MARINE ENVIRONMENT PROTECTION COMMITTEE
70th session
Agenda item 5

AIR POLLUTION AND ENERGY EFFICIENCY

Results of research project "Energy Efficient Safe Ship Operation" (SHOPEERA)

Submitted by Denmark, Germany, Norway and Spain

SUMMARY

Executive summary: This document provides background information and results of the research project "Energy Efficient Safe Ship Operation" (SHOPEERA)

Strategic direction: 7.3

High-level action: 7.3.2

Output: 7.3.2.1

Action to be taken: Paragraph 27

Related documents: MSC-MEPC.2/Circ.11; Resolutions MEPC.232(65), MEPC.255(67) and MEPC.262(68); MEPC 64/4/13, MEPC 64/INF.7; MEPC 67/INF.14; MEPC 69/INF.23; MEPC 70/5/20 and MEPC 70/INF.30

Introduction

1 The 2012 Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships, resolution MEPC.212(63), represent a major step forward in implementing the regulations on energy efficiency of ships, resolution MEPC. 203(62). However, concerns had been expressed regarding sufficiency of propulsion and steering abilities of ships to maintain their manoeuvrability in adverse conditions if the EEDI requirements are achieved by simple reduction of the installed engine power. This gave a reason for additional considerations and studies by IACS, which served as a basis for the Interim Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions, MSC-MEPC.2/Circ.11, which were updated in annex 1 to document MEPC 65/4/3 and subsequently adopted by resolution MEPC.232(65) and were further updated by resolutions MEPC.255(67) and MEPC.262(68).
2 To address these challenges, several research projects were initiated at international level, among them the 3-year research project SHOPERA (Energy Efficient Safe Ship Operation, www.shopera.org, 2013-2016), funded by the European Commission in the frame of FP7 and representing the whole spectrum of the European maritime industry, including classification societies, universities, research organizations, model basins, ship designers, shipyards and ship operators.

3 In the course of the project, SHOPERA had a close collaboration with a parallel research project of the Japanese maritime industry, which was coordinated by the Japan Society of Naval Architects and Ocean Engineers (JASNAOE). A close collaboration was established between the two projects with the aim of exchanging information about the progress of work of both projects and ultimately to prepare and submit a joint proposal for the draft revised Guidelines to MEPC 70 or MEPC 71. The joint proposal of the two projects is being submitted in document MEPC 70/5/20, with supplementary information submitted in document MEPC 70/INF.30.

4 Independently of the above joint submission with Japan, which refers to tankers, bulk carriers and combination carriers, the aim of the present submission is to inform all interested stakeholders about the whole range of results of the project SHOPERA, which covered all types of ships affected by the EEDI framework. The present submission elaborates on a proposal for more general scenarios of adverse conditions and generic manoeuvrability criteria for the manoeuvrability of ships in adverse conditions, on a practical assessment framework and the available/developed evaluation methods, on case studies of existing vessels and optimization studies on the potential of improvement of the performance and environmental safety for various types of ships. An overview of dissemination activities and publications of SHOPERA is provided in the annex for reference and in depth study of details.

Scenarios of adverse conditions and manoeuvrability criteria

5 In SHOPERA, a review of existing regulations, interviews of shipmasters and analysis of accident statistics and detailed accident investigations were conducted first in order to identify relevant scenarios, criteria and corresponding standards (environmental conditions) which should be employed to assess the sufficiency of propulsion and steering systems of ships for manoeuvrability in adverse conditions. They should reflect actual ship operation practices, which are important for manoeuvring in general and especially for manoeuvring in heavy weather.

6 Three scenarios of adverse conditions were identified, in which manoeuvrability characteristics of ships are challenged in different way:

   .1 *weather-vaning in the open sea*, which imposes less strict requirements on the manoeuvring, albeit in more severe weather conditions. Arguably, the inability to manoeuvre in the open sea should not lead to a loss of the ship anyway, because safety of ships, which are unable to manoeuvre and are drifting in beam sea, should be ensured by the Severe Wind and Rolling Criterion (Weather Criterion), resolution MSC.267(85), in most severe weather conditions;

   .2 *manoeuvring in coastal waters* imposes strong functional requirements on ship's manoeuvrability: in principle, any manoeuvre may be required, perhaps in a complex navigational situation and in a seaway from a direction unfavourable for manoeuvring. However, the relevant weather conditions are rather moderate, because in an increasing storm, shipmasters timely search for shelter or leave to the open sea. Therefore, this scenario requires
both a sufficient steering ability, to avoid grounding, collision or contact, in seaway headings not always favourable for steering, and a sufficient propulsion ability, to enable timely leaving coastal area; and

.3 **manoeuvring at limited speed in restricted areas**, typically during approaching or entering ports, where the ship's speed is restricted due to navigational requirements. Because this scenario does not lead to any restriction on the installed minimum power, it is not considered here.

7 Correspondingly, three criteria are proposed to assess the sufficiency of propulsion and steering systems of ships for manoeuvrability in adverse conditions:

.1 **weather-vaning ability**, i.e. the ability of the ship to change and keep heading in head to bow-quartering waves;

.2 **steering ability**, meaning here the ship's ability to perform any manoeuvre in seaway from any direction; and

.3 **propulsion ability**, understood as the ship's ability to maintain some speed (proposal: 6 knots) in seaway from any direction.

8 To define the corresponding standards (environmental conditions), beyond measured wind and wave data in the open sea and coastal areas, interviews of shipmasters and detailed accident investigations, also statistics of accident rates, locations and corresponding environmental conditions of accidents due to insufficient manoeuvrability in adverse conditions were collected by SHOPER; the key findings were:

.1 existing fleet is sufficiently safe with respect to manoeuvrability-related safety requirements on future ships;

.2 the most vulnerable ship types with respect to navigational accidents in adverse conditions are general cargo ships, followed by r-ro ferries, bulk carriers and tankers;

.3 recorded wave heights and wind speeds during accidents are much more moderate than those adopted in the 2013 Interim Guidelines; and

.4 according to interviews, 50% of shipmasters leave coastal areas before wind speed reaches Bft8 and the **significant** wave height achieves 5 m (noting that according to probabilistic theory the encountered maximum wave height may be under these conditions up to about 10 m).

