Framework for conceptual ship design accounting for risk-based life cycle assessment

Y. Garbatov, M. Ventura & C. Guedes Soares
Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

P. Georgiev
Technical University of Varna, 1, Studentska Str. UPB, 201, Varna, Bulgaria

T. Koch
Atlantec Enterprise Solutions GmbH, Oehleckerring 13 - 22419 Hamburg, Germany

I. Atanasova
Varna Maritime Ltd, 14 Orel str, Varna 9003, Bulgaria

ABSTRACT: This work develops a framework for conceptual ship design, accounting for the risk-based life cycle assessment. The framework deals with the conceptual ship design, risk-based target structural reliability assessment, risk-based maintenance, fast hull geometry prototyping and shipbuilding management. The developed framework, that will integrate different tools, does not address the requirements of one specific SME shipyard. Any potential shipyard can use the framework by providing the input information in terms of the building capacity and labour cost of new buildings and the framework will provide the required design solutions. The SME shipyard may also study what kinds of measures are needed to upgrade the already implemented technology and infrastructure so that the new ship design may be built.

1 INTRODUCTION

The framework presented here accounts for the time needed to run specialized software and the degree of expertise required for the use of advanced software in reduced time in the early stage of design. This issue is even more pronounced in the conceptual design, where a very rapid answer to the owner requirements is needed and a commitment may be made about the price of the ship.

Normally in the conceptual design, the naval architects, especially in SME shipyards, work with their worksheet developed using their long-time experience and statistics to make the first estimate of the main dimensions and hull form coefficients in estimating areas and volumes, system groups´ weights, resistance and propulsion, initial stability, seakeeping, free-board etc. leading to the estimation of CAPEX and OPEX and expected freight rate.

This framework covers conceptual ship design and optimization in terms of naval architecture (main ship dimensions) and marine engineering systems. Special focus is attributed to shipbuilding limitations of an SME shipyard in terms of engineering specification, construction and operational costs. The framework is based on the use technologies embedded in existing software applications. Those will be integrated with software able to perform LCCA (Life Cycle Cost Analysis) from the conceptual ship design stage (see Figure 1) to a more advanced one.

A data management system is to be developed in the software tool by collecting and analysing historical up-to-date data and applying quantitative models (estimating relationship) to perform forecasting.

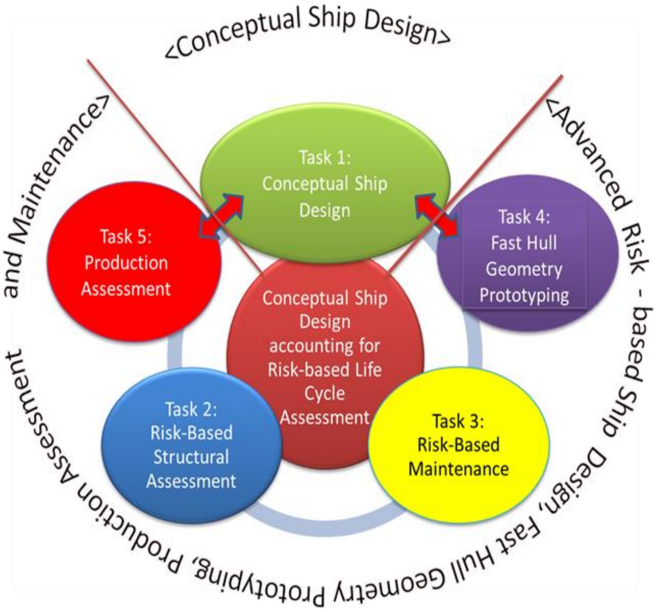


Figure 1 Framework for conceptual design accounting for risk-based LCA 2

The developed tool does not address the requirements of one specific shipyard. Any potential shipyard can provide information in terms of the building capacity and labour cost of new buildings. The shipyard may also study what kind of measures are needed to upgrade the already implemented technology and infrastructure so that this ship may be built and to be accounted for in the development of the CAPEX model.

2 CONCEPTUAL SHIP DESIGN

Conceptual ship design assesses the owner's specification requirements (ship type, DWT /TEU, speed, data of a similar ship, etc.), life cycle cost, including CAPEX and OPEX, structural reliability and shipyard capabilities. Specification requirements will consider aspects that may relate to ship hull descriptors, propulsive power, lightweight, dead weight, cargo capacity, free board, initial stability, seakeeping, midship section design, and ultimate strength assessment, including still water and wave-induced loads as well as the probability of progressive structural failure.

Shipyard capabilities will consider investing shipbuilding costs in terms of materials, equipment, human factors and project management. Due to the large number of items that need to be considered the Pareto optimization algorithm may be employed to conclude on the best design choice in defining the main characteristics of the ship (L, B, T, D, v, C_b, C_w, C_p, C_m etc.). Uncertainties originating from different sources will be accounted for in the project cost management and structural reliability.

The output will be a multi-objective (CAPEX, OPEX, expected freight rate, etc.) optimized ship model.

2.1 *Initial technical specification*

The design is defined as a compromise decision support problem with multiple goal constraints and the problem is formulated based on the owner's requirements related to the cargo deadweight, speed, range, regulations and if there exists data on similar ships to determine the ship main dimensions and some hull form coefficients (Parson, 2003, Damyanliev et al., 2017).

The design solution should satisfy system constraints such as the compliance with the minimum free-board and metacentric height as determined by the IMO criteria, natural period of roll greater than the period of encounter relevant to roll, natural period of heave greater than k per cent of the period of encounter relevant to heave; that is ship operates in super critical region, natural period of pitch is greater than n per cent of the period of encounter relevant to pitch; that is ship operates in super critical region, dimensional ratios L/B, L/D, L/T, B/D, B/T, T/D are within the limits that reflect the designer's experience-based insight.

