Sensitivity analysis of risk-based conceptual ship design

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ABSTRACT: The presented work performs a sensitivity analysis of conceptual ship design of a multi-purpose vessel employing a risk-based framework for design. The risk-based framework includes conceptual design to define initial dimensions and characteristics of the ship based on the optimization of the required freight rate, stochastic load modelling, progressive collapse accounting for corrosion degradation during the service life, reliability and cost benefit analysis and finally risk management and sensitivity analysis. The impact of three type design modification factors related to ship design modification: length, block coefficient and service speed; structural design modification associated with the re-scantlings of the midship section leading to different stiffness of principal structural components and cost modification factors associated with the labour, steel, equipment and outfit, machinery costs, profit and overheads are analysed here. Several conclusions with respect to the most significant modification factors are derived.

1 INTRODUCTION

Ship design and operation are predominantly governed by the ship owner's specification and applicable Regulations and Classification Rules.

The International Maritime Organization, IMO recognizes the importance of adopting the risk assessment procedures in their decision process by defining the Formal Safety Assessment, FSA (IMO, 2002, 2005, 2008, 2013) as a systematic methodology aimed at enhancing maritime safety, including the protection of life, health, maritime environment, cargo and ship integrity by using risk and cost-benefit assessments (see Figure 1).

Another development is the creation of the Port State Control, the PSC program with the objective of eliminating substandard ships from the waters. In addition, the maritime security is also an integral part of the IMO's responsibilities.

The FSA methodology (IMO, 2013), as presented in Figure 1, as stipulated by IMO, which is based on a Quantified Risk Analysis, QRA and provides widely application of QRA to the marine transportation. It is a structured methodology, aimed at enhancing the maritime safety, including the protection of life, health, the maritime environment and property.

Psaraftis (2012), Montewka et al. (2014) used FSA to create new rules and Papanikolaou et al. (2009) for design of ships in the damaged condition.

Recently this approach was used in sensitivity analysis on the optimum hull girder safety level of a Suezmax tanker by Guia et al. (2016).

The methodology employed here includes a synergistic decision models, ship hull reliability analysis algorithms, failure consequence assessment methods, and progressive collapse assessment methodology as has been given by the Common Structural Rules (IACS, 2015) and employed in the shipbuilding industry for the ship hull structural design and integrity assessment.

The ship's optimal safety level is assessed by performing a cost benefit analysis, CBA, where the objective is to establish an optimal safety level identified as a risk control option, RCO, which is represented by redesign of the initial ship design solution, including the main dimensions of the ship and midship section scantlings.

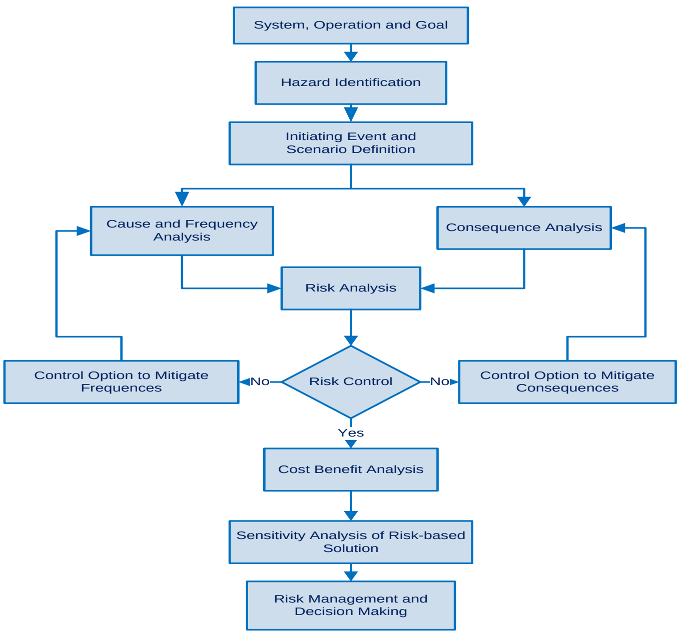

Figure 1 Formal Safety Assessment

A quantified risk analysis, based on the formal safety assessment is used in the recently developed framework for conceptual ship design accounting for risk-based life cycle assessment in (Garbatov et al., 2017b).

The analysis focuses on sensitivity analysis of three categories design modification factors related to ship design, structural scantling and economical aspects of the capital investment cost, CAPEX and operational cost, OPEX with respect to the progressive ship hull structural collapse and the related probability of structural failure as well as the cost of collapse consequences, structural measures, human life, loss of cargo, accidental spills, where the last two are related to the environmental impact.

2 CONCEPTUAL SHIP DESIGN

The design is defined as a compromise decision support problem with multiple goal constraints. Given the owner's requirements: cargo deadweight/containers, speed, range, regulations and data on similar ships to find the main dimensions of a ship.

The design solution has to satisfy the system constraints, where free-board has to be greater than the required classification free-board, metacentric height, natural period of roll and dimensional ratios (L/B, B/D and B/T) are within limits that reflect to the designer's experience-based insight (Damyanliev et al., 2017).

Satisfy bounds, where necessary, length of ship is between 95 and 130 m, breadth is between 17 and 25 m, depth is between 8 and 12 m, draft is between 4 and 8 m, velocity is between 10 and 20 knots, L/B is between 5 and 6.5, B/D is between 1.5 and 2.5.

Satisfy the design goal, the constraints are defined as the cargo deadweight/number of containers plus or minus deviation that equals to the owner's required cargo deadweight, design meta-centric height plus or minus deviation, which is equal to the required meta-centric height, displacement minus a deviation equals to the required cargo deadweight, that is, the minimum theoretical displacement, shaft horsepower minus deviation is equal to zero, that is, the minimum theoretical power.

The mathematical model of Holtrop and Mennen (1982) is widely used that can provide an estimation of the hull resistance and engine power demand, which can be used to select a propeller engine set (Carlton, 1994). An alternative possible solution is the use of other methods as ITTC (1978) or BSRA (Patullo & Thomson, 1965) methods. The Holtrop's formulation is based on a statistical analysis of resistance data. A resistance service margin is included to provide the added power required to overcome in service the added resistance from hull fouling, waves and wind effects.