9 These findings agree with the well-known findings of the HARDER project, which were later on adopted in the new harmonized probabilistic ship damage stability regulation of SOLAS 2009 and the Stockholm Regional Agreement on the damage stability of passenger ships, according to which more than 80% of collisions happened at significant wave heights below 2 m, and **significant wave heights in excess of 4 m were practically not recorded during collision accidents**. These findings also agree with the requirements of classification societies related to the redundancy or duplication of the propulsion system, EE-WG 1/4 (2010), namely, wind speed below 21 m/s and significant wave height below 5.4 m.

10 Although statistical information, evidence and interviews are important to estimate the relevant severity of environmental conditions, benchmarking of the existing fleet with respect to the new criteria appears a rational way to define the standard environmental conditions, namely: majority (or certain percentage) of existing vessels should be able to
satisfy standards. This way was used to define the standard environmental conditions in the 2013 Interim Guidelines (15.7 m/s wind speed and 4.0 m significant wave height for ships with the length between perpendiculars $L_{\text{pp}}$ less than 200 m to 19.0 m/s and 5.5 m, respectively, for $L_{\text{pp}}$ greater than 250 m).

11 The need for benchmarking is evident considering that:

1. it is impossible to design and operate economically viable ships that can manoeuvre in the worst possible weather events that can be theoretically encountered.

2. worst possible conditions in coastal areas are usually avoided by shipmasters, whereas in the open sea, ship's safety is safeguarded by the intact stability regulations, even if the ship is unable to manoeuvre (dead ship condition).

3. whereas the proposed criteria address relevant characteristics of a ship, her steering and propulsion system, as well as the weather environment, they are herein significantly simplified to remain practicable; therefore, the selection of a standard wave height should be considered as fine-tuning of the criteria to reliably differentiate between sufficiently and insufficiently safe ships, and not as an absolute measure identifying safe or unsafe operational conditions.

12 In SHOPERA, dedicated case studies concerning all ship types covered by EEDI regulations were used to define the herein proposed standard environmental conditions.

Assessment framework and evaluation methods

13 Compliance with the IMO Manoeuvrability Standards, resolution MSC.137(76), is demonstrated in full-scale calm water sea trials; full-scale trials are, however, impossible to conduct for the evaluation of manoeuvrability in adverse conditions. Evaluation of the proposed criteria in transient model experiments with self-propelled models in simulated irregular waves and wind, or with corresponding numerical simulations, is presently unfeasible for regulatory purposes, despite some progress of the state of the art at few research centres. The assessment procedures proposed by SHOPERA are based on a combination of freely chosen evaluation methods (experimental, numerical or empirical) for different components of the assessment procedure, depending on the designer's needs and preferences, and a combination of these components in a simple assessment procedure.

14 The assessment procedure itself can also be freely chosen between three complexity levels, ranging from a simple check, sufficient for the majority of conventional vessels, to more accurate assessment procedures required for cases with larger uncertainties, including innovative propulsion and steering solutions. The designer and Administrations are free to select between the following three alternative assessment procedures:

1. the most accurate, Comprehensive Assessment, allows the best accuracy. Still, the designer does not have to use tedious/expensive evaluation methods for the different elements of the assessment, but can choose between numerical, experimental or empirical methods, which should, however, all ensure satisfactory accuracy of results. This alternative may be necessary for ships with innovative propulsion and steering arrangements;
a less complex, *Simplified Assessment*, which still takes into account the physics of the problem, but uses a reduced number of assessment scenarios and reduced complexity of equations; this assessment also allows the choice between experimental, numerical or empirical methods to evaluate different elements of the procedure and has the complexity of a spreadsheet calculation; and

the simplest assessment procedure, a *Sufficient Propulsion and Steering Ability Check*, is based on pure empirical / statistical formulae, which define the required installed power as a function of main ship parameters and require few simple pocket computer calculations.

Both the comprehensive and simplified assessments require the definition of time-average forces due to waves including added resistance, wind forces, calm-water reactions, rudder-induced forces and propeller characteristics. According to the SHOPERA approach, these contributions can be defined separately, with different methods (experimental, numerical or empirical) as necessary. According to the performed sensitivity analysis, the most important contributions for propulsion and steering in adverse conditions are the time-averaged surge and sway forces due to waves, the surge and sway force and yaw moment due to calm-water reactions and the lateral rudder force. Evaluation of the available methods for different components has shown that:

1. experimental methods are available and well established for the evaluation of all elements;

2. numerical methods are, in principle, available and satisfactory for all elements with the exception of the time-average wave forces, where the uncertainties are greater; in any case, the use of numerical methods for regulatory purposes needs a significant procedural effort by Administrations and recognized organizations, before it can be generally adopted; and

3. especially important for practical approval is the availability of suitable empirical methods for all elements of the assessment procedure. SHOPERA has undertaken a thorough validation of empirical methods for calm-water reactions, wind forces and rudder forces, including bi-lateral benchmarking with the JASNAOE project and concluded that such methods are in principle available for practical use, if used within their applicability limits, with the exception of the time-average wave forces.

The development and validation of numerical and empirical methods for the time-average wave forces, including added resistance, was one of the most important research issues of SHOPERA and was addressed as following:

1. extensive model tests were performed for three ship types (a modern 14,000 TEU container ship design, a standard VLCC tanker and a small European RoPax) in over 1,300 conditions, including various draughts, water depths, forward speeds and wave directions, lengths and heights to generate a unique validation database for numerical and empirical methods;

2. several evaluation methods were developed and validated, ranging from high-fidelity CFD methods to 3D panel codes and simple empirical formulae; and
to evaluate the world-wide availability of methods that can be used in practical assessment, SHOPERA conducted an international benchmark study of numerical and empirical methods. The results showed a notable progress in the development of both numerical and empirical methods in the last years and availability, in principle, of numerical methods for practical regulatory purposes, if their application is properly verified.

A critical aspect of manoeuvrability of ships in adverse conditions is the correct modeling of the main engine and the propulsion system under high load in adverse conditions. Frequently used assumptions of constant torque, constant power or constant rotation speed may lead to misleadingly optimistic predictions. In SHOPERA, output limits of diesel engines under high load were investigated, and recommendations for the practical assessment were provided.

**Case studies of existing fleet and optimization exercises**

The aim of the conducted case studies and optimization exercises carried out by SHOPERA was, first, to systematically compare the proposed criteria with each other and to identify possible redundancies or loopholes. The studies were also used to:

1. Calibrate the standard weather conditions using assessment results of existing ships with respect to the new criteria;
2. Investigate the potential for conflict between the gradual strengthening of the EEDI requirements in subsequent implementation phases until 2015 and requirements to safe manoeuvring in adverse conditions;
3. Identify ship types, for with this potential is the largest; and
4. Investigate the potential of multi-objective optimization of ships with respect to conflicting safety and efficiency requirements.