The design problem is defined with multiple objectives and linear and nonlinear constraints and a suitable solution is determined by computer methods. The used optimization techniques are normally categorized in three forms: mathematical programming techniques such as the genetic algorithm; stochastic process techniques such as the Markov process; statistical methods such as the design of experiments (Rao, 2009). The choice of which optimization technique to be used depends on the type of the optimization problem, number of design variables, interaction of design variables, numerical tools used to perform simulations etc. (Ruas & Ventura, 2012, Ventura, 2014, Merino da Silva & Ventura, 2015, Ventura & Guedes Soares, 2015).

The optimization procedure may generate a feasible region of all possible design points, but not all design solutions are optimal for any given objective function and this results in a trade-off between the objective functions (Keane et al., 1991). To address the problem caused by the multiple objective functions, the Pareto frontier optimality may be employed (Komuro et al., 2006). The Pareto frontier is a set of all Pareto optimal solutions represented in the design space. Each Pareto optimal solution can be defined as a solution for which any improvement in one objective will result in the worsening of at least in one other objective (Messac & Mullur, 2007).

By analysing the Pareto Frontier, an optimal solution accounting for the existing constraints may be chosen using a utility function to rank the different designs, or by using 2D or 3D scatter diagrams to identify the more attractive ones. An additional constraint can also be introduced to represent the reliability to choose the most appropriate design solution (see Figure 2).

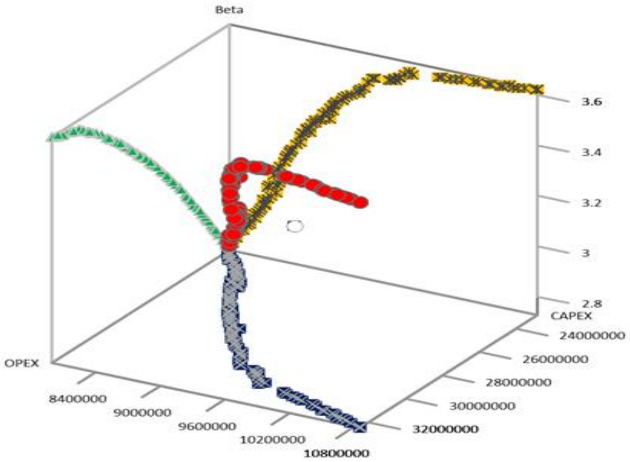


Figure 2 Pareto optimal solutions

2.2 *Design modules*

The mathematical model of Holtrop and Mennen (1982) is widely used in the conceptual design and it can provide an estimation of the hull resistance and propulsive power demand, which can be used to select a propeller engine set (Carlton, 1994). The Holtrop's models are also used to predict values for wake fraction coefficient and resistance increase (thrust deduction factor). As an alternative, other methods such as (ITTC, 1978) or BSRA (Patullo & Thomson, 1965) can also be applied.

The lightship weight and deadweight estimation of every category/type of ship components, with sufficient comparative data from similar ships on vessel's displacement needs to be employed.

The free-board can be approximated by a parabolic curve regression of the tabular values from the International Convention on Load Lines. Additionally, the corrections due to the block coefficient, depth, sheer profile and superstructure effective length need to be taken into account. The last two characteristics may also be based on the parent ship (IMO, 2005b).

Ship's transverse stability depends upon the metacentric height, which is calculated based on the vertical position of the centre of mass and of the centre of buoyancy, as well as the metacentric radius. An analytical model, based on a simplified geometric representation of the ship hull may be used for the estimation of the position of the buoyancy centre and of the metacentric radius.

Parameter estimates of the cost (CAPEX and OPEX) are based on design parameters such as ship size, weight, propulsion type, propulsive power, etc. This analysis uses a mathematical relationship between the input parameter and the cost that is historically determined through the regression analysis.

A CAPEX breakdown divides costs into material, labour, overhead, and profit. Material involves all shipyard purchases such as materials, equipment, subcontracted work, outside engineering services, etc. The labour includes wages and benefits paid to shipyard employees whose work is directly connected with a ship. Overhead is the sum of all internal shipyard costs that cannot be directly attributed to any individual contract (Benford, 1967, Erichsen, 1971).

The coefficients used in the regression equations to estimate the cost groups depend of the type of ship, owner requirements, material used for construction, labour cost, production technological profile of the shipyard in concerns and the cost driven by the market. These factors need to be adjusted at the moment of performing the analysis with respect to the present conditions.

OPEX cost depends of operational profile of the ship. There are some difficulties in defining CAPEX and OPEX and this is explained by the fact that is necessary to account for the factors that could result in the cost changes in order to enhance the forecast. This becomes a very important issue mainly due to the quite a long in-service time of ships and the change of prices in such a long period. Cost estimate uncertainties

3 RISK-BASED STRUCTURAL RELIABILITY

The analysis here focuses on the progressive collapse and the related probability of structural failure as well as the cost of the progressive collapse consequences, structural measures, human life, loss of cargo, accidental spills, where the last two are related to the environmental impact. Main challenges here are the development of a database summarizing the cost related parameters and the link of these parameters to the specific ship application in terms of forecast. The output will be a target structural reliability to which the design structural reliability needs to comply.

The safety is defined as a trade-off between the life cycle cost of the ship and different hazard issues during the service life. In this context, safety becomes a key aspect in ship design with serious economic consequences. Complying with the regulations as a primary concern, the safety becomes a driving force in the design process, where the tendency is to adopt a more holistic and proactive approach of safety, with the introduction and development of the Formal Safety Assessment (FSA) and Goal-based standards (GBS) at IMO. In this respect, several documents were published (IMO, 2002, 2005a, 2006a, b, 2007, 2008, 2013).

As part of the FSA methodology, the cost effectiveness analysis (CEA) and cost benefit analysis (CBA) allow the equilibrium of risk and costs in the design process, where the risk property incorporates the structural collapse, environmental pollution and loss of human lives in open sea.