The propulsive power is calculated by estimating the resistance on the ship hull, R_{TOT}, calculating the required Effective Horsepower, EHP and Shaft Horsepower, SHP as:

$$R_{TOT}=R_F(1+k_1)+R_{APP}+R_W+R_B+R_{TR}+R_A \qquad (1)$$

$$EHP=R_{TOT}\,V/746 \qquad (2)$$

$$SHP=EHP/0.65 \qquad (3)$$

where R_{TOT} is the total resistance, N, R_F is the frictional resistance, N, $(1+k_1)$ is the form factor for the viscous resistance, R_{APP} is the appendages resistance, N, R_W is the wave resistance, N, R_B is the pressure resistance of the bulbous bow, R_{TR} is the transom resistance, N, R_A is the correlation resistance from a tested model to the real ship and V_s is the service speed, m/sec.

The total weight of the ship is split into the proper ship's weight, the lightweight, W_{light}, tons, and the consumables and cargo weight, the deadweight W_{dead}, tons. The lightweight is used as an input parameter to estimate the building costs and the deadweight is determinant in estimating the operational costs of the ship (Garbatov et al., 2017a).

The lightweight is the sum of the weights of the ship hull, W_{hull}, tons, which includes the main hull structure, superstructure and bulkheads of the ship, the outfit and hull engineering, W_{oh}, tons accounts the hull insulation, joiner bulkheads, pipes, deck fittings, cargo booms, anchors, rudder, galley equipment and hatch covers, and the machinery, W_m, tons is the sum of the weights of the entire propulsion system (Garbatov et al., 2017a).

The deadweight includes the weight of the cargo, W_{con}, tons (containers in this case), fuel weight, W_{fuel}, tons and weight of fresh water, lubricating oil, stores and crew and other weight related to the machinery being idle, W_{misc}, tons.

To estimate the number of containers, TEU that the ship can transport in one voyage, a regression analysis developed in (Chen, 1999) is used:

$$TEU_{bfloat}=S_b\,(0.0196\,L_{oa}\,B\,D\text{-}148.6129) \qquad (4)$$

$$TEU_{dfloat}=0.050117\,L_{oa}\,B\,TN_d\text{-}82.6702 \qquad (5)$$

$$TEU=TEU_{bfloat}+TEU_{dfloat} \qquad (6)$$

where TEU_{bfloat} is the number of containers below the deck, TEU_{dfloat} is the number of containers on the deck, S_b is a stowage factor for TEU below the deck, L_{oa} the length overall and TN_d is the number of rows of TEU above the deck.

The total cost of the ship is derived from the annual operating cost and capital cost, where the first is the sum of the salary of crew members, costs related to the stores and supplies, insurances, port expenses and annual fuel cost, and the second one accounts for all expenses of the building of the vessel (Garbatov et al., 2017a).

The required freight rate, RFR, €/ton has been calculated by dividing the discounted annual average cost of the investment, AAC, € by annual cargo capacity, ACC, ton/year:

$$RFR=AAC/ACC \qquad (7)$$

The design problem is defined with multiple objectives and linear and nonlinear constraints and it is suitable for a solution by computer methods. A genetic algorithm with a termination criteria is employed (Deb et al., 2002, Wong et al., 2015) for a non-linear optimization problem in defining the best design solutions. The genetic algorithm of Deb et al. (2002) accommodates fast non-dominated sorting procedure, implementing an elitism for the multi-objective search, using an elitism preserving advanced approach allowing both continuous and discrete design variables. Pareto frontier (Komuro et al., 2006) is applied for a simultaneous minimization of the net sectional area and structural displacement. Employing the Pareto Frontier, an optimal solution accounting for the existing constraints may be chosen using a utility function to rank the different designs.

The Pareto optimal solution is defined as the solution for which any improvement in one objective will result in the worsening of at least in one other objective (Messac & Mullur, 2007). In this respect, recently a study of a stochastic structural optimization was presented in (Garbatov & Georgiev, 2017).

The Pareto solution for the ship length and breadth as a function of normalized RFR are shown in Figure 2 and Figure 3, where RFR_{min}=0 and RFR_{max}=1.

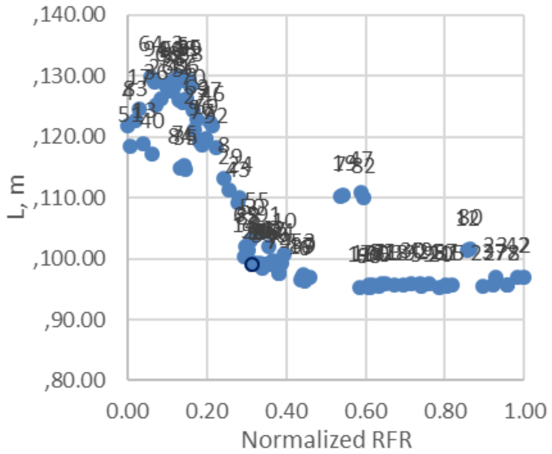

Figure 2 Pareto optimal design solutions of ship length

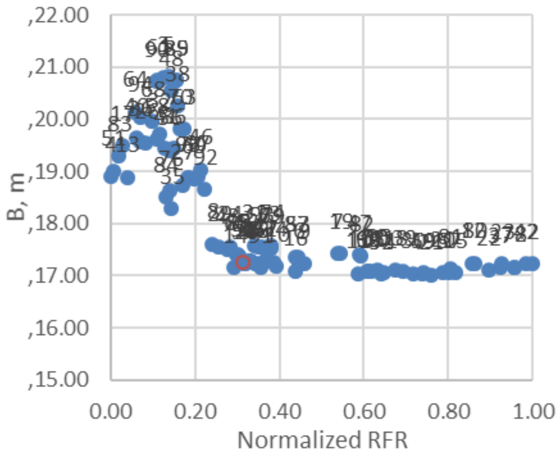

Figure 3 Pareto optimal design solutions of ship breadth

All Pareto design solutions comply with the design constraints and requirements and for the present analysis one design solution of a feeder multi-purpose/container vessel is considered, with main dimensions of L_{pp} =115.07 m, B =20.0 m, D=10.4 m, T=8.3 m, C_b =0.72, Vs =16 kn.

