SENSITIVITY ANALYSIS OF THE TOOL FOR ASSESSING SAFE MANOEUVRABILITY OF SHIPS IN ADVERSE SEA CONDITIONS

Mizythras, P.[1], Boulougouris, E.[1], Priftis, A.[1], Incecik, A.[1], Turan, O. [1], Reddy D. N.[2]

[1] University of Strathclyde, Glasgow, United Kingdom
[2] Lloyd's Register, United Kingdom

ABSTRACT

In 2013, International Maritime Organization (IMO) introduced the Interim Guidelines for determining the minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions. Considering the sufficiency of propulsion system in adverse sea conditions, the European project SHOPERA has developed alternative processes and tools for assessing safe manoeuvrability of ships. The main objective of these procedures is to identify the critical conditions where the vessel maintains its course keeping and manoeuvring ability at the vessel available propulsion power by using basic ship design values as input into the simplified methods proposed. Outcomes of this project were submitted and discussed in the 70th session of IMO's Marine Environmental Protection Committee. In this paper, a brief description of these new assessment procedures is presented and a sensitivity analysis is conducted. The analysis is performed for a range of different open water propeller and hull resistance characteristics, hull – propeller interaction factors and engine power limit values, investigating the influence of these various performance parameters on the performance of the vessel.

Keywords: manoeuvrability, minimum propulsion power, critical condition, sensitivity analysis

1. INTRODUCTION

The global climate policies aim to provide a sustainable environment to future generations. Thus, The United Nations Framework Convention on Climate Change (UNFCCC) has set as a target to hold the increase in global average temperature below 2^{o}C above the pre-industrial levels (UN, 2010). Based on this objective, numerous studies have been developed, investigating the greenhouse emissions of shipping sector for a number of possible scenarios (IMO, 2014, Lloyd's Register, 2016). Furthermore, the implementation of the new energy efficient solutions in the maritime industry requires the establishment of a framework that will indicate the efficient design and operation of the ship. International Maritime Organization (IMO) has adopted energy efficiency design index (EEDI) (IMO, 2011) and energy efficiency operation indicator (EEOI) (IMO, 2009) as evidences of the efficient propulsion system operation. However, considering that ships sail in a dynamic environment, serious concerns have been raised about the potential of energy efficient technologies to sustain the manoeuvrability of ships in adverse sea conditions.

Based on this practice, IMO has adopted relevant guidelines for ship designers and organisations for the estimation of the minimum power that is required for the ship propulsion (IMO, 2015). In these guidelines, two alternative options are described for the estimation of the minimum propulsion power. The first one includes the estimation of the minimum installed Maximum Continuous Rating (MCR) with a regression model that defines the minimum power line value as a function of the ship's deadweight and ship type. The other option includes a simplified assessment of the estimation of the minimum required advance speed and the installed power that is required to achieve this speed in head wind and waves, which are the most adverse conditions during ship navigation. Based on the required engine speed and power, the MCR is estimated, taking into account the manufacturer limitation for the torque-speed.

Following the serious concerns about the manoeuvrability of ships in adverse conditions, EU funded project SHOPERA was launched, focusing on the development of tools and methods that will contribute to the safety enhancement in comprised situations (Papanikolaou et al., 2015). Based on this idea and in respect of the developed regulatory framework, three alternative assessment procedures as described in the following have been suggested, in order to predict the maximum wave height and the corresponding speed where the rudder can sustain its steering ability. (IMO, 2016):

- Comprehensive Assessment, allowing the designer to select numerical, experimental or empirical methods for solving coupled nonlinear motion equations.
- Simplified Assessment, using reduced complexity of motion equations and limited number of considered situations.
- Sufficient Propulsion and Steering Ability Check, based on pure empirical formulae as a function of main ship parameters.

The project's aim was to select a simplified method to predict the minimum required power, so that the number of calculations can be reduced whilst preserving the accuracy of the physical model for the description of ship motions. In order to assess the accuracy of this simplified method, various analyses have been carried out for a number of hull shapes, by comparing the results obtained from the simplified method with those obtained from the comprehensive assessment (Shigunov et al., 2016).

In the present paper, the Simplified Assessment procedure is followed in order to assess the sensitivity of the performance parameters that are used as input. The parameters considered for the analysis include the hull resistance, propeller open water characteristics, hull/propeller interaction coefficients and power/speed engine limit. A sensitivity analysis has been carried out for two different ship categories, keeping the ship main parameters constant throughout the analysis.

2. METHODOLOGY

2.1 GENERAL

During the general Comprehensive Assessment procedure that has been suggested by SHOPERA project, oscillatory forces and moments due to waves are neglected, assuming that oscillation time scale is shorter than manoeuvring time scale (Shigunov et al., 2015a). As a result, this assumption leads to the simplified solution of motions equations in the horizontal plane, described by the following steady-state system:

Surge force: $$X_s + X_w + X_d + X_R + T(1-t) = 0 \quad (1)$$

Sway force: $$Y_s + Y_w + Y_d + Y_R = 0 \quad (2)$$

Yaw moment: $$N_s + N_w + N_d - Y_R l_R + T(1-t) = 0 \quad (3)$$

The terms of the equations (1) to (3) can be defined using different methods, including empirical formulae, numerical methods or model experiments. Depending on the available data, the desired accuracy and the investigated situations, a suitable method can be selected.