3.1 *Stochastic models of ultimate strength and load*

The midship section scantlings and the ultimate capacity are estimated using the progressive collapse method as stipulated in (IACS, 2006). An example of a progressive collapse assessment is shown in Figure 3.

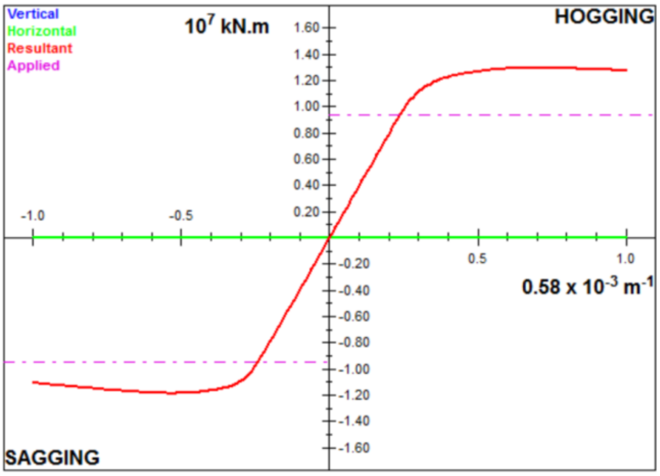


Figure 3 Progressive collapse assessment

The still water bending moment is normally fitted to a Normal distribution. The statistical descriptors of the still water bending moment can be defined by the regression equations as a function of the length of the ship, L and dead-weight ratio, W= (DWT/Full load) as proposed in (Guedes Soares & Moan, 1988). An example of PDF of still water bending moment of different loading conditions is shown in Figure 4.

The stochastic model of the vertical wave-induced bending moment as proposed in (Guedes Soares et al., 1996) is employed here. The distribution of the extreme values of the wave-induced bending moment at a random point of time, over a specified time period, is assumed as a Gumbel distribution, considering that the wave induced bending moment can be represented as a stationary Gaussian process (short-term analysis), then the wave induced bending moment, M_{vw} as given by the Classification Societies Rules may be modelled as a Weibull distribution with a probability of exceedance of 10^{-8}.

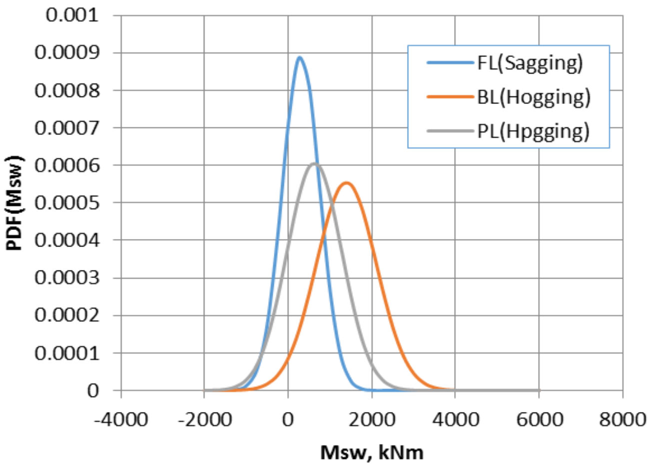


Figure 4 PDF of still water bending moment

The Gumbel distribution, for the extreme values of the vertical wave-induced bending moment, over a reference period is derived based on the Weibull distribution function. An example of PDF of wave-induced bending moment is shown in Figure 5.

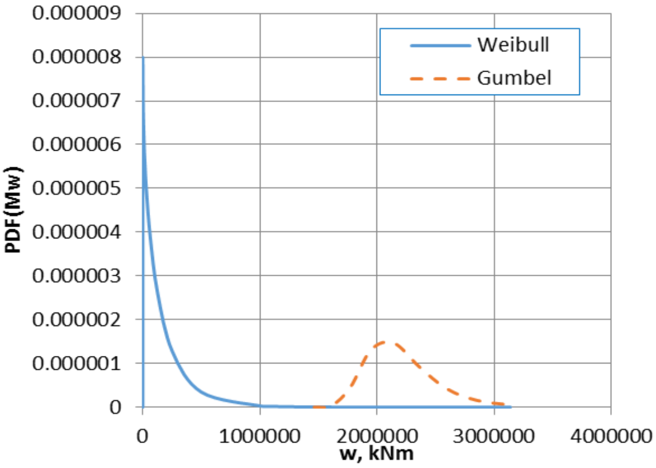


Figure 5 PDF of wave-induced bending moment

The stochastic model of the ultimate strength can be defined based on the 5% confidence level value of the ultimate bending moment, $M_u^{5\%}=M_u^c$ assumed as a characteristic one and may be calculated for an example 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 (Garbatov & Guedes Soares, 2016a).

3.2 *Structural reliability*

The probability of structural collapse here is estimating by using the FORM techniques (Hasofer & Lind, 1974).

The FORM methods provide a way of evaluating the probability of structural failure efficiently with a reasonably good accuracy, which is adequate for practical applications (Hasofer & Lind, 1974, Rackwitz & Filessler, 1978, Ditlevsen, 1979).

Using the FORM technique and the ultimate strength analysis of the ship hull, the limit state equation may be defined as:

$$g(\mathbf{X}) = M_u X_u - \left(M_{sw} X_{sw} + \Psi_w X_w X_{nl} M_{vw}\right) \qquad (1)$$

where M_u is the ultimate capacity with a model uncertainty factor X_u, M_{vw} is the vertical wave-induced bending moment. Ψ_w is a combination factor between the still water and wave induced bending moments. The model uncertainty factor X_w accounts for the uncertainties in the linear response calculation, and X_{nl} for the nonlinear effects. M_{sw} is the still water bending moment with a model uncertainty factor X_{sw}.

The ultimate capacity is estimated using the progressive collapse method as stipulated in (CSRBC, 2012) and the associated probability of structural collapse.