The studies concerned bulk carriers, tankers, general cargo vessels, container ships, LNG and gas carriers, reefers, ro-ro cargo vessels, RoPax vessels and cruise vessels, chosen within the whole range of representative sizes and installed power.

The systematic comparison between the three proposed criteria shows that the marginal wave height (i.e. maximum wave height, up to which the vessel can fulfil the respective criterion) according to the weather-vaning criterion is very well correlated with the marginal wave height according to the propulsion criterion, which means that one of these criteria may be redundant. The marginal wave heights according to the propulsion and steering criteria also correlate with each other to some degree, with significantly more spreading than for the comparison between the weather-vaning and propulsion criteria.

Results from the conducted case studies show that the marginal wave heights are **ship size-dependent** for all three criteria: larger vessels are able to satisfy the proposed criteria at greater wave heights than smaller vessels. This follows simply from the physics of the problem; whether the standard wave height should also be ship size-dependent, however, may be a subject of discussion with all interested stakeholders. The arguments for ship size-dependent standard wave height are:

1. The dependency of the marginal wave heights on the ship size was revealed from the application of manoeuvrability criteria to existing vessels, thus it reflects existing design and operational practices;
.2 consequences of accidents are generally greater for larger vessels, thus the frequency of accidents implied by the standard wave heights should be for them lower; and

.3 the impact of seaway on ship’s motions and maneuverability in waves diminishes with increasing ship size.

22 Results show also that the marginal wave heights differ, sometimes substantially, between different ship types. Bulk carriers and tankers show very similar marginal wave heights, which are lower to significantly lower than the marginal wave heights of other vessel types; this is mostly due to their lower specific installed power (installed power per ton of ship displacement) compared to the larger specific installed power of other vessel types of the same size, like containerships, as well as advanced propulsion and steering concepts typical for some other vessel types, like twin screw, diesel-electric propulsion, controllable pitch propellers or pods on RoPax and cruise vessels.

23 Thus, reaching a conclusion regarding ship type dependency of standard wave heights also requires a discussion with all interested stakeholders:

.1 the arguments in favour of ship type-dependent standard wave heights are, first, that the differences in the marginal wave heights between different ship types are the outcome of the application of manoeuvrability criteria to existing vessels, thus they reflect established design and operational practices; and, second, that the consequences of accidents differ, sometimes significantly, between different ship types, especially between passenger and cargo vessels; and

.2 on the other hand, the differences in the manoeuvrability characteristics in adverse conditions also reflect, at least partially, differences in the economic performance profiles of the various ship types, which should, however, not affect the required minimum safety level; this is evident when comparing e.g. the operational profile of RoPax ships with that of slow steaming tankers and bulk carriers.

24 Concerning possible conflicts between the requirements to safe manoeuvring in adverse conditions and the strengthening of EEDI requirements, especially at the later phases of EEDI implementation, the following results were obtained:

.1 if existing vessels, satisfying requirements of a certain phase of EEDI implementation, are compared across all ship types, bulk carriers and tankers show remarkably similar marginal wave heights, which are also lowest among all ship types;

.2 if vessels are selected that satisfy the criteria proposed by SHOPERA for manoeuvrability in adverse conditions at the standard wave heights according to the 2013 Interim Guidelines, bulk carriers and tankers seem to marginally fulfill the requirements of phase 2 EEDI implementation, but not of phase 3, whereas vessels of other types that satisfy the manoeuvrability criteria at the standard wave heights according to the 2013 Interim Guidelines, are able to satisfy or even over-satisfy the requirements of phase 3 (in the present formulation). The above findings of case studies for a sample of existing ships are confirmed by the conducted parametric optimization studies for a sample of tankers, bulk carriers and RoPax ships;
for EEDI phase 3-compliant bulk carriers and tankers to pass the proposed manoeuvrability requirements in adverse conditions, the standard wave heights need to be lowered compared to those in the 2013 Interim Guidelines. However, whether such vessels can be considered as representative vessels of fleet in service is a subject of discussion with all interested stakeholders; and

the conducted parametric optimisation studies for RoPax ships revealed ample manoeuvrability margins in adverse conditions, but problems of compliance with the EEDI phase 3 requirements, whereas the phase 2 requirements appear marginally fulfilled. This finding is also confirmed by other studies of the European passenger shipping industry and should be an additional subject of discussion among all interested stakeholders.

Dissemination of results

A large number of papers and conference presentations were produced by the SHOPERA consortium; a list of selected papers is given in the annex. Additionally, four public workshops were organized by the project for open discussion or results and exchange of opinions with the maritime industry, other projects and maritime safety stakeholders. Proceedings of these workshops are publicly available.

Further information can be found in the project website under http://www.shopera.org.

Action required of the Committee

The Committee is invited to note the above information and take action as appropriate.
ANNEX

BACKGROUND INFORMATION AND RESULTS
OF RESEARCH PROJECT "ENERGY EFFICIENT SAFE SHIP OPERATION" (SHOPERA)