2.2 PROPULSION CRITICAL CONDITION

Sailing in head seas is commonly accepted as the worst condition during ship propulsion in terms of hull resistance. Considering also that the ship should be able to keep course in waves and wind from any direction and keep an advance speed of at least four knots, the critical propulsion condition can be identified as the maximum wave height where the ship is able to sail with the minimum required speed (IMO, 2012a, b). Assuming that drift forces are neglected in low speeds and head seaways from 0^o to 60^o off bow, sway forces and yaw moments can also be neglected (Shigunov, 2015b). As a result, the equations (1) to (3) are reduced to the surge force equilibrium equation:

$$X_s + X_w^{00} + X_d^{00} + X_R + T(1 - t_H) = 0 \quad (4)$$

Following the simplified assessment, the resistance forces have been calculated using an empirical formulae. The calm water resistance and wind added resistance are calculated using ITTC regression methods (ITTC, 2014) while the wave added resistance is calculated using a regression analysis formula based on numerical solutions (Shigunov et al., 2016). For the simplification of the calculation process, the rudder resistance is assumed to be expressed as a proportion of the required thrust, reducing the computational effort for the final calculation of the latter. Consequently, the required thrust and power for the ship can be estimated using equation (4).

Using the propeller speed and the ship's transmission system (direct or gear connection), the available power from the propulsion system can be estimated. In case of Fixed Pitch Propellers (FPP), the power is calculated for the available power/speed engine limit; while in Controllable Pitch Propellers (CPP) the MCR power is used as the maximum available power and the available thrust is estimated with a suitable selection of propeller's pitch ratio. As a result, the critical condition for the propulsion is defined as follows:

For FPP propellers: $P_B^{req} \le P_B^{av}$ (5)

For CPP propellers: $T^{req} \le T^{av}$ (6)

In the simplified method, the propeller open water characteristics are estimated using the bollard pull assumption (zero advance speed). However, during this study, the actual advance speed ratio is used, considering that the advance speed does not increase the computational effort of the overall process. Also, the estimation of the propeller characteristics for the actual speed provides better accuracy in case the method is used for the prediction of the maximum permitted wave height at higher speeds.

2.3 THE CRITICAL CONDITION FOR MANOEUVRING

Based on the results of Comprehensive Assessment on various ships and various sea states conditions, and supported by ship's master experience, the critical condition that requires the enhancement of manoeuvrability is when the ship sails with forward speed while the wave and wind directions are close to the beam seaway. As a result, the evaluation of time-average wave and wind forces of equations (1) to (3) can be reduced to beam seaways (Shigunov et al., 2016). Furthermore, the converged solution of the motions equation indicates that the calm water yaw moment lever is greater than the rest. Based on this assumption, Equations (1) to (3) are simplified to a system of two equations:

$$X_s + X_w^{90} + X_d^{90} + X_R + T(1 - t_H) = 0 \tag{7}$$

$$Y_R = -b(Y_w^{90} + Y_d^{90}) \tag{8}$$

where

$$b = l_s/(l_s + l_R) \tag{9}$$

The superscript 90 means that the evaluation of these forces is required only in beam waves and winds. Assuming that the rudder resistance depends directly on the available thrust from the propeller, equation (7) can be used for the estimation of the available thrust at the vessel's maximum speed for a specific wave height. In case of FP propellers, the maximum speed is defined by the power/speed engine limit curve and the propeller performance for the selected beam seaway state. On the other hand, in case of CP propellers, it is assumed that the installed engine performs at the MCR point and the maximum speed is defined by selecting the correct pitch ratio that will provide adequate thrust to the ship.

The forces in equations (7) and (8) are calculated using empirical methods, calibration factors and regression models obtained from numerical computations (Shigunov et al., 2016). The simplified Equation (8) is used for the calculation of the required lateral force on the rudder. The available lateral force on the rudder is calculated using the simplified rudder model that was developed by Söding (Brix, 1993). The critical condition that sustains the manoeuvrability of ship is defined by the comparison of the available and required lateral rudder forces at the maximum vessel speed that is permitted from the propulsion system:

$$Y_R^{av} \leq Y_R^{req} \tag{9}$$

Based on this condition, the critical condition is described by the maximum wave height and the maximum vessel's speed that provides adequate force on the rudder in order to cover vessel's required manoeuvrability.

3. SENSITIVITY ANALYSIS

3.1 CASE STUDIES

In order to check the validity and reliability of the proposed formulation, a sensitivity analysis has been conducted. Two different vessel types have been used for the analysis, namely the KVLCC2 tanker, designed by MOERI (Van et al., 1998), and the Duisburg Test Case (DTC), a 14,000 TEU container vessel (Moctar et al., 2012). The ship lines, hull main dimensions, propeller data and hull-propeller performance factors for these two vessels are available online. Both vessels use FP propellers for their propulsion. The available open water characteristics have been used for the estimation of DTC model's propeller performance, while the propeller characteristics of KVLCC2 papers have been obtained using the polynomials of Wageningen B-screw series (Oosterveld & Van Oossanen, 1975) for the given propeller.

The MCR power of the installed engine, the design speed of both vessels and the corresponding propeller speed are given in Table 1.