A design modification factor (DMF) is employed to allow the design to be modified in a realistic way and identify the effect on the ultimate capacity of the structure for the purpose of estimating the optimal reliability. A change in the ultimate strength is most effectively achieved by DMF that modifies the dimensions of the stiffeners and the thicknesses of the most sensible part of the structures (Horte et al., 2007). An example of design scantling modifications and resulting ultimate strength is shown in Figure 6.

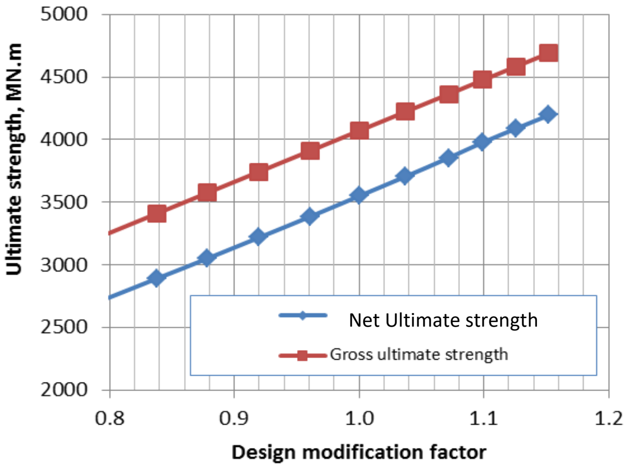


Figure 6 Design scantling modifications

3.3 *Cost of failure*

The ship's optimal safety level is assessed by performing a cost benefit analysis (CBA). The objective is to establish an optimal safety level identified as a risk control option (RCO) the change in the initial midship section design scantlings.

The total expected cost is the sum of two distinct costs, one, the cost associated with the structural collapse of the ship and the other the cost of implementing the risk control option, RCO. The first involves costs associated with the progressive collapse, environmental pollution and loss of human life, while the second involves the costs related to CAPEX of 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, a cost effectiveness analysis is performed (Horte et al., 2007)

The cost associated with the structural failure is the cost associated with 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 structural collapse is estimated considering the service life of the ship and a discount rate of γ.

In the present analysis, the cost of implementing a safety measure accounts for the modification of the midship section structure, accounting for the cost of material and labour.

The cost associated with the loss of cargo is estimated by considering a percentage of the total amount of cargo of the ship in the case of structural failure.

The implied cost of averting a fatality, ICAF used in the risk model here may be obtained from the average of OCDE (2014) countries. The optimum ICAF value may be derived from the Life Quality Index, LQI, which is defined as a function of the GDP per capita.

The loss of human life is accounted for by including the ICAF in the objective function as suggested in (Horte et al., 2007).

An example of the cost of structural collapse and safety measure can be seen in Figure 7.

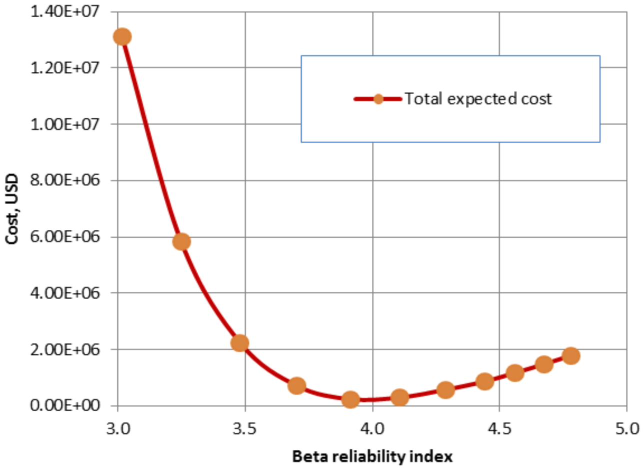


Figure 7 Optimal structural reliability

The range of target reliability indexes, i.e. the target reliability index, β_t at the 25th year of service life of the ship can vary between 1.5 and 5. The corresponding annual probability of failure, P_f is calculated as $P_f=\Phi^{-1}(-\beta_t)$, where Φ represents the standard normal probability distribution.

The optimum/target reliability index is estimated by minimizing the total cost object function as can be seen in Figure 7, where β_{opt} is 3.91, corresponding to the minimum of the curve of the total expected cost.

4 RISK-BASED MAINTENANCE

Voyage simulations will help to analyse the influence of ship operations in terms of cost, safety and efficiency accounting for the severity of the environmental conditions. For an example, based on the route specified, the environmental conditions will be taken into a consideration. In this way, the cost of preventive and corrective maintenance will be estimated with the aim to optimize vessel operations (i.e. to minimize downtime / maximize availability).

Here a database about the structural degradation and preventive and corrective maintenance costs is needed and linked to the application so as to provide a forecast of the governing cost and degradation parameters. The output will be a maintenance plan that will aim to govern OPEX. It has to be noted that the maintenance planning may result in redesign of the ship.

Planning of ship structural maintenance in the past has been done based on structural reliability approaches (Guedes Soares & Garbatov, 1998) involving models that represent the time development of corrosion deterioration as proposed in (Garbatov et al., 2007). This model is able to describe an initial period without corrosion due to the presence of a corrosion protection system, a transition period with a nonlinear increase of wastage up to a steady state of long-term corrosion wastage.

This type of model combined with models of probability of detection during inspections is the basis of reliability based maintenance planning of marine structures that have been developed in (Garbatov & Guedes Soares, 2008a, 2010).

Earlier approaches were based on using structural reliability theory combined with models of the structural degradation with time. The approach employed here is based on the statistical analysis of the corrosion wastage data leading to probabilistic models of time to fail, which are used as a basis for maintenance decisions.

The classical theory of the system maintenance describes the failure of structural components by probabilistic models often of the Weibull family, which represent failure rates in operational phases and in the aging phases of the life of components as described in various textbooks (Moubray, 1997, Rausand, 1998).