Contents

1 Introduction to project SHOPERA – Objectives ..............................................................3
2 Scenarios and Criteria .......................................................................................................4
  2.1 Terminology ..................................................................................................................4
  2.2 Existing Regulations ...................................................................................................4
  2.3 Accidents ......................................................................................................................5
  2.4 Interviews of Ship Masters .......................................................................................9
  2.5 Proposal for Scenarios and Criteria .........................................................................9
  2.6 Environmental Conditions .......................................................................................10
    Wave Height ..................................................................................................................10
    Wind Speed ..................................................................................................................14
    Other Sea State Parameters .......................................................................................15
3 Assessment Procedures ..................................................................................................18
  3.1 General .......................................................................................................................18
  3.2 Comprehensive Assessment .....................................................................................18
  3.3 Evaluation Methods for Components of Forces and Moments .................................20
  3.4 Simplified Assessment .............................................................................................22
    Principles .......................................................................................................................22
    Simplified Steering Ability Assessment ..................................................................22
    Simplified Propulsion Ability Assessment ..............................................................23
  3.5 Sufficient Propulsion and Steering Ability Check .....................................................24
  3.6 Engine and Propulsion .............................................................................................25
    Engine Model ...............................................................................................................25
    Other Types of Engine and Propulsion .....................................................................26
    Propeller Model and Hull-Propeller Interaction .........................................................27
4 Case Studies ....................................................................................................................27
  4.1 Introduction .................................................................................................................27
  4.2 Comparison between Criteria ....................................................................................27
  4.3 Definition of Standard Wave Heights Using Comprehensive Assessment ...............29
  4.4 Comparison between Ship Types using Simplified Assessment ...............................34
5 Optimisation .....................................................................................................................36
  5.1 Parametric Model for the Global Optimization of RoPax Ships .................................37
  5.2 Global Optimization of two RoPax Ships ..................................................................38
    Optimization of a small RoPax Ship ...........................................................................38
    Optimization of a larger RoPax Ship .........................................................................40
  5.3 Parametric Model for the Global Optimization of Tankers and Bulk Carriers ...........41
    Optimization of a SUEZMAX Tanker .......................................................................43
    Optimization of a VLCC Tanker ...............................................................................44
    Optimization of a 37,000t Bulk Carrier ....................................................................44
    Optimization of a 58,600t Bulk Carrier ....................................................................46
6 References ........................................................................................................................Error! Bookmark not defined.
Appendix 1. Coordinate System, Symbols and Definitions ........................................49
  Coordinate System.................................................................49
  Symbols ..................................................................................49
  Physical Constants...................................................................50
Appendix 2. Validation of Evaluation Methods .................................................51
  Test matrix................................................................................51
  Validation of Time-Average Waves Forces ..................................52
  Validation of Methods for Rudder Forces ....................................54
  Validation of Maneuvering Simulations in Calm Water and in Waves ....56
  References................................................................................58
Appendix 3. Benchmarking of Time-Average Wave Forces & Moments ..............59
  Introduction ............................................................................59
  The Subject Ships...................................................................60
    Duisburg Test Case ................................................................60
    KVLCC2 ship ......................................................................60
  Added Resistance in Waves .....................................................60
  Results of Calculation of Drift Forces and Moments ......................62
  Conclusions ............................................................................63
  References................................................................................64
Appendix 4. Details of Simplified Steering Ability Assessment ..........................65
  Background ............................................................................65
  Simplified Empirical Methods for Forces .....................................67
Appendix 5. Details of Simplified Propulsion Ability Assessment ......................69
  Background ............................................................................69
  Simplified Empirical Methods for Forces .....................................69
Appendix 6. Propulsion Assessment Procedure agreed with Japan ....................72
Appendix 7. List of Selected Publications by SHOPERA Consortium ...............79
1 Introduction to project SHOPERA – Objectives

The introduction of the Energy Efficiency Design Index (EEDI) was a major step towards improving energy efficiency and reducing greenhouse gas (GHG) emissions of shipping. It has also raised concerns that some ship designers might choose to lower the installed power to achieve EEDI requirements instead of introducing innovative propulsion concepts. This can lead to insufficient propulsion and steering abilities of ships to maintain manoeuvrability under adverse weather conditions, thus to a serious ship safety problem. Work carried out by IACS highlighted this issue and led to the development of first draft guidelines for consideration by IMO in 2011, IMO MEPC 62/5/19 and MEPC 62/INF.21, which resulted later in 2012 Interim Guidelines, see IMO MEPC 64/4/13, MEPC 64/INF.7, updated in 2013 in Res. MEPC.232 (65).

Even though the 2013 Interim Guidelines prevent irrational reduction of installed power, their sufficiency was disputed, especially concerning the definition of the minimum power lines, adversity of the weather conditions to be considered in the assessment and removal of comprehensive assessment. Several research initiatives in various European countries and Japan, aiming at updating these guidelines (see, e.g. IMO submissions MSC 93/21/5 and MSC 93/INF.13 by Greece, MEPC 67/INF.22 by Japan, MEPC 67/4/16 by Denmark, Japan and the Republic of Korea, and MEPC 67/INF.14 by Germany, Norway and the United Kingdom) were started and are expected to lead to the rationalization of the interim guidelines, may be at MEPC 70 in October 2016.

To address the above challenges by in-depth research, the EU funded project SHOPERA (Energy Efficient Safe SHip OPERAtion) (2013-2016) was launched in October 2013. SHOPERA is developing suitable numerical methods and software tools and is conducting systematic case studies, which will enable the development of improved guidelines and their submission for consideration to IMO. A strong European RTD consortium was formed1, representing the whole spectrum of the European maritime industry, including classification societies, universities, research organisations and model basins, ship designers, shipyards and ship operators. The project's objectives are:

- Develop criteria and corresponding environmental conditions for the assessment of the sufficiency of propulsion and steering systems of ships for manoeuvrability in adverse conditions, including open sea, coastal waters and restricted areas.
- Develop and adapt existing high fidelity hydrodynamic simulation software tools for the efficient analysis of the seakeeping and manoeuvring performance of ships in complex environmental and adverse weather conditions.
- Perform seakeeping and manoeuvring model tests in seaway by using a series of prototypes of different ship types to provide the required basis for the validation of employed software tools.
- Develop simplified assessment procedures, to the extent feasible, which should enable a quick assessment of the safety margins of ship designs with respect to the minimum propulsion and steering requirements for manoeuvrability in adverse weather conditions.
- Integrate validated methods and software tools for manoeuvrability assessment of ships in adverse weather conditions into a ship design software platform and combine it with a multi-objective optimization procedure, targeting sufficient propulsion and steering requirements for safe ship operation in adverse weather conditions while keeping the right balance between ship economy, efficiency and safety.

1 http://www.shopera.org, National Technical University of Athens (NTUA, coordinator), DNVGL, Lloyds Register (LR), Marintek (MRTK), Instituto Superior Tecnico (IST), Univ. Duisburg-Essen (UDE), Registro Italiano (RINA), Flensborg Schiffbau Gesellschaft (FSG), Uljanik Shipyard (ULJ), VTT, Flanders Hydraulics Research (EVFH), CEHIPAR, Strathclyde University (SU), Denmark Technical University (DTU), Tech. Univ. Berlin (TUB), Delft University of Technology (DUT), Naval Architecture Progress (NAP), Danaos Shipping Company Ltd. (DANAOS), FOINIKAS Shipping Co., CALMAC Ferries Ltd.
Conduct investigations of the impact of the proposed requirements on the propulsion and steering abilities of ships for manoeuvrability in adverse conditions on the design and operational characteristics of various ship types by design teams comprising designers, shipyards, shipowners, classification societies, research institutes and universities. The impact on EEDI was also investigated by implementation of the developed holistic optimisation procedure in a series of case studies.