Table 1: Performance parameters of case studies

	KVLCC2	DTC
MCR power (kW)	29,340	80,080
Vessel design speed (knots)	15.5	25.0
Propeller design speed (rev/s)	1.34	1.70

The available engine power in the case of FP propellers is estimated by the power/speed limit as described previously. To simplify the process for the estimation of the engine limit, the power and speed are given in a non-dimensional form and the maximum power and speed of engine are defined by the MCR point and propeller design speed. The slope of the limit curve shall be representative of the engine type installed onboard these ship types. Considering that the vast majority of the containerships and oil tankers of this size use two-stroke, turbocharged diesel engine, the corresponding power/speed limit curve is used. The engine limit includes the limitations that are defined by the air surge limit and the maximum torque limit of the engine (MAN B&W, 2000). Usually, the curves of these two limits, as well as their intersection, are defined by the engine manufacturers and the propulsion system components. In a non-dimensional form, it can be assumed that the engine limit curve remains constant for a specific category of engines.

3.2 PARAMETER ANALYSIS

The sensitivity analysis includes the evaluation of the simplified assessment methods for the propulsion and manoeuvring critical conditions in various performance parameters. These parameters are used as input to the method, affecting the hull performance and the overall propulsion power. The first parameter that is investigated is the resistance of the hull in calm water conditions, as well as the added wave and wind resistance. Considering that the resistance is calculated using empirical methods, this analysis investigates the effect of the available resistance method's accuracy on the overall assessment.

Additional performance parameters requiring further investigation are the hull-propeller interaction factors, defined as the thrust deduction and wake fraction factors. In simplified assessment, these factors are either calculated using empirical formulae which are applied in calm sea water conditions, or they are estimated based on experimental data for specific sea conditions. In steady-state conditions, the factors are assumed to remain constant throughout the simulation process. As a result, an analysis is required in order to identify the influence of these factors on the overall process.

Another important parameter is the propeller characteristics. The propeller performance is described by open water characteristics, estimated by experimental tests, computational simulations or use of regression models. Considering that these characteristics can differ in real applications and taking into account the accuracy of the selected methods, this sensitivity analysis will present the impact of the propeller performance to the estimation of minimum power performance.

Finally, an important parameter to consider is the engine power/speed limit. The limit of an engine is defined in a non-dimensional form. As a result, the only possible modification that can affect the engine limit is its curvature. For this reason, three points are required to be fixed at the engine limit curve. The first two points include the start where the engine provides 0% power at 0% speed and the end of the curve where engine provides 100% of MCR power at 100% of speed. Even if the engine's manufacturer permit the operation of the engine at 105% of MCR or 105% of the design speed for a small period of time, in terms of this study the maximum limit is defined at 100%, considering steady-state conditions. The third point that requires to be maintained is the intersection of the air surge limit curve and the maximum torque engine limit. This point, according to the engine manufacturers and depending on engine type, is located between 90% and 96.7% of design speed. In terms of this study, the third point is located at 96.7% of the design speed and the curvature is modified accordingly. (Fig. 1).

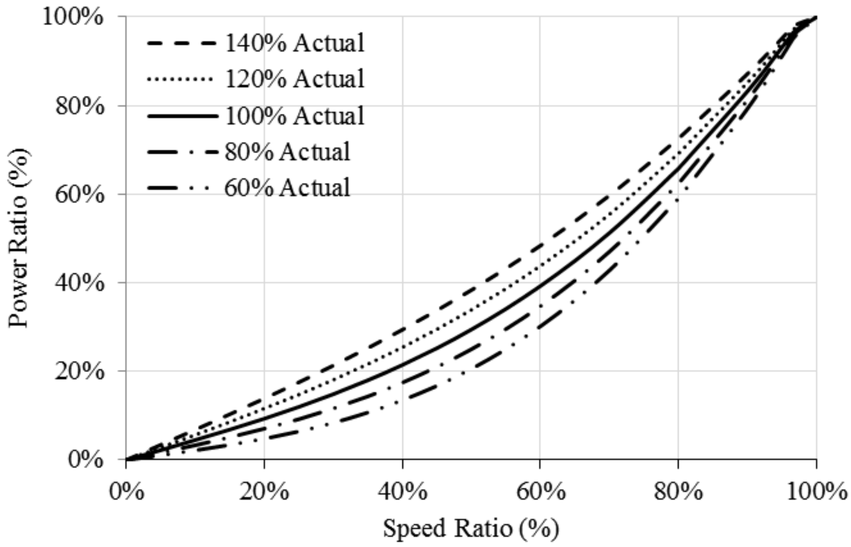

Figure 1. Power/speed engine limit curve for various assumptions

4. RESULTS

4.1 PROPULSION RESULTS

Using the simplified assessment tool, the propulsion critical condition is investigated for each hull. The maximum wave height for each parameter modification is depicted in Figures 2 to 5 for KVLCC2 vessel and DTC vessel. According to Figure 2, the wave height is inversely proportional to the resistance. The added wave and wind resistance have greater influence on the simplified method assessment case, in comparison with the calm water resistance. As a result, the accuracy of the calculation of the added resistance is crucial for the successful estimation of the minimum propulsion. In case the wave resistance is underestimated, the tool indicates a lower minimum propulsion power on board.