3 STOCHASTIC LOAD MODELLING

The loads is defined for full, partial and full loads, where the long-term value of the still water and wave-induced bending moments are estimated based on IACS (2015). The primary total bending moment load on the ship hull can be decomposed into two components: the still water bending moment M_{SW} and wave induced bending moment M_W.

Statistical descriptors of the still water bending moment may be defined by using the regression equations as defined in (Guedes Soares & Moan, 1988):

The statistical descriptors of the still water bending moment in full, ballast and partial loads are following the Normal probability distribution, N_{FL} (160.8 MN.m, 54.4 MN.m), N_{BL} (295 MN.m, 72.6 MN.m) and N_{PL} (244.9 MN.m, 69.2 MN.m), where the first descriptor define the mean value and the second one the standard deviation. The still water bending moment is in a hogging condition for the full, ballast and partial loads.

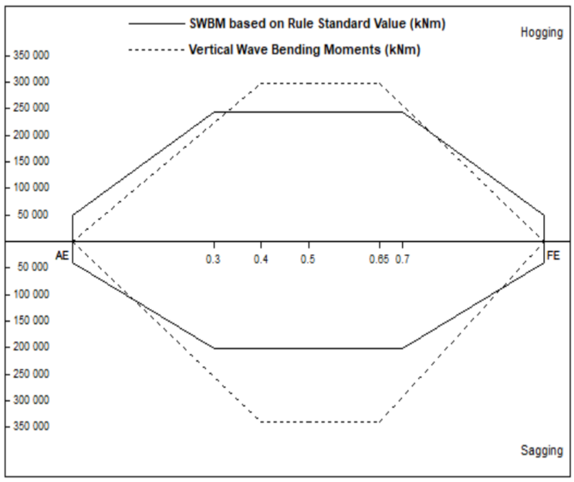

Figure 4 $M_{SW,CS}$ and $M_{W,CS}$ bending moments, (MARS2000, 2011)

The stochastic model for defining the vertical wave-induced bending moment, proposed in (Guedes Soares et al., 1996), is employed here. The mean value and standard deviation of the vertical wave-induced bending moment in the full, ballast and partial loading conditions are defined by the Gumbel distribution function as $F_{G,FL}$(443.73 MN.m, 14.84 MN.m), $F_{G,BL}$(341.19 MN.m, 13.15 MN.m), and $F_{G,PL}$(373.32 MN.m, 13.04 MN.m) respectively.

4 PROGRESSIVE COLLAPSE

Assessing the ship hull structural risk of an ageing multipurpose ship requires the development of an ultimate limit state function with a reference to the progressive ship hull structural collapse of the primary ship hull structure, where the reference is made to the midship section. The ship hull is considered to behave globally as a beam under transverse load subjected to still water and wave-induced effects.

The midship section scantling and the ultimate capacity is estimated using the progressive collapse method as stipulated by the Classification Society Rules and using the BV software (MARS2000, 2011).

The 5% confidence level value of the ultimate bending moment, $M_U^{5\%}=M_U^c$ is assumed as a characteristic one, which respect the value estimated by MARS2000 (2011) software and additionally it is assumed that COV equals to 0.08 and it is fitted to the Lognormal probability density function, $f_{LN}(M_U)$.

5 CORROSION DEGRADATION

The non-linear time variant corrosion degradation model is used in the present study to estimate the structural degradation in time. The mean value, Mean value $[d^{cd}(t)]$ and standard deviation, St Dev $[d^{cd,1}(t)]$ of the corrosion depth as a function of time are defined as (Guedes Soares & Garbatov, 1999, Garbatov et al., 2007):

$$\text{Mean value } [d^{cd}(t)]=d_\infty[1-\exp(-(t-\tau_C)/\tau_t], \; t>\tau_C \qquad (1)$$

$$\text{St Dev } [d^{cd}(t)]= a \, \text{Ln}(t-\tau_C- b) - c], \; t>\tau_C \qquad (2)$$

where a, b and c are regression coefficients.

The analysed ship hull structural system is assumed to be subjected to general corrosion degradation, where the coating life, τ_C=5 years and transition life, τ_t = 7 for all structural components and the long-term corrosion thickness of any individual structural component is defined based on the corrosion margins as defined by the Classification Society Rules and implemented in the BV software MARS2000 (2011).

6 RELIABILITY

The reliability of a ship hull structural system is defined as the likelihood of maintaining its ability to fulfil the design functions for some period. The objective is to estimate the reliability based on its ultimate strength when extreme loads act upon the ship hull structure subjected to corrosion degradation.

The probability of ship hull structural collapse here is estimating by using the FORM techniques (Hasofer & Lind, 1974). The limit state function is defined as:

$$g(\mathbf{X}|t)=x_u M_u - x_{SW} M_{SW} - x_W x_S M_W \qquad (3)$$

where M_U is the ultimate capacity with a model uncertainty factor, x_U, which is assumed to be described by a Normal probability density function, $N_{xU}(1.05, 0.1)$. The model uncertainty factor, x_W accounts for the uncertainties in the linear response calculation of wave-induced bending moment, $N_{xW}(1, 0.1)$ and x_S is to account for the non-linear effects, $N_{xS}(1, 0.1)$. The model uncertainty factor in the steel water bending moment is accounted by x_{SW}, $N_{xSW}(1, 0.1)$ (Silva et al., 2014, Garbatov & Guedes Soares, 2016).

The ultimate bending moment is estimated based on the BV software MARS2000 (2011) and employing the commercial software COMREL (2017), the beta reliability index is calculated.

The probability of failure P_f is obtained from the beta reliability index as:

$$P_f = \Phi(\beta) \qquad (4)$$

where Φ is the standard normal probability distribution function.

The reliability index for the gross and net designs can be related assuming that the gross ship hull structural design respects the non-corroded ship hull structure up to the moment when the corrosion protection fails, and the net design respects the end of the service life when the structure is already corroded, and no maintenance actions took place. The service life of ship hull structural system is considered as τ_S=25 years.