2 Scenarios and Criteria

2.1 Terminology

To facilitate understanding, the following terminology is used throughout the report:

- The term **criterion** refers to a characteristic of the ship, such as ability to turn, ability to keep course etc., by which ship’s abilities, considered relevant relevant for the considered problem, are judged.

- Corresponding **measure**, e.g. turning diameter or overshoot angle, quantifies numerically the performance of ship with respect to the considered criterion. For manoeuvrability in adverse conditions, an obvious and frequently used measure is the marginal (maximum) weather severity, up to which the ship is able to fulfil the criterion (e.g. maximum wave height at which the ship can change course).

- The term **standard** (sometimes called **norm** or **limit** for the ship to be considered as fulfilling the corresponding criterion). Here, it is the specified significant wave height (and the related wind force) at which the ship should be able to fulfil the corresponding criterion.

2.2 Existing Regulations

Manoeuvrability of ships is presently normed by *IMO Standards for Ship Manoeuvrability, IMO (2002)*, which address turning, initial turning, yaw checking, course keeping and emergence stopping abilities, evaluated in simple standard manoeuvres in calm water. These Standards have been often criticized for not addressing ship manoeuvring characteristics at low speed, in restricted areas and in adverse weather conditions; the importance of the latter increased after the introduction of EEDI.

In *EE-WG 1/4 (2010)*, IACS put together the requirements of classification societies related to the redundancy or duplication of the propulsion system to indicate relevant criteria and environmental conditions for steering and propulsion in adverse weather conditions; a summary of these requirements in Table 1 (\(v_d\) means design speed, \(v_w\) wind speed, \(h_s\) significant wave height) indicates, basically, two requirements: to change (or keep) heading and to maintain some minimum advance speed (or to keep position, i.e. zero speed).

Studies by IACS on minimum power requirements for manoeuvrability in adverse weather conditions started with analysis of functional requirements to manoeuvrability in the open sea and coastal areas, *MEPC 62/5/19 (2011)* and *62/INF.21 (2011)*, concluding that manoeuvring in coastal waters is more challenging than in the open sea; the resulting criteria for ship propulsion and steering abilities were formulated in *MEPC 64/4/13 (2012)* and *64/INF.7 (2012)*: the ship should be able, in seaway from any direction, to (1) keep course and (2) keep advance speed of at least 4.0 knots. The corresponding weather conditions are not too severe, because ship masters do not stay near the coast in an increasing storm and either search for a shelter or leave to the open sea and take a position with enough room for drifting. The standard
environmental conditions defined by IACS (wind speed 15.7 m/s at significant wave height 4.0 m for ships with \( L_{pp}=200 \) m to 19.0 m/s and 5.5 m, respectively, for \( L_{pp}=250 \) m and greater) were derived by benchmarking of tankers, bulk carriers and containerships in the EEDI database against these two criteria.

Table 1. Criteria and weather conditions for redundancy and duplication of propulsion system according to requirements of classification societies, EE-WG 1/4 (2010)

<table>
<thead>
<tr>
<th>Class</th>
<th>Criteria</th>
<th>( \nu_w )</th>
<th>( h_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GL</td>
<td>Change and keep heading (weather-vaning)</td>
<td>21 m/s</td>
<td>5.4 m</td>
</tr>
<tr>
<td>GL</td>
<td>Advance speed ( \geq ) min(7 knots, 0.5( \nu_w ))</td>
<td>11 m/s</td>
<td>2.8 m</td>
</tr>
<tr>
<td>LR</td>
<td>Steering ability; advance speed ( \geq ) 7 knots</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BV</td>
<td>Advance speed ( \geq ) 7.0 knots</td>
<td>Bft 5 (8.0 to 10.7 m/s)</td>
<td>corresp. to ( \nu_w )</td>
</tr>
<tr>
<td>ABS</td>
<td>Weather-vaning without drifting</td>
<td>33 knots (17.0 m/s)</td>
<td>4.5 m</td>
</tr>
<tr>
<td>DNV</td>
<td>Weather-vaning at advance speed ( \geq ) 6 knots</td>
<td>Bft 8 (17.2 to 20.7 m/s)</td>
<td>corresp. to ( \nu_w )</td>
</tr>
</tbody>
</table>

2.3 Accidents

In SHOPERA, available detailed investigations of accidents related to insufficient manoeuvrability in adverse weather conditions were studied. Summarising, as the most frequent cause of heavy weather-related grounding accidents is waiting at anchor in heavy weather and too late starting of the engine. In several accidents, MAIB (1996, 2009, 2012), ATSB (2008), vessels were not able to move away from the coast or turn into seaway despite full engine power applied. Table 2 summarises corresponding criteria, relevant for insufficient propulsion or course-changing abilities, as well as the corresponding weather conditions.

Table 2. Summary of accident reports

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Relevant criteria</th>
<th>Environmental Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIB (2009)</td>
<td>Course changing</td>
<td>Bft 9-10 (20.8 to 28.4 m/s), ( h_s &gt; 10 ) m</td>
</tr>
<tr>
<td>MAIB (1996)</td>
<td>Course changing</td>
<td>gale force wind (17.3 to 20.8 m/s), low waves</td>
</tr>
<tr>
<td>MAIB (2012)</td>
<td>Propulsion</td>
<td>( \nu_w = 40 ) knots (20.6 m/s), ( h_{max} = 4 ) m</td>
</tr>
<tr>
<td>ATSB (2008)</td>
<td>Propulsion</td>
<td>( \nu_w = 38-46 ) knots (19.5 to 23.7 m/s), ( h_s = 6.0-6.6 ) m</td>
</tr>
<tr>
<td>MAIB (2002)</td>
<td>Propulsion</td>
<td>Bft 5-7 (8.0 to 17.1 m/s), low waves</td>
</tr>
<tr>
<td>MAIB (2009a)</td>
<td>Propulsion</td>
<td>Bft 10 (24.5 to 28.4 m/s)</td>
</tr>
<tr>
<td>MAIB (2012a)</td>
<td>Course changing</td>
<td>( \nu_w = 38-45 ) knots (19.5 to 23.2 m/s)</td>
</tr>
</tbody>
</table>

Regarding adverse weather conditions related to accidents, we may recall the well-known statistics of the HARDER project indicating that more than 80% of the collisions happened at significant wave height below 2 m, whereas significant wave heights exceeding 4 m were practically not recorded. Similar results were obtained from a comprehensive statistical analysis of ship accidents\(^2\) in adverse sea conditions, conducted in SHOPERA by Ventikos et al (2014). Two main sources were used for the collection of the necessary information, namely the IHS Sea-Web marine casualty database and the public area of the marine casualties and incidents database of the International Maritime Organization (IMO) Global Integrated Shipping Information System (GISIS). The information collected from these sources was cross-checked, wherever possible, with accident reports acquired from other sources (various National Maritime Safety authorities).