The increase of propeller torque coefficient reduces the maximum permitted wave height (Fig. 3). Considering that the thrust coefficient and the engine limit are not affected, the constant speed of advance and thrust corresponds to higher torque from the engine and consequently to higher power. For this reason, the engine reaches the MCR power in lower wave heights. On the other hand, increased thrust coefficient improves the propulsion ability of ship due to the additional force that is provided by the propeller. However, it should be noted that the thrust and torque propeller coefficients are modified simultaneously. Therefore, the contribution of both propeller coefficients shall be considered for the final power estimation.

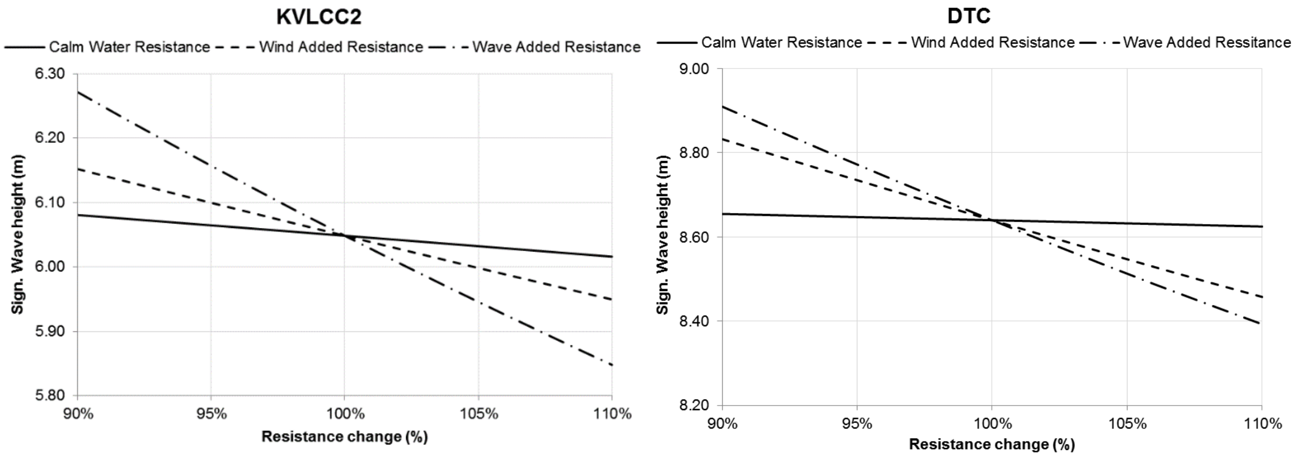

Figure 2. Analysis of maximum head wave height at speed of 4 knots, using calm water, wave added and wind added resistance as control parameters for a) the KVLCC2 vessel and b) the DTC vessel.

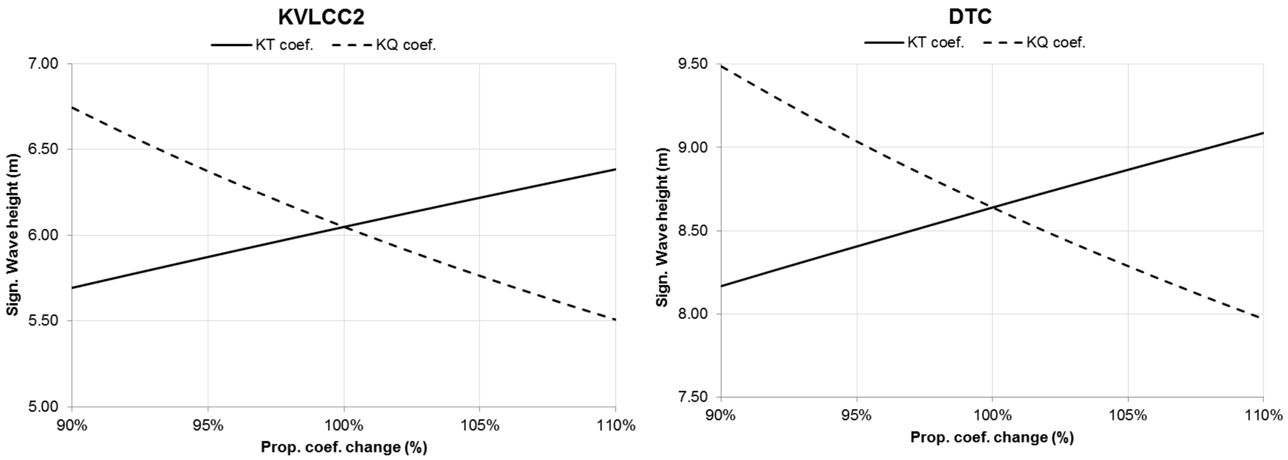

Figure 3. Analysis of maximum head wave height at speed of 4 knots, using propeller thrust and torque coefficients as control parameters for a) the KVLCC2 vessel and b) the DTC vessel.

The influence of the hull-propeller interaction factors on the prediction of maximum wave height is presented in figure 4. The modification of wake fraction factor has no effect on the final results, but the increase of thrust deduction reduces the permitted wave height. Based on the definition of the thrust deduction factor, when the factor is increased, the required thrust force for a given resistance needs to be increased.