The approach applied here is based on the historical data of thickness measurements or corresponding corrosion wastage thickness. Based on the progress of corrosion, critical corrosion levels are defined as “failure”, which is modelled by a Weibull distribution.

Corrosion data of deck plates collected in (ABS, 2002) are used here as an example. The analysis demonstrates how this data can be used to address important issues such as inspection intervals, condition based maintenance action and structural replacement. An effort is made to establish realistic decisions about when to perform maintenance on the structure that will reach a failed (corroded) state. Different scenarios are analysed and optimum interval and age structural replacements are also demonstrated.

The approach applied here has been supported by the recent studies reported in (Garbatov & Guedes Soares, 2008b, 2009a, b, 2016b). Four different levels of censoring related to the failure state of corroded plates are introduced here as an example: low corrosion tolerance, moderate corrosion tolerance, high corrosion tolerance and extreme corrosion tolerance respectively. The corrosion tolerance levels are set up here as permissible corrosion levels and any time at which corrosion depths may reach them is classified as a complete failure and others are censored as can be seen in Figure 8.

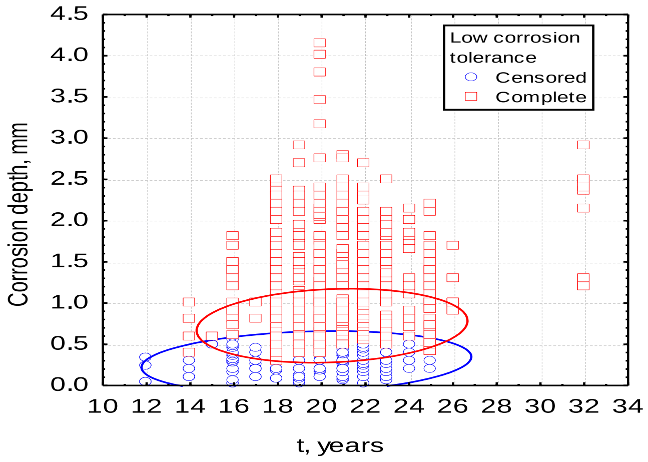


Figure 8 Low corrosion tolerance (Garbatov & Guedes Soares, 2009b)

The statistical descriptors of the Weibull distribution for the different levels of corrosion tolerance limits, defined here as low, moderate, high and extreme corrosion tolerance.

A major part of the operating expenditures are the maintenance costs during the vessel’s lifecycle. In general this cost contributes to 25%-35% of the total operating expenditures, OPEX (Turan et al., 2009). It depends on many factors, including the quality of the work delivered by the new build shipyard, the geographical location of the vessel, its access to periodic maintenance, operational profile, etc.

When necessary, the replacement durations can be incorporated into the replacement model, as is required when the goal is the minimization of the total downtime or, equivalently, the maximization of the availability. However, any cost that is incurred due to the replacement needs to be included as a part of the total cost before failure or in the total cost of a failure replacement.

It is important to create a procedure for analysing the potential failure by classifying the severity or the effect of failures on the structure, which is widely used in many industries during various phases of the service life (DoD, 1984, Kececioglu, 1991, Langford, 1995).

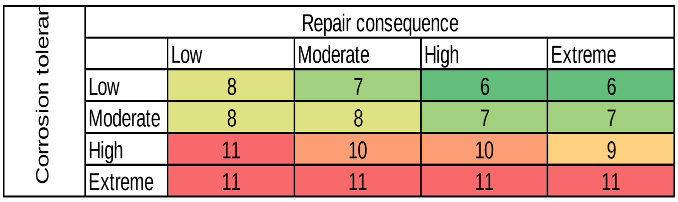
A failure mode may be defined as the manner by which a failure is observed and it generally describes how the failure occurs. Tools used in the design stage for identifying failures and determining their consequences are risk priority numbers, occurrence/severity matrix, risk ranking tables and criticality analysis.

These methods are adapted to identify the total cost of a replacement before failure, total cost of a replacement after failure, preventive replacement interval, failure replacement interval, time for inspection, and time required to make a repair or replacement. The present approach accounts for the corrosion tolerance, consequence of preventive replacement, consequence of failure/corrective replacement, consequences of replacements accounting for the inspection interval and the time required to make a repair or replacement. These factors may be defined based on the statistical analysis of data on real observations or by an expert judgment.

The replacement policy is one where replacements occur at fixed intervals of time; failure replacements occur whenever necessary. The problem is to determine the optimal interval between the replacements and to minimize the total expected cost of replacing the corroded plates per unit time. Several solutions as examples are shown here.

To determine the optimal interval between replacements the total expected replacement cost per unit time is minimized. An example of the optimal preventive replacement intervals is given in Table 1.

Table 1 Optimal preventive replacement interval, years



Corrosion tolera		Repair consequence			
		Low	Moderate	High	Extreme
	Low	8	7	6	6
	Moderate	8	8	7	7
	High	11	10	10	9
	Extreme	11	11	11	11

5 FAST HULL GEOMETRY PROTOTYPING

The fast hull geometry prototyping will be able to produce a hull form as a function of the intended main dimensions, some form coefficients and a number of shape parameters associated with each of the main ship types. The process will start by producing a midship section and a number of longitudinal curves (flat of bottom, flat of side, sectional area curve, etc.) defined parametrically. These curves control the variation of the shape along the length in order to obtain a number of cross-sections describing a hull with the intended dimensions and hydrostatic properties.

The objective here is not to obtain a faired hull form, but a numeric description of the hull form that will guarantee, by comparison with the empirical estimating formulas, not only a rather improved accuracy in the computations of hydrostatic properties and stability, but also the possibility to consider the ship at draughts other than design draught.