A characteristic sample of results of this analysis is given in Figure 1 to Figure 8 and associated Table 3 to Table 6.

---

\(^2\) Accident period 1980-2013; ships over 400 GT built after 1980; analysed accidents were related to adverse and heavy weather conditions, excluding poor visibility (e.g. fog).
From these statistics it is evident that:

1. The most vulnerable ship types with respect to navigational accidents in adverse conditions are general cargo ships, followed by Ro-Ro ferries, bulk carriers and tankers, Figure 1.
2. For these ship types, the accident location varies between port areas (almost exclusively for Ro-Ro ferries) and generally limited waters, such as port and restricted waters (for general cargo vessels and bulkers); for tankers, we observe some increased sensitivity in en route (open seas) conditions, Figure 2.
3. Inclusion in the statistical analysis of very rare abnormal weather events (hurricanes, typhoons etc.) does not significantly alter the statistics, Figure 3 and Figure 4.
4. Observed mean wind speeds of about 10 m/s and significant wave heights of 1.49 m are remarkably low, Figure 5 and Figure 6; this also applies to the statistical quartiles, Table 3, with lower values observed for collisions and groundings and the highest recorded values related to contacts.
5. There is a statistically significant difference in mean wave height between ship types, which means that some ship types are more affected by wave height than the others, Figure 7.
6. The calculated accident rates, related to the Fleet at Risk, are in the range of $10^5$ to $10^3$ accidents per ship per year, Table 4, i.e. by one order of magnitude lower than accident rates calculated in Formal Safety Assessments, which do not consider the prevailing weather conditions.
7. Among the three navigational accident types, groundings exhibit the highest rates for cargo carrying ships in general, whereas for Ro-Ro ships contacts are associated with the highest rates, Table 5.
8. Based on the available information, hull damage was selected as a main consequence variable for the risk analysis. The collected data were organized in categories of increasing level of severity, considering their qualitative nature, Table 6.
9. The risk analysis implemented the concept of risk triplets, Kaplan and Garrick (1981), defined by (Scenario, Frequency, and Consequence) and enabled the generation of three distinct types of risk-related curves, based on accident frequencies per ship type, per ship type and size class, and per ship and accident type. A characteristic result of this analysis is shown in Figure 8.
10. Overall, groundings and contacts in heavy weather conditions are the accident types with the highest risk across all ship types.
11. Comparison of risk levels between ship types shows that Ro-Ro Ferries and RoRo Cargo ships exhibit high risk values due to high accident frequency and medium level of consequences, whereas Gas Carriers, Tankers and Bulk Carriers exhibit high risk values due to the observed high level of accident consequences.
Figure 1. Percentage of ship types involved in navigational accidents under adverse weather conditions by accident type

Figure 2. Percentage of ship types engaged in navigational accidents under adverse weather conditions by accident location

Figure 3. Distribution of accident types when including very extreme (abnormal) weather conditions

Figure 4. Comparison of accident location when including very extreme (abnormal) weather condition

Figure 5. Frequency histogram for wind speed

Figure 6. Frequency histogram for wave height

Table 3. Mean and quartiles for wind speed and wave height per accident type

<table>
<thead>
<tr>
<th></th>
<th>WIND SPEED (m/s)</th>
<th>WAVE HEIGHT (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Collision</td>
<td>Contact</td>
</tr>
<tr>
<td>Mean</td>
<td>9.48</td>
<td>11.49</td>
</tr>
<tr>
<td>25th</td>
<td>6.69</td>
<td>8.45</td>
</tr>
<tr>
<td>50th</td>
<td>8.63</td>
<td>11.64</td>
</tr>
<tr>
<td>75th</td>
<td>11.00</td>
<td>14.04</td>
</tr>
</tbody>
</table>

https://edocs.imo.org/Final Documents/English/MEPC 70-INF.33 (E).docx
Table 4. Fleet at Risk and accident rates per ship type

<table>
<thead>
<tr>
<th>Ship Type</th>
<th>Period</th>
<th>Fleet at Risk</th>
<th>Accidents</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Containerships</td>
<td>1996-2013</td>
<td>63594</td>
<td>8</td>
<td>1.26E-04</td>
</tr>
<tr>
<td>Cruise Ships</td>
<td>1996-2013</td>
<td>5252</td>
<td>11</td>
<td>2.09E-03</td>
</tr>
<tr>
<td>Ro-Ro</td>
<td>1996-2013</td>
<td>19173</td>
<td>56</td>
<td>2.92E-03</td>
</tr>
<tr>
<td>Pure Car Carriers</td>
<td>1996-2013</td>
<td>9814</td>
<td>8</td>
<td>8.15E-04</td>
</tr>
<tr>
<td>Gas Carriers</td>
<td>1996-2013</td>
<td>22195</td>
<td>6</td>
<td>2.70E-04</td>
</tr>
<tr>
<td>Tankers</td>
<td>1990-2013</td>
<td>145159</td>
<td>23</td>
<td>1.58E-04</td>
</tr>
<tr>
<td>Bulk Carriers</td>
<td>1990-2013</td>
<td>143158</td>
<td>49</td>
<td>3.42E-04</td>
</tr>
<tr>
<td>General Cargo</td>
<td>1996-2013</td>
<td>23462</td>
<td>74</td>
<td>3.15E-03</td>
</tr>
</tbody>
</table>