Finally, the engine power/speed limit curve has the greatest impact on the estimation of the propulsion ability in both vessels. When the engine power limit is reduced at low engine speeds (Fig. 1), the engine's power is insufficient to permit vessel's navigation in more adverse head seas (Fig. 5). As a result, the engine's surge limit has a great influence on the prediction of the maximum wave height. Despite the importance of engine limit reduction at low speeds, the effect is less important when the engine limit at low speeds is increased. Comparing the results of simplified assessment tool in various vessel speeds, it is proved that the influence of the engine's limit is more important when ship sails in lower speeds, where the FP propeller operates in lower speeds.

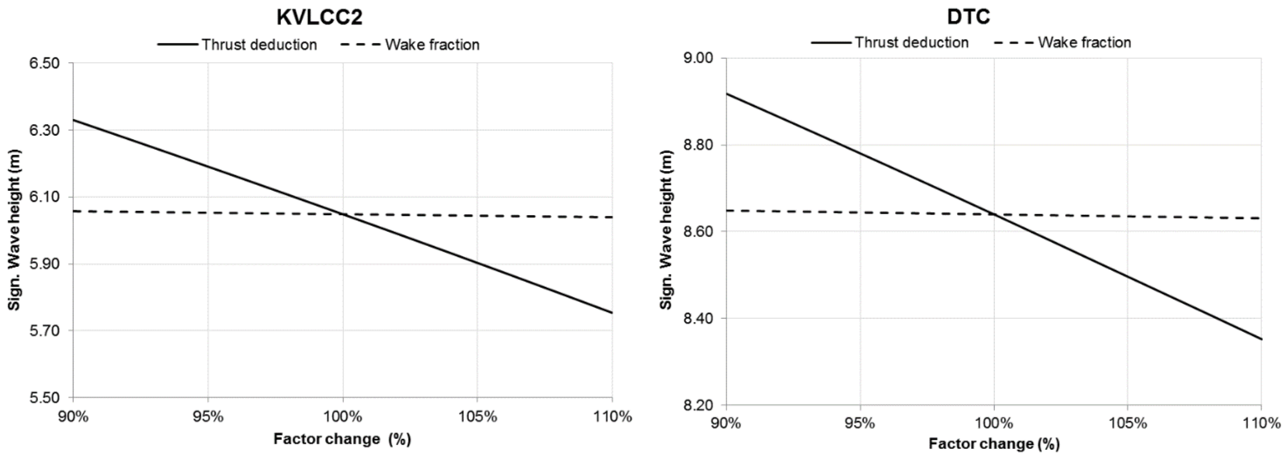

Figure 4. Analysis of maximum head wave height at speed of 4 knots, using wake thrust and thrust deduction factors as control parameters for a) the KVLCC2 vessel and b) the DTC vessel.

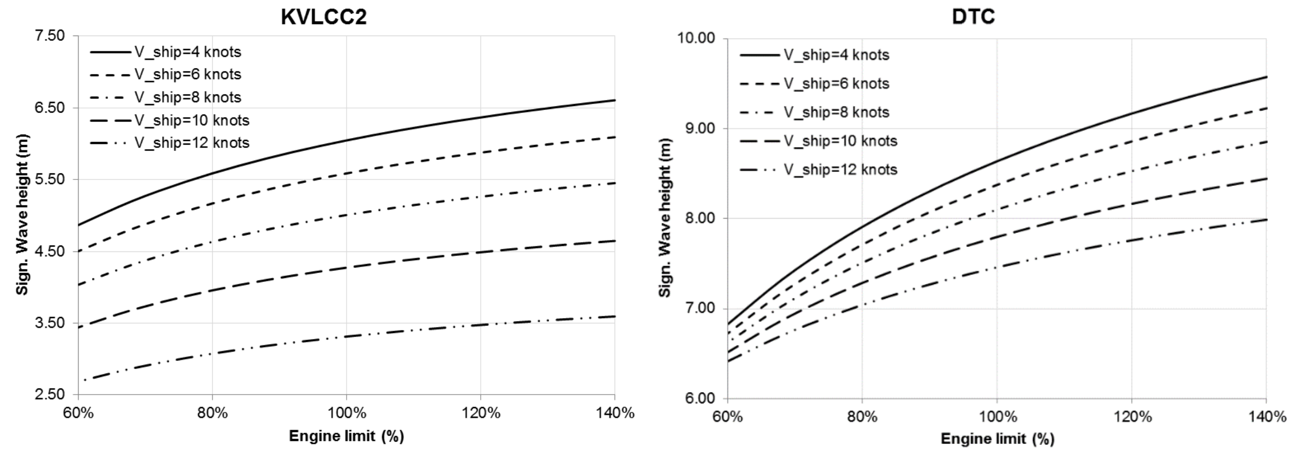

Figure 5. Analysis of maximum head wave height at various vessel speeds, using power/speed engine limit as control parameter for a) the KVLCC2 vessel and b) the DTC vessel.

Comparing the results between the two different ship types, the influence of the performance parameters is similar in both cases. The only difference is between the sizes where the power of DTC is greater than KVLCC2's power, providing additional thrust to the hull.

4.2 MANOEUVRING RESULTS

Manoeuvrability in both case studies has been investigated for the same control parameters. The results in Figures 6 to 9 show the change of the maximum wave height and vessel speed for the KVLCC2 and DTC vessels. In both cases, when the original value of one parameter is modified, the rest remain constant.