Additionally, by specifying a number of parameters characterizing the internal layout in the cargo area (type of section configuration, height of the double bottom, width of the side tanks, etc.) it will be possible to compute approximately the cargo and ballast volumes and the respective centroids in the cargo area (Ventura & Guedes Soares, 1998, Varela et al., 2009, Varela et al., 2011, Ventura & Guedes Soares, 2011, Jafaryeganeh et al., 2016). This information will allow, at the concept design, much improved estimates of the ship equilibrium position and of the intact stability at different load conditions (fully loaded, partially loaded, ballasted, etc.), extending.

An approach (Georgiev & Kolev, 2015) that can be employed for a fast ship hull prototyping is based on the transformation of an existing parent hull combining the scaling and Lackenby (1950) transformation.

Figure 9 and Figure 10 show the parent ship hull and the corresponding transformation with an increased ship slenderness.

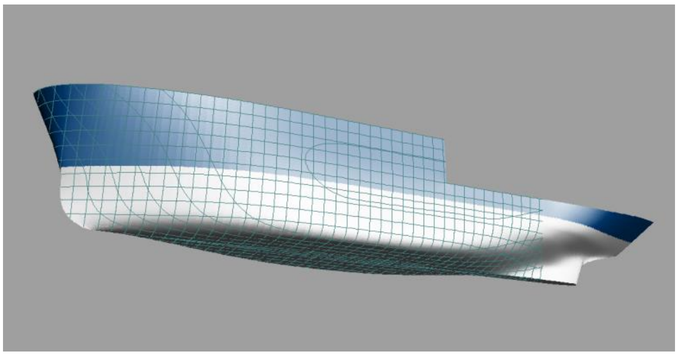


Figure 9 Parent hull form

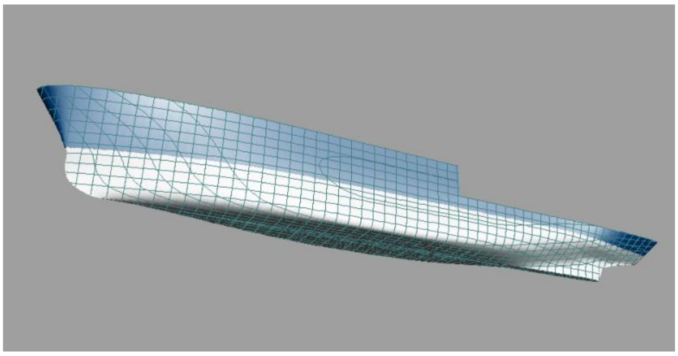
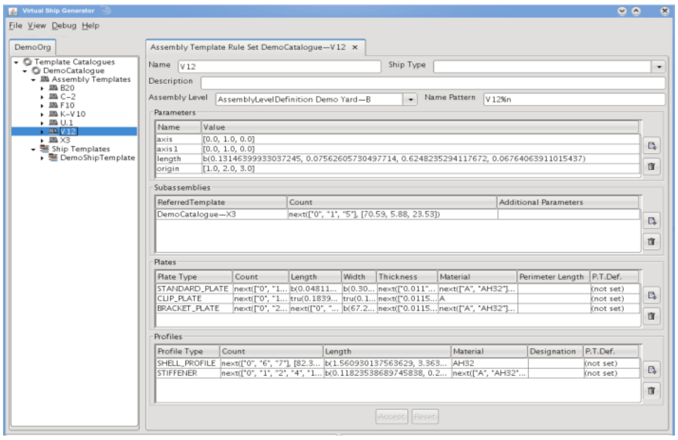


Figure 10 Transformation of the parent hull form with an increased ship slenderness

6 PRODUCTION ASSESSMENT

Production assessment is carried out in order to determine production properties such as material requirements, resource demands, and schedule and cost estimation at an early stage. As input, data is needed about the production tasks, expected work content and technologies involved. Since such data is usually not readily available at such early stages of design, particular attention is given to data generation. A specialised data generation step will use the design parameters defined so far to drive a generative process that is based on parametric structural templates to be combined with additional control data to steer the data generation process. Such templates will be applicable to hull production as well as outfitting related tasks.

Templates are maintained in a catalogue and can be provided in different ways. A prototype application for this is shown in Figure 11. A promising approach is based on the identification of structural patterns identified on the work break-down structure (Koch, 2011) or system layout of existing designs.



Name: V12
Ship Type:
Description:
Assembly Level: AssemblyLevelDefinition Demo Yard—B
Name Pattern: V12%n

Parameters

Name	Value
axis	[0.0, 1.0, 0.0]
axis1	[0.0, 1.0, 0.0]
length	b(0.13146399933037245, 0.07562605730497714, 0.6248235294117672, 0.06764063911015437)
origin	[1.0, 2.0, 3.0]

Subassemblies

ReferredTemplate	Count	Additional Parameters
DemoCatalogue—X3	next(["0", "1", "5"], [70.59, 5.88, 23.53])	

Plates

Plate Type	Count	Length	Width	Thickness	Material	Perimeter Length	P.T.Def.
STANDARD_PLATE	next(["0", "1...	b(0.04811...	b(0.30...	next(["0.011"...	next(["A", "AH32"]...		(not set)
CLIP_PLATE	next(["0", "1...	tru(0.1839...	tru(0.1...	next(["0.0115...	A		(not set)
BRACKET_PLATE	next(["0", "2...	next(["0", "...	b(67.2...	next(["0.0115...	next(["A", "AH32"]...		(not set)

Profiles

Profile Type	Count	Length	Material	Designation	P.T.Def.
SHELL_PROFILE	next(["0", "6", "7"], [82.3...	b(1.560930137563629, 3.363...	AH32		(not set)
STIFFENER	next(["0", "1", "2", "4", "1...	b(0.11823538689745838, 0.2...	next(["A", "AH32"...		(not set)

Figure 11 Template Library management

Alternatively, templates can be established by user input, which is useful for innovative designs involving unconventional solutions. In Figure 12, a pseudo-visualisation can be seen that provides the approximate geometric positioning and extent for production blocks.

