

5.1.1 *Cost of the ship*

The cost of the ship, $C_S(t_j|DMF,\beta)$, is a function of the ship's age, that is, the initial cost of the ship ($t_0 = 0\ years$) and the scrapping cost($t_n = 25\ years$) accounting for corrosion degradation (Guedes Soares & Garbatov, 1999) estimated as (Garbatov, et al., 2018):

$$C_s(t_j|DMF,\beta) = C_s(t_0|DMF,\beta) - [C_s(t_0|DMF,\beta) - C_s(t_n|DMF,\beta)] \times [1 - e^{-\frac{t_j-\tau_C}{\tau_t}}], t_j > \tau_C \quad (23)$$

$$C_s(t_j|DMF,\beta) = C_s(t_0|DMF,\beta), t_j < \tau_C \quad (24)$$

where $C_S(t_0|DMF,\beta)$ is the initial cost of the ship, $C_S(t_n|DMF,\beta)$ is the scrapping cost, t_j is the year of the operation $[t_j \in 0,\tau_S]$, τ_s = 25 years is the service life of the ship, $\tau_C = 6.5$ years is the coating life, $\tau_t = 11$ years is the transition life and C_{scrap} = 270 €/ton is the assumed value of scrap cost.

5.1.2 *Cost associated with loss of cargo*

The cost associated with the loss of cargo, C_C, in €, is estimated as (Garbatov et al, 2018):

$$C_c = C_{cargo} \times f_{cargo} \times P_{cargo} \quad (25)$$

where C_{cargo} = *1,200 €/ton* is the assumed value of the cost of a ton of cargo, f_{cargo} = 20% is the considered partial factor of the cargo lost and P_{cargo} is the total amount of cargo of the ship, estimated as 7,200 tons.

5.1.3 *Cost associated with the accident spill*

The cost of the accident spill, C_d, in €, is estimated as:

$$C_d = f_{spill} \times P_{sl} \times CATS \times W_{fuel\ oil} \quad (26)$$

where f_{spill} = 10% is the considered partial factor of the fuel oil spill, P_{sl} = 10% is the probability that the fuel oil split reaches the shoreline (SØrgard et al.,1999), *CATS = 60,000 USD/ton* (SAFEDOR, IMO, 2008) is the cost of one ton of accidentally spilt fuel oil and $W_{fuel\ oil}$ (Parsons, 2003) is the total weight of fuel oil in tons.

5.1.4 *Cost associated with the loss of human life*

The costs associated with the loss of human life, C_v, in €, in this case, the loss of crew members is estimated as:

$$C_v = n_{crew} \times f_{crew} \times ICAF \quad (27)$$

where n_{crew} is the number of crew members, f_{crew} is the probability of loss of the life of a crew member (considered 25 %), and *ICAF* is the implied cost of averting the fatality (Horte et al., 2007).

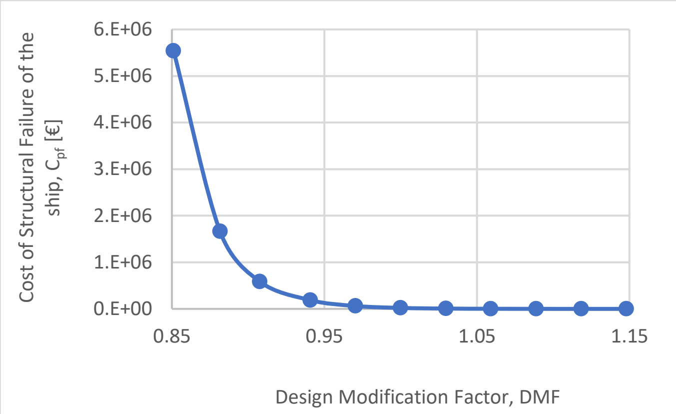

Figure 15. Cost of structural failure of the ship, C_{pf} in €, for design modification factor (DMF).

5.2 *Cost of implementing structural safety measures*

The cost of implementing a structural safety measure accounts for the DMF, which is also associated with the reliability level (β), including the cost of material and labour, that is, the redesign of the midship section hull structure. The cost of structural redesign $C_{me}(DMF,\beta)$ is positive or negative depending on if the value of DMF is more significant or smaller than one respectively (Garbatov et al., 2018):

$$C_{me}(DMF,\beta) = \Delta W_{steel}(DMF,\beta).C_{steel} + C_{labour}(DMF,\beta) \quad (28)$$

where $\Delta W_{steel}(DMF,\beta)$ is the weight of steel, in tons, because of the design modifications factor (*DMF*), C_{steel} is the cost of steel ($k_A = 580\ €/ton$, and C_{labour} is the cost of labour for the construction a $\Delta W_{steel}(DMF,\beta)$. The weight of steel, in tons, because of the design modification factor (*DMF*) is estimated as (Garbatov et al., 2018):

$$\Delta W_{steel}(DMF,\beta) = (DMF-1) \times W_{steel} \quad (29)$$

where W_{steel} is the weight of steel related to the ship hull structural design estimated according to *CAPEX*.