The reliability index as a function time, $t\in[0, \tau_S]$ is defined as:

$$\beta(t)= \beta_{gross} -[\beta_{gross} - \beta_{net}][1-[\exp[-[(t-\tau_{C,\,ship})/\tau_{t,\,ship}]]]], \; t>\tau_C, \qquad (5)$$

$$\beta(t)= \beta_{gross}, \; t<\tau_C \qquad (6)$$

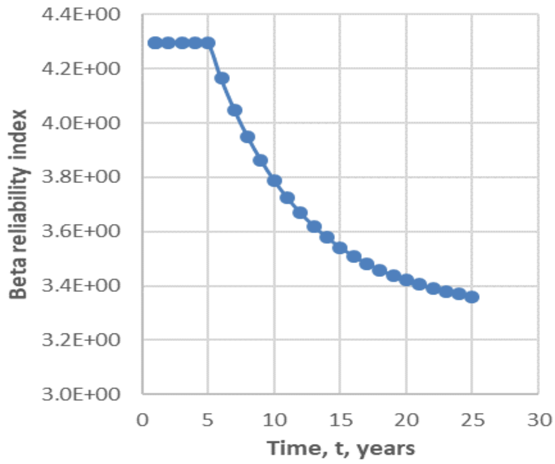

Figure 5 Beta reliability index as a function of time, DMFs=1

The importance of the contribution of each stochastic variable to the uncertainty of the limit state function $g(\mathbf{X})$ is assessed by the sensitivity factors, which can be defined as:

$$\alpha_i=-[\partial g(\mathbf{X}|t)/ \partial x_i]/\sqrt{[\Sigma =-[\partial g(\mathbf{X}|t)/ \partial x_i]^2]} \qquad (7)$$

Figure 6 shows the sensitivities of the limit state function with respect to the changes in the stochastic variables. A positive sensitivity indicates that an increase in the stochastic variable reflects to an increase in the failure function and negatively contributes to the increase of reliability.

It can be seen from Figure 6 that the most important uncertainty on the analysed ship hull is the uncertainties related to the model used to estimate the ultimate bending moment followed by the ultimate bending moment value and still water bending moment etc.

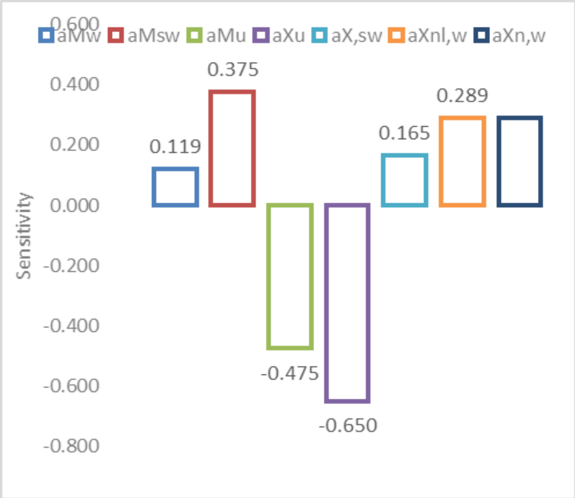

Figure 6 Sensitivities of stochastic variables, t=0

7 COST BENEFIT ANALYSIS

The risk-benefit analysis is used to perform a risk management. This analysis compares the costs and risk to determine where the optimal risk value is on a cost basis. The optimal value occurs when the cost to control risk is equal to the cost of risk due to the ship hull structural collapse.

The ship's optimal safety level is assessed by performing a cost benefit analysis, where the objective is to establish an optimal safety level identified as a risk control option in changing the initial design.

The total expected cost is the sum of two distinct costs, one is the cost associated with the structural collapse of the ship and the other is the cost of implementing the risk control option. The first involves costs associated with the ship hull structural progressive collapse, environmental pollution and loss of human life, while the second involves the costs related to the constructional cost of the steel hull structure, where the amount of material and labour cost is a function of the weight of the structure. The methodology to obtain the optimum safety level, i.e. the optimum/target reliability index is employing the cost effectiveness analysis (Horte et al., 2007).

The cost benefit analysis of the modified midship section structure is performed based on the total expected cost, C_t and firstly, will be dealt with the structural design modification factor related to re-scantlings of the midship section leading to a different thickness of principal structural components, DMF_2:

$$C_t=C_{Tf}+C_{me} \tag{8}$$

where C_{Tf} is the total cost associated with the structural failure of the ship and C_{me} is the cost of the implemented structural safety measure as a function of DMF_2. Each of the costs is as a function of the reliability index, β, as this in return influences the cost of structural failure and the risk control option, estimate the safety target beta reliability level, β_t.

The cost associated with the ship hull structural failure is the cost related to the loss of the ship and cargo, environmental pollutions, clean-up related to oil spills and loss of human life.

The cost associated with the ship hull structural collapse is estimated over the service life of the ship, accounting for a discount rate of γ is defined as:

$$C_{Tf}=\Sigma P_f[C_n+C_c+C_d+C_v)]e^{-\gamma t} \tag{9}$$

where P_f is the probability of failure, C_n is the cost of the ship in the year t, C_c is the cost associated with the loss of cargo, C_d is the cost of accidental spill and C_v is the cost associated with the loss of human life.

The cost of the ship at any time $t\in[0, \tau_S]$, is a function of the initial cost of the ship at t=0, and the scraping cost at t= τ_S^{th} year estimated as:

$$C_n(t)=C_n(0)-[C_n(0)-C_n(\tau_S)][1-[\exp[-[(t-\tau_{C,\,ship})/\tau_{t,\,ship}]]]], \quad t>\tau_C \tag{10}$$

$$C_n(t)=C_n(0), \ t<\tau_C \tag{11}$$

where $C_n(0)$ is the initial cost of the ship, $C_n(\tau_S)$ is the scrapping value of the ship and t is the year of operation, $t\in[0, \tau_S]$. The cost of ship as a function of time is shown in Figure 7.