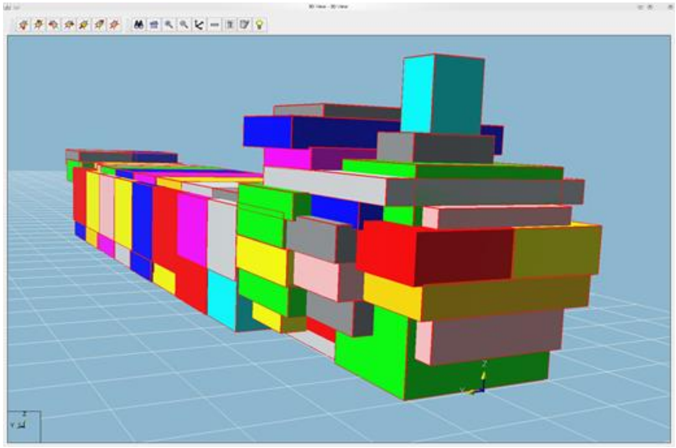


Figure 12 Generation production work load equivalent

The data generation process provides most of the necessary input to production scheduling and simulation. Using a hybrid approach of schedule optimisation and discrete-event simulation, an estimate of the bill of material, hull erection strategy, overall schedule for the supply chain and production. Consequently, it will also estimate the cost of manufacturing according to the particulars of each shipyard facility and practice. Based on the present analysis a subroutine will be implemented in the conceptual design. Figure 13 shows the overall flow of operations to carry out the production assessment simulation.

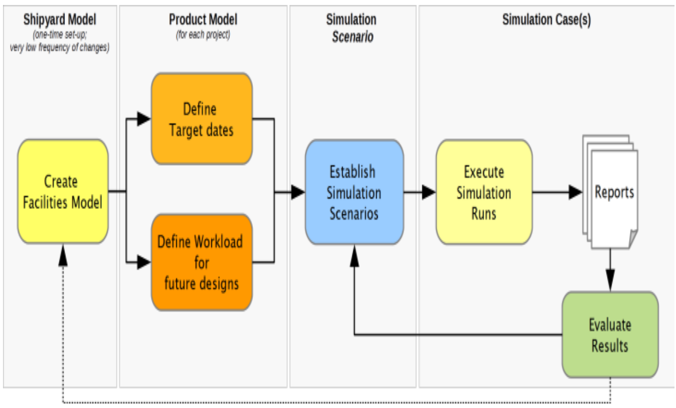


Figure 13 Production simulation workflow for conceptual design

It is important to note that the process fully supports the iterative methodology that needs to be applied in conceptual design. Thanks to the means of the data generation, modifications due to changes resulting from alternate design solutions will be easily adopted. Similarly, alternate production methods can be considered.

7 CONCLUSION

The framework for conceptual ship design accounting for risk-based life cycle assessment, covering the life cycle cost, environmental and risk assessments is developed here\. It approaches the shift of an SME shipyard from a mainly repair functionality to a new-construction functionality with a capacity to build new ships.

A special focus is attributed to the shipbuilding limitations of SME shipyards in terms of the engineering specification, construction, operational, maintenance and end life (scrap) costs in the life cycle optimization.

Retrofitting options can be considered for decommissioning. The greener design, accounting for the environmental impact, is taken into consideration in defining the target structural reliability level.

The framework can be employed to design ships in an early/concept design stage by SME shipyards accounting for their constructional capacity.

ACKNOWLEDGEMENT

This paper reports a work developed in the project ”Ship Lifecycle Software Solutions”, (SHIPLYS), which was partially financed by the European Union through the Contract No 690770 - SHIPLYS - H2020-MG-2014-2015.

8 REFERENCES

Abs 2002. Database of Corrosion Wastage for Oil Tankers. American Bureau of Shipping.

Benford, H. 1967. *The Practical Application of Economics of Merchant Ship Design*, The Society of Naval Architecture and Marine Engineering.

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

Csrbc 2012. Common Structural Rules for Bulk Carriers, Material, Ch 3, Section 1, Table 1.

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

Ditlevsen, O. 1979. Generalised second moment reliability index. *Journal of Structural Mechanics*, 7**,** 435-451.

Dod, U. S. 1984. Procedures for Performing a Failure Mode Effects and Criticality Analysis.

Erichsen, S. 1971. *Optimum capacity of ships and port terminals*, Ann Arbor, University of Michigan.

Garbatov, Y. & Guedes Soares, C. 2008a. Corrosion wastage modeling of deteriorated bulk carrier decks. *International Shipbuilding Progress*, 55**,** 109-125.

Garbatov, Y. & Guedes Soares, C. 2008b. Reliability of aged ship structures. *In:* Paik, J. & Melchers, R. (eds.) *Condition Assessment of Aged Structures.* Cambridge, UK: Woodhead Publishing Limited, 253-286.

Garbatov, Y. & Guedes Soares, C. 2009a. Corrosion wastage statistics and maintenance planning of corroded hull structures of bulk carriers. *In:* Guedes Soares, C. & Das, P. K. (eds.) *Analisys and Design of Marine Structures.* London, UK: Taylor & Francis Group, 215-222.

Garbatov, Y. & Guedes Soares, C. 2009b. Structural maintenance planning based on historical data of corroded deck plates of tankers. *Reliability Engineering & System Safety*, 94**,** 1806-1817.

Garbatov, Y. & Guedes Soares, C. 2010. Maintenance Planning for the Decks of Bulk Carriers and Tankers. *In:* Furuta, H., Frangopol, D. M. & Shinozuka, M. (eds.) *Reliability and risk of structures, infrastructures and engineering systems.* London, UK: Taylor & Francis Group, 3517-3524.

Garbatov, Y. & Guedes Soares, C. 2016a. 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. 2016b. Reliability of deteriorated marine structures based on measured data. *International Journal of Maritime Engineering*, 158.

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.