The influence of the control parameters on the overall performance of ship manoeuvrability is similar to the influence of control parameters on the propulsion ability. However, the sensitivity analysis reveals some differences. According to Figure 6, the calm water resistance has great influence at the final prediction of maximum beam wave height, while the final result is not affected by the change of wind added resistance because of the low contribution of wind resistance in beam seaways.

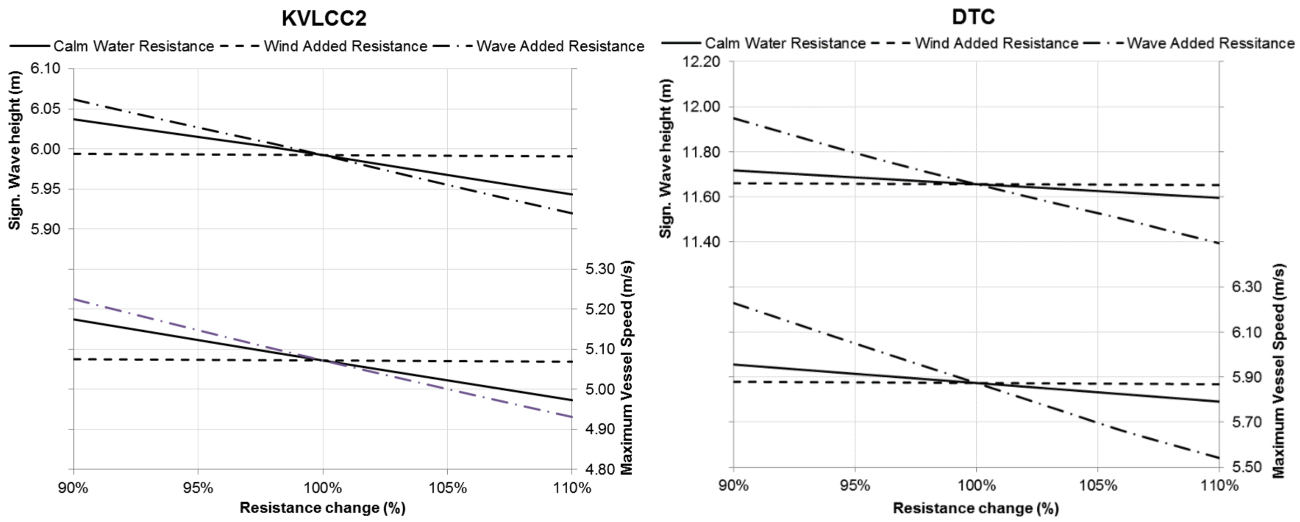

Figure 6. Analysis of maximum head wave height and vessel's speed using calm water, wave added and wind added resistance as control parameters for a) the KVLCC2 vessel and b) the DTC vessel.

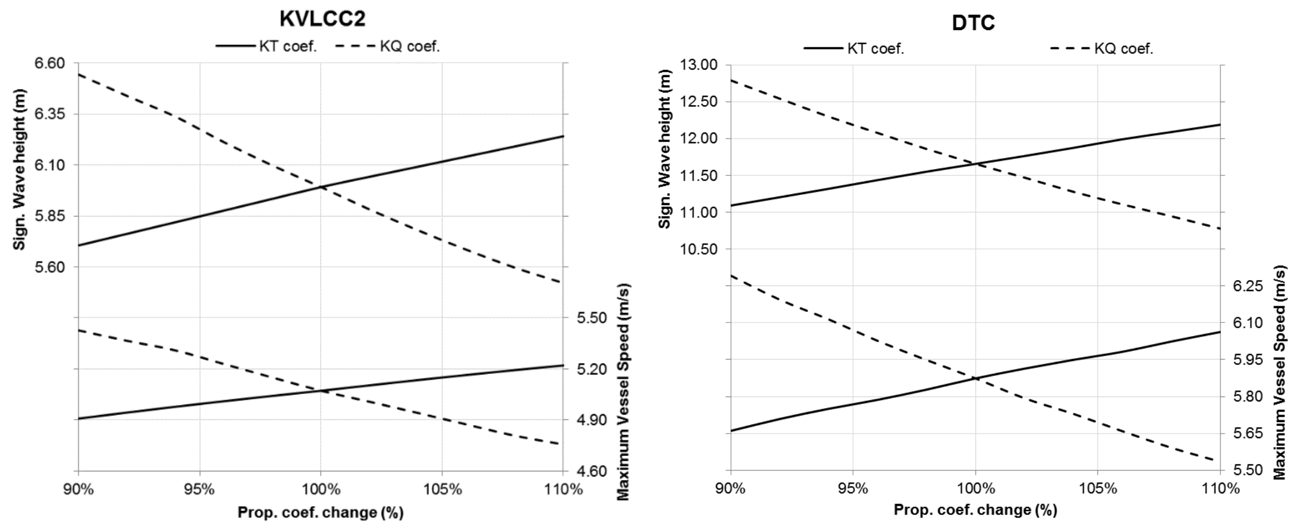

Figure 7. Analysis of maximum head wave height and vessel's speed using propeller thrust and torque coefficients as control parameters for a) the KVLCC2 vessel and b) the DTC vessel.

In addition, the effect of wake fraction factor on the manoeuvrability is notable (Fig. 8). During the assessment of propulsion ability, the wake factor did not affect the final results. However, in this case, the increase of wake fraction leads to a decrease of the maximum wave height. At the same time, the increase of wake fraction factor does not affect the maximum vessel speed at the corresponding wave height. Therefore, when the wake factor increases, the speed of advance at the propeller decreases and consequently the advance ratio is decreased, leading to lower thrust at the propeller. In this case, the maximum beam wave height is reduced in order to sustain the manoeuvring ability of the rudder.