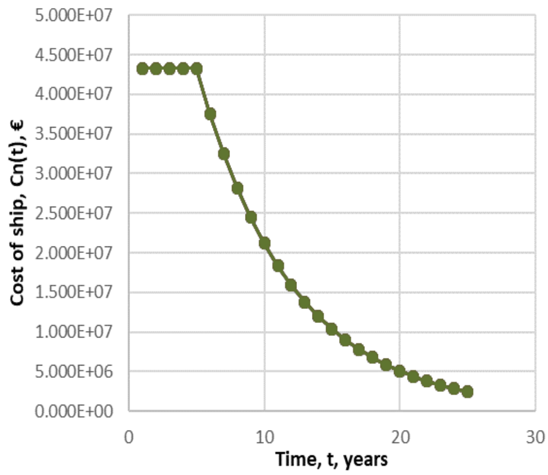

Figure 7 Cost of ship as a function of time, DMF_1

In the present analysis, the cost of implementing a safety measure accounts for the redesign of the midship section structure, accounting for the cost of material and labour. Depending on the level of the modification, the cost of structural redesign, C_{me} may result in a positive or negative value respectively:

$$C_{me}(DMF_2)=\Delta W_{steel}(DMF_2)\ C_{steel}+C_{labor,steel}(DMF_2) \tag{12}$$

where $\Delta W_{steel}(DMF_2)=(DMF_2-1)W_{steel}$ is the weight of steel due to the design modifications, tons, DMF is the design modification factor, which is also associated with the beta reliability level, β, W_{steel} is the weight of the steel of the reference ship hull structural design, tons, C_{steel} is the cost of steel, €/ton and $C_{labour,\,steel}(DMF_2)$, €/ton is the labour cost of the constructing ΔW_{steel} (DMF_2), tons.

The cost associated with the loss of cargo, C_c, € is estimated by considering a part of the total amount of cargo of the ship in the case of ship hull structural failure.

In the case of ship hull structural failure, a part of the total amount of oil and fuel may be spilled. P_{spill} is the considered as a partial factor of spill, $P_{s,p}$ is the probability that the oil and fuel is reaching the shoreline (Sørgard et al., 1999). In the case of an accidental oil spill, $P_{spill} \cdot P_{s,p} \cdot W_{oil\ and\ fuel}$ is the weight of spill that needs to be cleaned up, which leads to a cost of:

$$C_d = P_{spill} \cdot P_{sl} \cdot CATS \cdot W_{oil\ and\ fuel} \qquad (13)$$

where CATS·is the cost of one ton accidentally spilled oil and fuel that needs to be cleaned.

The cost of human life is accounted for by ICAF as used in a study performed in (Horte et al., 2007):

$$C_v = n_{crew} \cdot P_{crew} \cdot ICAF \qquad (14)$$

where n_{crew} is the number of crew members, P_{crew} is the probability of loss of the life of a crew member.

The risk-beta-reliability index relationship as a function of time is shown in Figure 8 where the risk is estimated as a product of the probability of failure, P_f and the consequential cost of failure represented by the total expected cost, C_t.

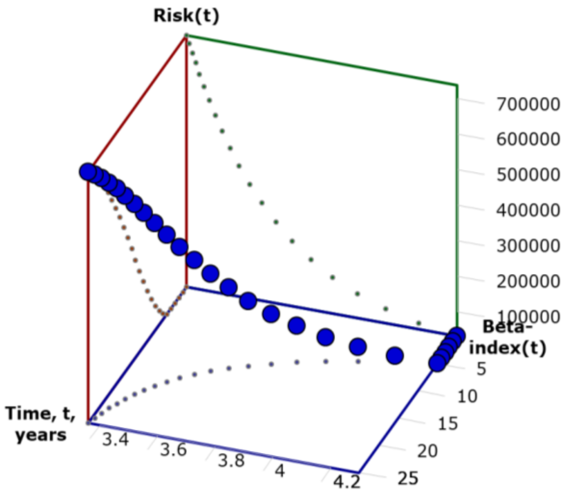

Figure 8 Risk-reliability relationship as a function of time

8 SENSITIVITY ANALYSIS OF RISK-BASED DESIGN

The Differential Sensitivity Analysis, DSA is used to evaluate a risk based conceptual design, enabling an instantaneous analysis of changes in the total cost due to changes in the input, defined here as design modification factors.

At the beginning, a simulation is conducted with all design modification factors at their original value. For each of the following simulations, one design modification factor is changed. The change of the output can be directly related to the design modification factor and reliability and risk level.

Three type design modification factors are analysed here DMF_1 to DMF_3.

DMF_1 includes the ship design modification factors related to L_{pp}, C_b and V_s. L_{pp} directly impact Three methods are normally used to select the target reliability level: (1) agreeing upon a reasonable level in the case of a novel structural system without prior history; (2) calibrating the beta reliability level implied in currently successfully used design codes; (3) choosing the target reliability level that minimizes a total consequence cost over the service life of the structural system in the case of design in which failure results in economic losses and consequences.

on the subjected still and wave-induced loads and the L/B ratio, which is commonly referred to as an indicator of the ship propulsion and seakeeping and the L/D ratio as an indirect indicator of the stiffness of the ship hull. The reduction in the design speed results in a lowering in a fuel and oil consumption, which may reduce the OPEX up to 30%.

DMF_2 represents the structural design modification factor related to re-scantlings of the midship section leading to a different thickness of principal structural components.

DMF_3 is related to the cost modification factors associated with the labour, steel, equipment and outfit, machinery costs, profit and overheads.

All design modification factors vary in the range from -15% to 15%, are imposed to the ship design solutions and in the case of the length and the block coefficient of the ship is considered a redesign of the ship hull to satisfy the Classification Society Rules.

Figure 9 shows the sensitivity of the $DMF_{1,3}$ with respect to the RFR, which incorporate CAPEX and OPEX and representing the economic impact, demonstrating different gradients. The gradient of $\Delta RFR/\Delta DMF$ can be read as a first qualitative estimation of the sensibility of the studied variables, which have higher positive values for the C_b and V_s and negative higher gradient in the case of the length between perpendiculars.