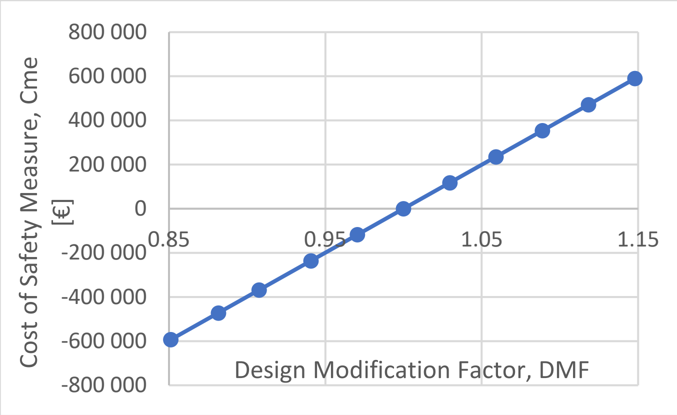

Figure 16. Cost of safety measure, C_{me} in €, for design modification factor (DMF).

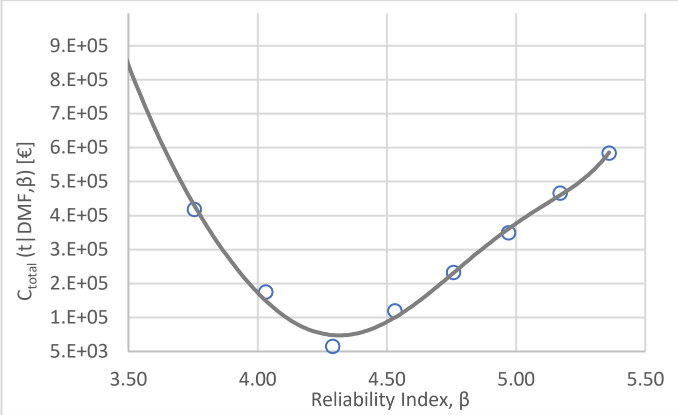

Figure 17. Expected total cost, C_t, in €, as function for reliability index, β.

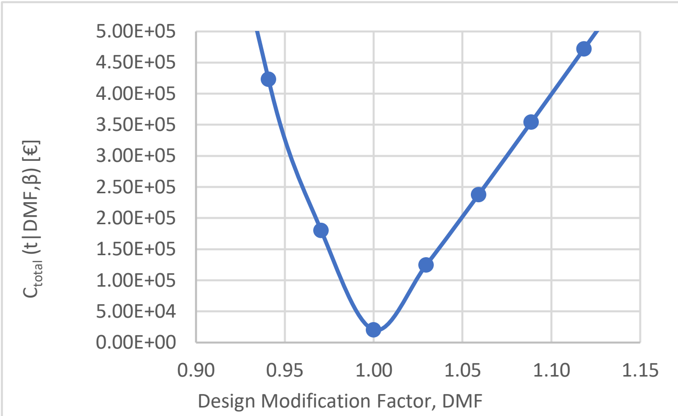

Figure 18. Expected total cost, C_t, in €, as function for design modification factor, DMF.

5.3 *Optimum safety level*

The main objective of the cost-benefit analysis is to identify an optimum level of ship safety, i.e., the optimum/target reliability index, controlling the risk associated with changing the initial design. The cost-benefit analysis of the modified structure, according to the structural DMF related to the scantlings of the midship section, is carried out based on the expected total cost (C_t), in €, defined as (Garbatov et al, 2018):

$$C_t = C_{failure} + C_{DMF} \tag{30}$$

where $C_{failure}$, in €, is the total cost associated with the progressive collapse of the ship's hull structure and C_{DMF}In €, is the total cost of implementing structural safety as a function of the structural DMF, controlling the associated risk, involving the construction costs of the hull material, the quantity of material required and the labour cost as a function of the lightship weight.