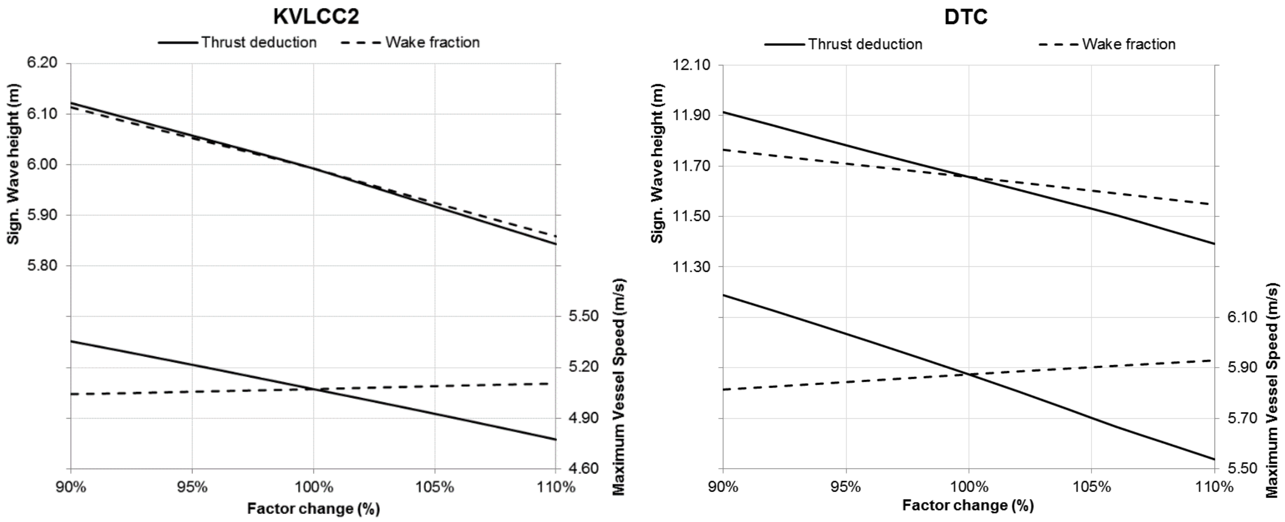

Figure 8. Analysis of maximum head wave height and vessel's speed using wake thrust and thrust deduction factors as control parameters for a) the KVLCC2 vessel and b) the DTC vessel.

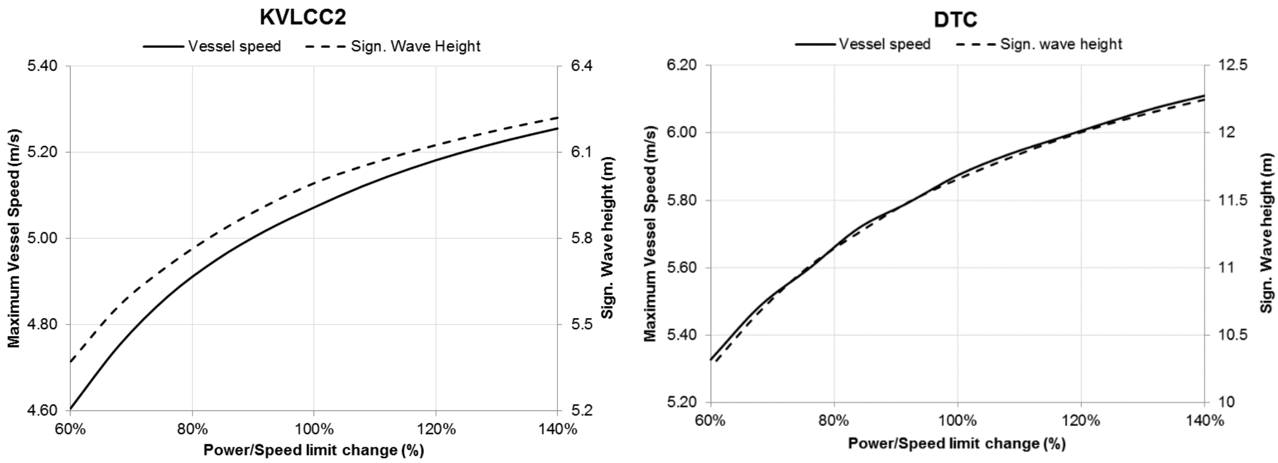

Figure 9. Analysis of maximum head wave height and vessel's speed using power/speed engine limit as control parameters for a) the KVLCC2 vessel and b) the DTC vessel.

Finally, the change of maximum vessel speed in every analysis follows the change of the maximum beam wave height, except for the wake fraction factor case, where the maximum vessel's speed either remains constant or is slightly increased when factor is increased.

5. CONCLUSIONS

Based on the simplified assessment method that was developed in the EU funded project SHOPERA and suggested to the IMO as a tool for the estimation of the minimum required propulsion power, a sensitivity analysis was performed, investigating the various performance parameters that affect the propulsion and manoeuvring abilities of a ship. This analysis acts as a supplementary study to the sensitivity studies that were conducted during the project, assessing the accuracy of the assumptions that were considered for the simplified method.