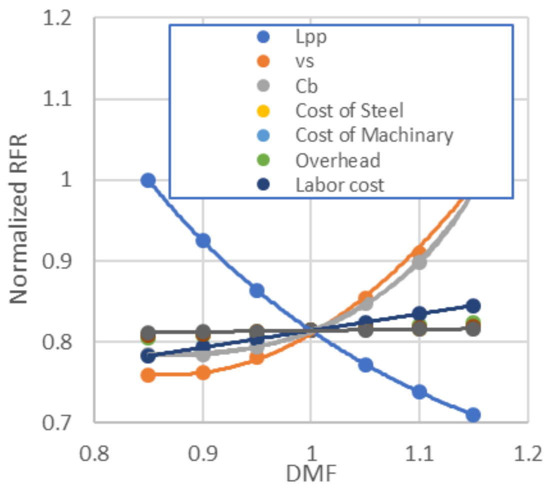

Figure 9 Normalized RFR as function of the $DMF_{1,3}$

The cost of the steel, machinery, equipment, labour os construction, overhead and profit has a positive, but not significant effect on RFR.

It can be noticed that with increasing the ship length the required freight rate is reducing, which in accordance with the general acceptance that the bigger ships are more efficient in transporting cargo. It is to be also pointed out that the increasing the speed and block coefficient of the ship the required freight rate sharply increase. As for the other DMS, the contribute to the increase of the RFR but in a very reduced scale.

Figure 10 shows the sensitivity of the $DMF_{1,3}$ with respect to the normalized Beta reliably index, which incorporates the loads and resistance and related uncertainties, demonstrating only the most significant effects related to the length between perpendicular and block coefficient of the ship.

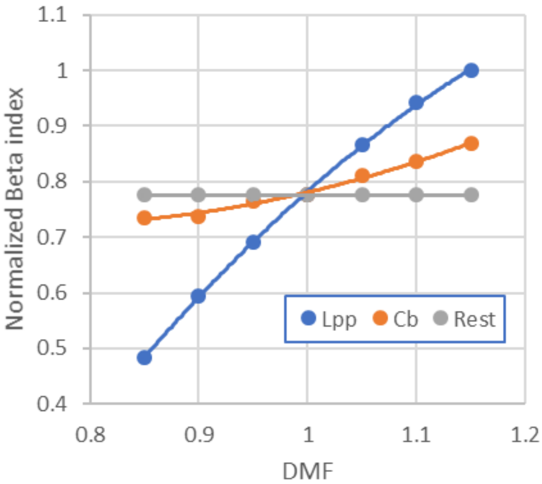

Figure 10 Normalized Beta reliability index as a function of DMFs

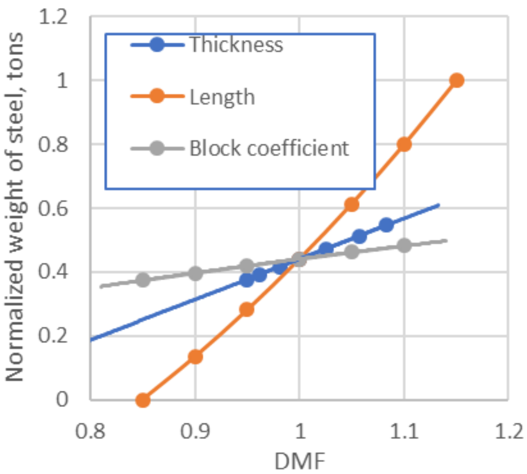

Figure 11 Weight of steel as a function of DMFs

Increasing the length and block coefficient of the ship leads to an increase in the thickness of the deck structures to satisfy the Classification Society Rules, which in turn increases the stiffness of the ship and the subjected load and results in an increase of the invested cost, CAPEX. Here a trade-off needs to be seen in identifying the optimum target reliability index. The weight of the steel, at the beginning of the service life, t=0 years (gross), as a function of the most significant DMFs related to the ship design and scantling is shown in Figure 11.

The consequence cost of structural collapse, which is based on the probability of failure times the associated cost, Eqn (9), with respect to the same DMF is shown in Figure 12. It can be noticed that the most significant factor in reducing the consequence cost of structural failure is the thickness, followed by the length and the block coefficient of the ship.

Figure 12 also shows that a very high correlation between the cost of structural failure as a function of the thickness and length of the ship exists, estimated as 0.81 and practically no-correlation, about 0.01, between other relationships is observed.

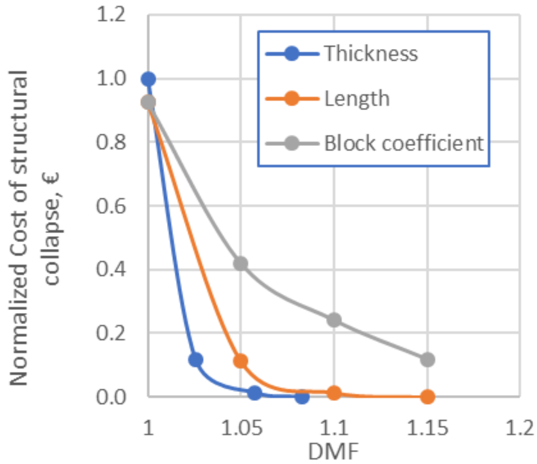

Figure 12 Cost of structural collapse as a function of DMFs

9 RISK MANAGEMENT FOR DECISION MAKING

Coupling the risk control to the risk assessment, a risk management may be performed. The risk management is a process of making decisions for safety, regulatory changes, and choose different system structural configurations based on the output generated in the risk assessment.

The risk management requires an optimal allocation of the available capacity in supporting the objective and design functionality of the ship hull structural system. It also requires the definition of the acceptable risk level, and a comparative evaluation of alternative options for decision making. The goal of the management is to reduce the risk to an acceptable level.