Table 5. Rates of accidents in database per ship and accident type

<table>
<thead>
<tr>
<th>Categories</th>
<th>Container Ships</th>
<th>Cruise Ships</th>
<th>Ro-Ro</th>
<th>Crude Oil Tankers</th>
<th>LNG</th>
<th>LPG</th>
<th>General Cargo</th>
<th>Bulk Carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision</td>
<td>1.57E-05</td>
<td>7.62E-04</td>
<td>5.22E-04</td>
<td>3.44E-05</td>
<td>-</td>
<td>-</td>
<td>7.67E-04</td>
<td>9.78E-05</td>
</tr>
<tr>
<td>Contact</td>
<td>1.57E-05</td>
<td>9.52E-04</td>
<td>1.72E-03</td>
<td></td>
<td>4.51E-05</td>
<td>5.77E-05</td>
<td>4.26E-04</td>
<td>4.19E-05</td>
</tr>
<tr>
<td>Grounding</td>
<td>9.43E-05</td>
<td>3.81E-04</td>
<td>6.26E-04</td>
<td>1.24E-04</td>
<td>4.51E-05</td>
<td>1.73E-04</td>
<td>1.83E-03</td>
<td>2.03E-04</td>
</tr>
</tbody>
</table>

Table 6. Description of categories for hull damage data

<table>
<thead>
<tr>
<th>Categories</th>
<th>Dummy Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>0</td>
<td>No hull damage reported.</td>
</tr>
<tr>
<td>YES</td>
<td>2</td>
<td>Hull damage reported.</td>
</tr>
<tr>
<td>DAMAGE ABOVE WATER LINE</td>
<td>4</td>
<td>Minor hull damage reported above water line</td>
</tr>
<tr>
<td>DAMAGE BELOW WATER LINE</td>
<td>6</td>
<td>Hull damage reported below water line that led to Loss Of Watertight Integrity (LOWI).</td>
</tr>
<tr>
<td>TOTAL LOSS</td>
<td>8</td>
<td>Severe and extended hull damage that led to Loss Of Watertight Integrity (LOWI) and resulted in the sinking of the ship.</td>
</tr>
</tbody>
</table>

Figure 7. Mean wave height per ship type

Figure 8. Risk related curves based on rates per ship and accident type (all ship types)
2.4 Interviews of Ship Masters

Interviews of masters of about 50 containerships, bulk carriers and tankers conducted in the projects PerSee and SHOPERA indicate that in the open sea, the captain usually has more freedom and can decide what severity of weather conditions is acceptable for his ship, depending on the freeboard, cargo, stability and propulsion and steering characteristics of the vessel. On the other hand, when caught in most violent storms, steering against seaway may be impossible for any vessel; in such circumstances, drifting with seaway was considered as an acceptable option for a limited time if there is enough room for drifting. However, the available power is important for escaping the storm and bringing the ship into safe weather conditions.

Manoeuvring in coastal areas was reported as more challenging than manoeuvring in the open sea, because, in principle, any manoeuvre, sometimes in unfavourable seaway direction with respect to the ship, may be required. Environmental conditions are, however, less severe than in the open sea, because ship masters do not remain near the coast in a growing storm, but either search for shelter or leave to the open sea.

As relevant manoeuvring problems, steering problems were mentioned in the interviews insignificantly more often than propulsion problems (83% vs. 60% of cases, respectively); insufficient engine power was mentioned more frequently for bulk carriers and tankers, whereas insufficient rudder capability more frequently for container vessels. As a very specific manoeuvring problem in restricted waters, manoeuvrability at limited speed (due to navigational restrictions, e.g. during approaching ports) was mentioned, in strong wind and, sometimes, strong current, but usually without large waves because of protected areas.

2.5 Proposal for Scenarios and Criteria

Based on the above results, Shigunov and Papanikolaou (2014) proposed to differentiate three scenarios, in which steering and propulsion abilities of ships are challenged in a different way and which require, therefore, specific criteria: open sea, coastal areas and restricted areas at limited speed. For the open sea, the ability of ship to weather-vane, i.e. keep heading in head to bow-quartering seaway, was proposed as a criterion. Regarding corresponding environmental conditions, it was noted that none of existing ships can steer against waves and wind in most severe possible storms, therefore, benchmarking of the existing world fleet with respect to the weather-vaning criterion was proposed to define the standard wave height. For the coastal areas, two criteria were proposed: the ability of the ship to perform any manoeuvre and the ability to maintain some speed over ground to enable leaving the coastal area before the storm escalates; due to navigational restrictions, both criteria should be possible to fulfil in seaway from any direction. The corresponding environmental conditions are less severe than in the open sea and should also be defined by benchmarking of existing ships against these criteria. Manoeuvrability at limited speed in restricted areas refers to situations where the ship master has to reduce the applied engine power (and thus forward speed) significantly below available power because of navigational restrictions, e.g. during approaching to or entering ports, navigation in channels and rivers etc. Because full available power cannot be applied in this scenario, the corresponding manoeuvrability criteria will not impose any restrictions on minimum propulsion power, thus this scenario is not considered here.

Based on this, SHOPERA proposed the following three criteria for manoeuvrability in adverse weather conditions: weather vaning ability in heavy weather in the open sea and steering and propulsion abilities in increasing storm in coastal areas.
In the practical assessment, weather-vaning ability was treated in a simplified way, as the ability of the ship to keep position in bow to bow-quartering seaway; this simplification follows from the observation, confirmed by model tests, that the ship (with the traditional steering devices at the stern) will not be able to keep heading under the action of environmental forces if the forward speed is not sufficiently large, because of significantly reduced manoeuvring reactions on the hull and steering force on the rudder.

The steering ability in increasing storm in coastal areas is understood as the ability of the ship to perform any manoeuvre in seaway from any direction. An equivalent, but easier to verify in practice criterion is proposed, that the ship should be able to start or continue course change in seaway from any direction. This formulation should be distinguished from the traditional course-keeping problem: the steering ability is understood here as the ability of the steering system to overcome environmental forces and start (or continue) course change during an arbitrary manoeuvre (i.e. capability of the steering system); for this ability, it does not matter whether each intermediate state during manoeuvre is stable or not, thus the stability of the ship on each particular course is not addressed, whereas the traditional definition of course-keeping addresses stability of straightforward motion. Note that the proposed criterion does not exclude the ship's ability to perform also straightforward motion (which is one of "all" required manoeuvres): even if a ship is directionally unstable on some course, it will still be able to follow this course using rudder for continuous course corrections (which is an operational drawback and not a safety issue, and is relevant in few situations per operational life).

The propulsion ability in increasing storm in coastal areas ensures that the ship is able to leave coastal area in a sufficient time before the storm escalates. As the minimum required advance speed, 6.0 knots was chosen by SHOPERA, instead of 4.0 knots used in 2013 Interim Guidelines, to take into account possibly strong currents in coastal areas.