Estimating the target reliability level β influences the structural failure cost associated with risk control since each of the costs defined above is a function of the reliability index β. According to the study, the range of values of the ideal/target reliability index (β) over the ship's service life can vary between 2.79 and 5.38. The degradation of structural corrosion is reflected in the increased probability of failure as a function of the ship's life service.

Garbatov& Sisci (2018) demonstrated that the partial safety factors related to the target reliability index (β) represent an acceptable risk level for the minimum cost in the structural design of a multi-purpose ship. The three modification factors that impact the most on the reliability and cost of structural collapse consequences are block coefficient, length, and structural redesign.

5.3.1 *External factors*

Due to armed conflicts, political and economic crises, natural disasters, climate change throughout human history, and the recent pandemic COVID-19, commodity price speculation is considerable, leading to fluctuating world market prices. According to the base price of steel per tonne, K_A = 580 €/ton, a price increase of 20% and 50% was analysed, as well as a price decrease of the same order of magnitude. It was assumed that the fluctuation in the price of steel K_A, in *€/ton*, would imply the resale or scrap price of the ship, as they are related, i.e., it is increased or decreased in the same order of magnitude.

For a target reliability level β = 4.76, corresponding to a DMF = 1.06, implies a total expected cost C_t = 237,934€. An eventual 50% increase in the steel price ($K_{A\ (+50\%)}$ = 870 €/ton) implies an increase in the total expected cost C_t = 286 021€.

Comparing the two values, with a rise in steel price, the total cost increases by approximately 50,000€. A 50% depreciation in the price of steel ($K_{A\ (-50\%)}$ = 290€/ton), the total expected cost is C_t = 189 846€, a total cost saving of around 50,000€, i.e., the same value. At a constant base steel price (K_A = 580€/ton), for different DMF, i.e., for different target reliability levels (β) of the structure, the total expected cost increases ($C_{t\ (DMF\ =\ 1.06)}$ = 237,934€; $C_{t\ (DMF\ =\ 1.09)}$ =

354,411€), i.e., the difference in total cost is approximate of the order of 120,000€.

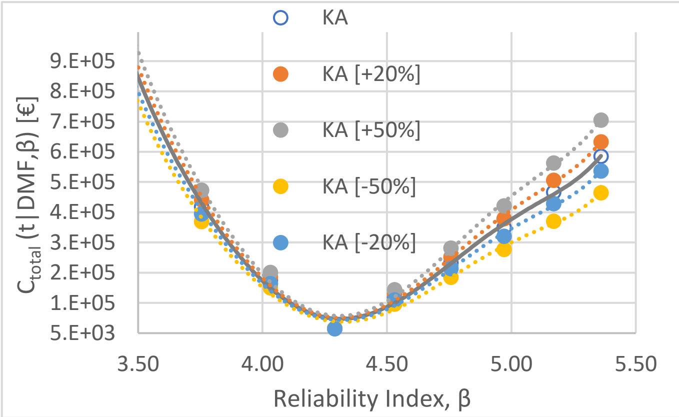

Figure 19. Expected total cost, C_t, in €, as function for reliability index, β.

An increase in steel price increases the difference in total cost, i.e., for $K_{A\ (+50\%)}$ = 870 €/ton, the difference in expected total cost (C_t) rises to 140,000€. On the other hand, if there is a 50% depreciation in the price of steel ($K_{A\ (-50\%)}$ = 290€/ton), the difference in expected total cost (C_t) rises to 90,000€ but is based on lower-cost values.

6 CONCLUSION

The main objective of the cost-benefit analysis is to identify an optimum level of ship safety, i.e., the optimum/target reliability index, controlling the risk associated with the modification factor related to the resizing of the midship section structure by varying the thickness of the main structural components, based on the expected total cost. The minimum value of the expected total cost risk curve is the optimised structural design solution that is most cost-effective, leading to lower construction and operational costs, satisfying existing requirements for safe transport, corresponding to the optimal/target reliability level of the structure that determines the probability of system failure and its consequences.

Several external factors have implications in the analysis of the cost of the ship, one of them being the fluctuation of the price of raw materials, in this case, steel. It is expected that the higher the design modification factor (DMF), that is, the higher the weight of steel, corresponding to a higher level of reliability of the structure, that is, a reduction in the progressive collapse of the structure, the impact of steel price fluctuation is more significant. The choice of the target/ideal reliability level of the structure to be designed versus the design modification factor (DMF) should be as optimal as possible, as the impact of raw material fluctuation can increase costs.

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