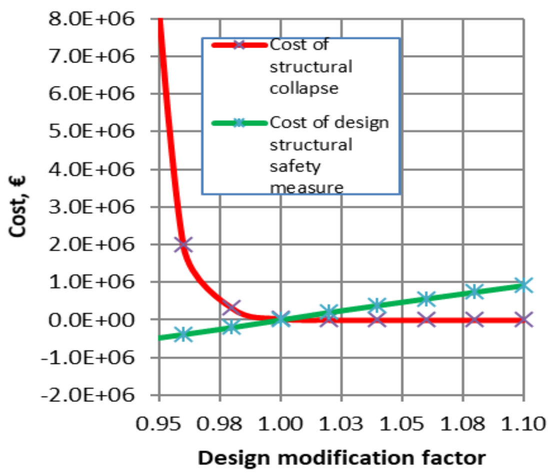

Figure 13 Cost of ship hull structural collapse and safety measure as a function of DM_2

The cost of ship hull structural collapse and design structural safety measure as a function of DMF are shown in Figure 13. It can be noticed that the cost of the control design structural safety measure equals to the cost of the ship hull structural collapse (consequence cost) at $DMF_2 \approx 1$, where the associated beta reliability index is the same and the crossing point may be assumed as an optimal risk value.

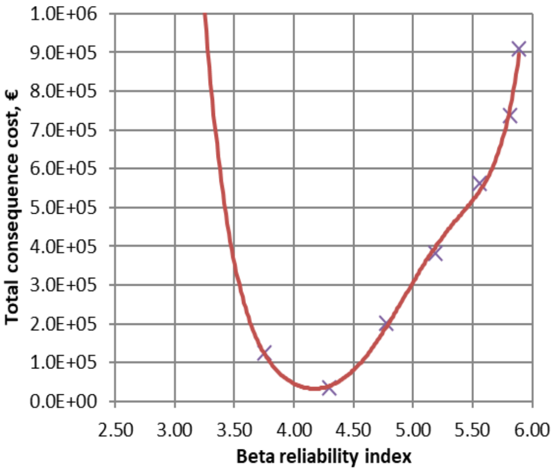

Figure 14 Total consequence cost, DMF_2

The range of target beta reliability index, β_t at the τ_Sth year of service life of the ship hull structural system may vary between 1.5 and 5. The target beta reliability index is estimated by minimizing the total consequence cost, C_t defined as a function of the beta reliability index. The optimum/target reliability index is shown in Figure 14, where $\beta_t = 4.296$, corresponding to the minimum of the curve of the total consequence cost, $C_t(\beta)$.

A code calibration is a commonly used approach providing the means to design on previous experiences. It can be used to determine the implied reliability and risk levels in the code, then the target levels can be set in a consistent manner to be used in future designs (see Figure 15).

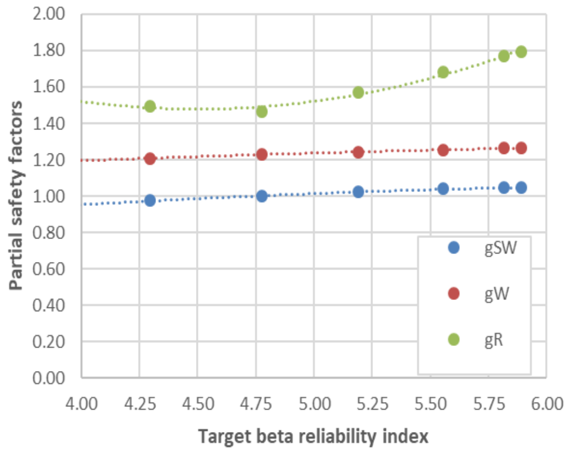

Figure 15 Partial safety factors

The partial safety factors, γ_R, γ_{SW}, γ_W are estimated based on the characteristic values of the ultimate, still water and wave-induced bending moments $M_U{}^c$, $M_{SW}{}^c$ and $M_W{}^c$, estimated at the 5% and 95% confidence level of the original probability density functions and the design values of all parameters involved in the limit state functions, $M_U{}^*$, $M_{SW}{}^*$, $M_W{}^*$, $x_U{}^*$, $x_{SW}{}^*$, $x_W{}^*$ and $x_S{}^*$ respecting the target reliability beta index level, β_t:

$$\gamma_R = M_U{}^C/(x_U{}^* M_U{}^*),\ \gamma_{SW} = (x_U{}^* M_{SW}{}^*)/M_{SW}{}^C,\ \gamma_W = (x_S{}^* x_W{}^* M_W{}^*)/M_W{}^C \quad (15)$$

The resulting partial safety factors can be used in the preliminary design, conditional on the imposed target reliability index, which represents an acceptable risk level and minimum cost by satisfying the following design criterion:

$$M_u/\gamma_R \geq \gamma_{SW} M_{SW} + \gamma_W M_W \quad (16)$$

The estimated partial safety factors for the analysed ship hull structural system are presented in Figure 15, where for the target beta reliability index, $\beta_t = 4.296$, the partial safety factors for still water, wave-induced and ultimate bending moments are $\gamma_{SW} = 0.974$, $\gamma_W = 1.208$, $\gamma_R = 1.496$.

CONCLUSIONS

A sensitivity analysis using a risk-based framework for the conceptual ship design of a multi-purpose vessel was performed here evaluating the impact of three types of design modification factors related to ship design, structural scantling and cost descriptors. The sensitivity analysis demonstrated that the structural redesign factor and length and block coefficient of the ship have the most significative impact on the RFR, reliability and structural collapse consequence cost. Safety factors that can be used in the preliminary ship design, conditional on the imposed target reliability index, which represents an acceptable risk level and minimum cost were also developed. It has been also shown that the sensitivity analysis, which identifies the importance of the ship design parameters can be used to calibrate the target reliability level.

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REFERENCES

Carlton, J. S. 1994. *Marine Propellers and Propulsion*.

Chen, Y. 1999. *Formulation of a Multi-Disciplinary Design Optimization of Containerships.* Faculty of the Virginia Polytechnic Institute and State University.

COMREL. 2017. Available: http://www.strurel.de/index.html.

Damyanliev, T. P., Georgiev, P. & Garbatov, Y. 2017. Conceptual ship design framework for designing new commercial ships. *In:* Guedes Soares, C. & Garbatov, Y. (eds.) *Progress in the Analysis and Design of Marine Structures.* London: Taylor & Francis Group, 183-191.

Deb, K., Pratap, A., Agrawal, S. & Meyarivan, T. 2002. A Fast and Elitist Multi-objective Genetic Algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6, 182-197.