The results of this study indicate that the applied methods for the estimation of the performance parameters shall be accurate, with special focus on the estimation of the wave added resistance, propeller characteristics and power/speed engine limit. Focusing on the latter two parameters, the use of experimental data can provide adequate accuracy for the final estimation of the minimum propulsion power. Moreover, the engine surge limit at low engine speed seems to be important for FP propellers, improving the performance of the vessel in head and beam seaways and increasing the available thrust to the propeller. Of course, the limit is valid assuming that this is the only limit applied to the engine, neglecting any additional limitations applied to the propulsion plant from the engine control system.

Finally the effect of the performance parameters on the motions equations system is irrelevant to the seaway direction. The only difference between the sensitivity analyses that took place for two different critical conditions was the effect of wind resistance and the wake fraction, parameters that are directly connected to the process that is used for the estimation of the maximum wave height. In general, the overall performance of the simplified assessment method developed predicts as accurate as the input performance parameters are. However, the predicted results are reasonable, indicating that this tool has a great potential for a successful estimation of the minimum required propulsion power.

NOMENCLATURE

Notations	
X	force in x-direction (N)
Y	force in y-direction (N)
N	moment in z-direction (Nm)
T	propeller thrust (N)
t	thrust deduction factor (-)
l	moment lever (m)
P	engine power (W)
Subscripts	
s	calm-water
w	wind
d	wave
R	rudder
H	hull
b	break
Superscripts	
90	beam headways
00	head seaways
av	available
req	required

ACKNOWLEDGEMENTS

Authors of this paper would like to express their deepest gratitude to Dr Vladimir Shigunov for his valuable comments and support. Special recognition goes also to the people who worked in the EU funded project SHOPERA and developed the tools which are used in this research study.

REFERENCES

Brix, J. E., 1993. Manoeuvring Technical Manual. Seehafen Verlag, Hamburg

IMO, 2009. The Marine Environment Protection Committee, MEPC.1/Circ.684. Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator.

IMO, 2011. The Marine Environment Protection Committee, Resolution MEPC.203(62). Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto.

IMO, 2012a. The Marine Environment Protection Committee, MEPC.64/4/13, Air Pollution and Energy Efficiency – Consideration of the Energy Efficiency Design index for new ships – Minimum propulsion power to maintain the manoeuvrability in adverse conditions, Submitted by IACS, BIMCO, INTERCARGO, INTERTANKO and OCIMF.

IMO, 2012b. The Marine Environment Protection Committee, MEPC.64/Inf.7, Air Pollution and Energy Efficiency – Background Information to document MEPC 64/4/13, submitted by IACS.

IMO, 2014. Third IMO GHG Study 2014: Executive Summary and Final Report.

IMO, 2015. The Marine Environment Protection Committee, Circular MEPC.1/Circ.850/Rev. 1, 2013 Interim Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions, as amended.

IMO, 2016. The Marine Environment Protection Committee, MEPC 70/Inf.33, Air Pollution and Energy Efficiency – Results of research project “Energy Efficient Safe Ship Operation” (SHOPERA), submitted by Denmark, Germany, Norway and Spain.

ITTC, 2014. Recommended Procedures and Guidelines - Speed and Power Trials, Part 2 - Analysis of Speed/Power Trial Data.

Lloyd’s Register, 2016. Low Carbon Pathways 2050, v1.0, 16 October 2016.

MAN B&W, 2000. Engine Selection Guide – Two-stroke MC/MC-C Engines, 5th Edition, February 2000.

Moctar, O., Shigunov, V. & Zorn, T., 2012. Duisburg Test Case: Post-Panamax Container Ship for Benchmarking, Ship Technology Research, Vol. 59(3), pp. 50-64.

Oosterveld, M.W.C. & Van Oossanen, P., 1975. Further computer-analyzed data of the Wageningen B-screw series. International Shipbuilding Progress, 22(479), p. 13.

Papanikolaou, A., Zaraphonitis, G., Bitner-Gregersen, E., Shigunov, V., El Moctar, O., Guedes Soares, C., Reddy, D. N. & Sprenger, F., 2015. Energy Efficient Safe Ship operation (SHOPERA). 12th International Marine Design Conference – IMDC, 11-14 May 2015, Tokyo, Japan.

Shigunov, V. & Papanikolaou, A., 2015a. Criteria for Minimum Powering and Maneuverability in Adverse Weather Conditions. Ship Technology Research, Vol. 62(3), pp. 140-147.

Shigunov, V., 2015b. Manoeuvrability in Adverse Conditions. ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering, 31 May – 15 June 2015, St. John's, Newfoundland, Canada.

Shigunov, V., Papanikolaou, A. & Chroni, D., 2016. Maneuverability in Adverse Conditions: Assessment Framework and Examples. 15th International Ship Stability Workshop, 13-15 June, Stockholm, Sweden.

UN, 2010. United Nations Framework Convention on Climate Change, FCCC/CP/2010/7/Add.1, Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010.

Van, S.H., Kim, W.J., Yim, D.H., Kim, G.T., Lee, C.J. & Eom, J.Y., 1998. Flow Measurement Around a 300K VLCC Model, Proceedings of the Annual Spring Meeting, SNAK, Ulsan, pp. 185-188.