Georgiev, P. & Kolev, P. 2015. Influence of pre-defined non-dimensional ratios and affine mapping on ship properties. *In:* Guedes Soares, C., Dejhalla, R. & Pavleti, D. (eds.) *Towards Green Marine Technology and Transport.* London: Taylor & Francis Group, 483-491.

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. 1998. Reliability of maintained ship hull girders subjected to corrosion and fatigue. *Structural Safety,* 20, 201-219.

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.

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 2006. *Common structural rules for bulk carriers,* 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 2005a. 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 2005b. International Convention on Load Lines. *1966 and Protocol of 1988, as amended in 2003, Consolidated Edition.* 4 Albert Embankment, London SE1 7SR: International Maritime Organization Publishing.

Imo 2006a. FSA-Report of the correspondence group. *MSC 81/18.* 4 Albert Embankment, London SE1 7SR: International Maritime Organization Publishing.

Imo 2006b. Linkage between FSA and Goal-based new ship construction standards. *MSC 81/INF.6.* 4 Albert Embankment, London SE1 7SR: International Maritime Organization Publishing.

Imo 2007. Environmental risk evaluation criteria. *MEPC 56/18/1.* 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].

Jafaryeganeh, H., Ventura, M. & Guedes Soares, C. 2016. Parametric Modelling for Adaptive Compartment Design of Container Ships. *In:* Guedes Soares, C. & Santos, T. (eds.) *Marine Technology and Engineering 3.* London, UK:: Taylor & Francis Group, 655-663.

Keane, A. J., Price, W. G. & Schachter, R. D. 1991. Optimization Techniques In Ship Concept Design. *Transaction of the Royal Institute of Naval Architecture,* A.133, 123-129.

Kececioglu, D. 1991. *Reliability Engineering Handbook,* Englewood Cliffs, New Jersey, Prentice-Hall Inc.

Koch, T. Simulating the Production of Future Marine Products. Proceedings of the 10th International Conference on Computer and IT Applications in the Maritime Industries (COMPIT '11), 2011 Berlin, Germany. 98-108.

Komuro, R., Ford, E. D. & Reynolds, J. H. 2006. The use of multi-criteria assessment in developing a process model. *Ecological Modelling,* 197, 320-330.

Lackenby, H. 1950. On the Systematic Geometrical Variation of Ship Forms. *Transactions of INA,* 92, 289-315.

Langford, J. W. 1995. *Logistics: Principles and Applications,* McGraw Hill.

Mars2000 2011. *BUREAU VERITAS Rules for the Classification of Ships and IACS Common Structural Rules for Bulk Carriers and Tankers,* BV.

Merino Da Silva, D. & Ventura, M. 2015. Design optimization of a bulk carrier for river/sea ore transport. *In:* Guedes Soares, C. & Santos, T. A. (eds.) *Maritime Technology and Engineering.* London, UK: Taylor & Francis Group.

Messac, A. & Mullur, A. A. 2007. Multiobjective optimization: Concepts and methods, Chapter 4. *Optimization of structural and mechanical systems.*

Moubray, M. 1997. *Reliability centered maintenace,* Butterworth Heinemann.

Ocde 2014. OCDE Factbook-Economic, Environmental and Social Statistics. 96-106.

Parson, M. 2003. *Parametric Design*.

Patullo, R. N. M. & Thomson, G. R. 1965. The BSRA Trawler Series Beam-Draught and Length-Displacement Ratio Series resistance and propulsion tests.: RINA.

Rackwitz, R. & Filessler, B. 1978. Structural Reliability under Combined Random Load Sequences. *Computers & Structures,* 9, 489-494.

Rao, S. S. 2009. *Engineering optimization: theory and practice,* John Wiley & Sons.

Rausand, M. 1998. Reliability centered maintenance. *Reliability Engineering & System Safety,* 60, 121-132.

Ruas, J. & Ventura, M. 2012. Non-Linear Optimization Applied to Preliminary Ship Design. *In:* Guedes Soares, C., Garbatov, Y. & Sutulo, S. (eds.) *Maritime Engineering and Technology.* London, UK: Taylor & Francis Group.

Turan, O., Olcer, A., Lazakis, I., Rigo, P. & Caprace, J. 2009. Maintenance/repair and production-oriented life cycle cost/earning model for ship structural optimisation during conceptual design stage. *Ships and offshore structures,* 107-125.

Varela, J., Ventura, M. & Guedes Soares, C. 2011. Product Data Model of Hull Structures and Digital Prototyping System for Basic Structural Design. *Ships and Offshore Structures,* 6.

Varela, J. M., Ventura, M. & Guedes Soares, C. 2009. Digital Prototyping of Hull Structures in Basic Design. *Analysis and Design of Marine Structures.* London, UK: Taylor & Francis Group.

Ventura, M. 2014. Ship Dimensioning in the Initial Design. *In:* Guedes Soares, C. & Lopez Pena, A. (eds.) *Developments in Maritime Transportation and Exploitation of Sea Resources.* London, UK: Taylor and Francis Group, 531-539.

Ventura, M. & Guedes Soares, C. Hull Form Modelling Using NURBS Curves and Surfaces. *In:* Oosterveld, M. W. C. & Tan, S. G., eds. Proceedings of Practical Design of Ships and Mobile Units, 1998 The Hague, Netherlands. Elsevier, 289-296.

Ventura, M. & Guedes Soares, C. 2011. Geometric Modelling and Product Data Management in Ship Design. *In:* Guedes Soares, C., Garbatov, Y., Fonseca, N. & Teixeira, A. (eds.) *Marine Technology and Engineering.* London, UK: Taylor & Francis Group.

Ventura, M. & Guedes Soares, C. 2015. Integration of a voyage model concept into optimization procedure. *In:* Guedes Soares, C., Dejhalla, R. & Pavletic, D. (eds.) *Towards Green Marine Technology and Transport.* London, UK: Taylor & Francis Group, 539-548.