Garbatov, Y. & Georgiev, P. 2017. Optimal design of stiffened plate subjected to combined stochastic loads. *In:* Guedes Soares, C. & Garbatov, Y. (eds.) *Progress in the Analysis and Design of Marine Structures.* London: Taylor & Francis

Group, 243-252.
Garbatov, Y. & Guedes Soares, C., 2016, Reliability assessment of a container ship subjected to asymmetrical bending, Proceedings of the 13rd International Symposium on Practical design of ships and other floating structures (PRADS2016), Copenhagen, Denmark, Paper D155.
Garbatov, Y., Guedes Soares, C. & Wang, G. 2007. Nonlinear Time Dependent Corrosion Wastage of Deck Plates of Ballast and Cargo Tanks of Tankers. *Journal of Offshore Mechanics and Arctic Engineering,* 129**,** 48.
Garbatov, Y., Ventura, M., Georgiev, P., Damyanliev, T. P. & Atanasova, I. 2017a. Investment cost estimate accounting for shipbuilding constraints. *In:* Guedes Soares, C. & Teixeira, A. (eds.) *Maritime Transportation and Harvesting of Sea Resources.* London: Taylor & Francis Group, 913-921.
Garbatov, Y., Ventura, M., Guedes Soares, C., Georgiev, P., Koch, T. & Atanasova, I. 2017b. Framework for conceptual ship design accounting for risk-based life cycle assessment. *In:* Guedes Soares, C. & Teixeira, A. (eds.) *Maritime Transportation and Harvesting of Sea Resources.* London: Taylor & Francis Group, 921-931.
Guedes Soares, C., Dogliani, M., Ostergaard, C., Parmentier, G. & Pedersen, P. T. 1996. Reliability Based Ship Structural Design. *Transactions of the Society of Naval Architects and Marine Engineers (SNAME),* 104**,** 359-389.
Guedes Soares, C. & Garbatov, Y. 1999. Reliability of maintained, corrosion protected plates subjected to non-linear corrosion and compressive loads. *Marine Structures,* 12**,** 425-445.
Guedes Soares, C. & Moan, T. 1988. Statistical Analysis of Still-Water Load. Effects in Ship Structures. *Transactions of the Society of Naval Architects and Marine Engineers (SNAME),*, 96**,** 129-156.
Guia, J., Teixeira, A. P. & Guedes Soares, C. 2016. Sensitivity analysis on the optimum hull girder safety level of a Suezmax tanker. *In:* Guedes Soares, C. & Santos T. A. (eds.) *Maritime Technology and Engineering 3.* London, UK: Taylor & Francis Group, 823-830.
Hasofer, A. M. & Lind, N. C. 1974. An exact and invariant first-order reliability format. *Journal of Engineering Mechanics Division, ASUE,* 100**,** 111-121.
Holtrop, J. & Mennen, G. G. J. 1982. An approximate power prediction. *International Shipbuilding Progress,* 29**,** 166 - 170.
Horte, T., Wang, W. & White, N. 2007. Calibration of the hull girder ultimate capacity criterion for double hull tankers. *Proceedings of the 10th International symposium on practical design of ships and other floating structures (PRADS),*. Houston, USA, 235-246.
IACS 2015. Common Structural Rules for Bulk Carriers and Oil Tankers. London: International Association of Classification Societies.
IMO 2002. Consolidated text of the guidelines for formal safety assessment (FSA) for use in the IMO rule-making process. *MSC/Circ.1023/MEPC/Circ.392.* 4 Albert Embankment, London SE1 7SR: International Maritime Organization Publishing.
IMO 2005. Amendments to the guidelines for formal safety assessment (FSA) for use in the IMO rule-making process. *MSC/Circ.1180-MEPC/Circ.474.* 4 Albert Embankment, London SE1 7SR: International Maritime Organization Publishing.
IMO 2008. Formal safety assessment on crude oil tankers. 4 Albert Embankment, London SE1 7SR.
IMO 2013. Revised guidelines for formal safety assessment (FSA) for use in the IMO rule-making process. *MSC-MEPC.2/Circ.12.* 4 Albert Embankment, London SE1 7SR: International Maritime Organization Publishing.
ITTC. 1978. *ITTC Performance Prediction Method* [Online]. Available: http://ittc.sname.org/2002_recomm_proc/7.5-02-03-01.4.pdf. [Accessed 13 10 2013].
Komuro, R., Ford, E. D. & Reynolds, J. 2006. The use of multi-criteria assessment in developing a process model. *Ecological Modelling,* 197**,** 320-330.
MARS2000 2011. Bureau Veritas, Rules for the Classification of Ships and IACS Common Structural Rules for Bulk Carriers and Tankers, Bureau Veritas.
Messac, A. & Mullur, A. A. 2007. Multiobjective optimization: Concepts and methods, Chapter 4. *Optimization of structural and mechanical systems.*
Montewka, J., Goerlandt, F. & Kujala, P. 2014. On a systematic perspective on risk for formal safety assessment (FSA). *Reliability Engineering & System Safety,* 127**,** 77–85.
Papanikolaou, A. D., Guedes Soares, C., Jasionowski, A., Jensen, J. J., McGeorge, D., Poylio, E. & Vassalos, D. 2009. *Risk-Based Ship Design,* Springer.
Patullo, R. N. M. & Thomson, G. R. 1965. The BSRA Trawler Series Beam-Draught and Length-Displacement Ratio Series resistance and propulsion tests.: RINA.
Psaraftis, H. N. 2012. Formal Safety Assessment: an updated review. *Journal of Marine Science and Technology,* 17**,** 390-402.
Silva, J. E., Garbatov, Y. & Guedes Soares, C. 2014. Reliability assessment of a steel plate subjected to distributed and localized corrosion wastage. *Engineering Structures,* 59**,** 13-20.
Sørgard, E., Lehmann, M., Kristoffersen, M., Driver, W., Lyridis, D. & Anaxgorou, P. 1999. Data on consequences following ship accidents. *Safety of shipping in coastal waters (SAFECO II).* DNV.
Wong, J. Y. Q., Sharma, S. & Rangaiah, G. P. 2015. Design of Shell-and-Tube Heat Exchangers for Multiple Objectives using Elitist Non-dominated Sorting Genetic Algorithm with Termination Criteria.