The corresponding environmental conditions for these three criteria need to be defined by benchmarking of existing vessels with respect to these criteria.

Table 7. Scenarios, functional requirements, criteria and environmental conditions

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Functional Requirements</th>
<th>Criteria</th>
<th>Environmental Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme weather, open sea</td>
<td>Weather-vaning in bow seaway</td>
<td>Weather-vaning ability: Keep heading in bow to bow-quartering waves</td>
<td>Severe to extreme</td>
</tr>
<tr>
<td>Increasing storm, coastal waters</td>
<td>Any manoeuvre and ability to move in wind and waves from any direction</td>
<td>Steering ability: Start or continue course change in waves and wind from any direction, Propulsion ability: keep speed of at least 6.0 knots in waves and wind from any direction</td>
<td>Moderate to severe</td>
</tr>
</tbody>
</table>

2.6 Environmental Conditions

Wave Height

The existing 2013 Interim Guidelines do not consider manoeuvring criteria for the open sea. SHOPERA has introduced the weather-vaning criterion for the open sea, which requires corresponding standard environmental conditions. A straightforward choice of the North Atlantic scatter table, IACS (2001), is not suitable to define the weather conditions to be used with the weather-vaning criterion: First, although this scatter table is based on visual onboard observations, BMT (1986), it is unknown whether ships were able to manoeuvre in the reported sea states and what manoeuvres they were able to perform. Second, the North Atlantic scatter table, IACS (2001), has been obtained by the extrapolation of observed probabilities of encounter of observed sea states towards lower probabilities, which introduced more severe
sea states, which were never observed onboard and in which the manoeuvring abilities of existing ships have never been challenged; in particular, it is unknown whether existing ships can or cannot weather-vane in such sea states. Finally, safety of a ship that is not able to weather-vane in a certain sea state in the open sea and thus has to drift in beam seaway will still be ensured due to the IMO Severe Wind and Rolling Criterion (Weather Criterion), IMO (2008). Therefore, benchmarking of the existing fleet with respect to the weather-vaning criterion appears as the most rational way to define the standard wave height: the standard wave heights should be defined in such a way that the majority of the existing vessels fulfil the related requirements, taking into account that the present safety level with respect to manoeuvrability-related accidents in heavy weather is satisfactory, Ventikos et al. (2014).

For increasing storm in coastal waters, the 2013 Interim Guidelines use two criteria, course keeping and advance speed. The corresponding standard wave heights were defined by benchmarking of tankers, bulk carriers and containerships in the EEDI database against these two criteria, which led to the significant wave height 4.0 m and wind speed 15.7 m/s for ships with $L_{pp}=200$ m and significant wave height 5.5 m, and wind speed 19.0 m/s for $L_{pp}=250$ m and greater, with a linear interpolation of wave height and wind speed for $L_{pp}$ between 200 m and 250 m. SHOPERA aimed at validation of the proposed weather conditions with respect to the measurements. The problem is, on the one hand, that there are no unified recommendations for the seaway parameters for coastal areas. Second, met-ocean climate of coastal areas strongly depends on the region and local bathymetry, which cannot be taken into account in regulations addressing ship safety in unrestricted service.

In Figure 9, wave data are compared for three coastal locations studied in SHOPERA, the access channel to the port of Antwerp (measurement data available from Flemish Banks Monitoring Network, 2016, and cover the period from 1984 to 2004), Scottish waters (hindcast data generated by the UK Met Office for the period from 2000 to 2008) and the port of Leixões (wave hindcast data simulated by IST for the period from 2000 to 2012).

The 40 nautical mile long access channel to the port of Antwerp is dredged in a rather protected sand banks area, whereas both the Scottish coastal waters and the port of Leixões are not as protected. Correspondingly, the former area indicates milder wave heights that the latter two. Noting different duration of observations for the three considered areas (which leads to different observed minimum probabilities), and that these probabilities are too high to define design values, the measurements can be compared for the same probability of occurrence (e.g. $10^{-4}$); this leads to the maximum significant wave heights for the access channel to the port of Antwerp, Scottish waters and the port of Leixões of about 4.5 m, 5.5 m and 6.0 m, respectively.

---

3 Note, however, the agreed seaway conditions of the Regional Stockholm Agreement (SOLAS, Part B, Res. 14) for the assessment of the damage stability of RoPax ships in coastal waters, specifying a JONSWAP spectrum with a significant wave height of not more than 4.0m in European waters, with a probability of non-exceedance of 98.5%.
Figure 9. Empirical and fitted marginal distributions of significant wave height for access channel to port of Antwerp (left), Scottish waters (middle) and the port of Leixões (right)

Noting that these measurements refer to fixed observation locations, whereas ship masters do not remain on the same position near the coast in a growing storm, but either search for shelter or leave to the open sea, SHOPERA has used also several other sources to estimate rationally the required standard wave heights. Statistics of the weather conditions during manoeuvring-related accidents in adverse weather conditions, Ventikos et al. (2014), shows remarkably mild environmental conditions during accidents (mean wind speed of about 10 m/s and mean significant wave height about 1.5 m, Figure 5 and Figure 6), which agrees with the earlier statistics from the HARDER project, indicating significant wave height below 2.0 m in 80% of collisions and absence of collisions at significant wave heights greater than 4.0 m

The study by IACS, EE-WG 1/4 (2010), Table 1, also identifies rather mild standard wave heights for weather-vanning (wind speed up to 21 m/s and significant wave height up to 5.4 m) and advance speed (wind force up to Bft 8 at 6.0 knots advance speed) requirements.

On the other hand, maximum significant wave heights and wind speeds during manoeuvrability-related accidents achieve, according to SHOPERA statistics, in rare cases 7.0 m and 20 m/s, respectively. Detailed accident reports, Table 2, indicate wind force up to Bft 10 (in excess of 23 m/s) and significant wave heights above 6.0 m during few accidents in coastal areas. However, the well-documented case ATSB (2008), where the significant wave height exceeded 6.0 m, clearly indicates unacceptably long waiting of the vessel at anchor in an increasing storm as the reason of the accident. Figure 10 shows the number of ships at anchor as percentage of the initial number of vessels at anchor depending on the significant wave height during this storm. Whereas the two vessels, which experienced the accident and a near-accident, have been waiting at anchor until significant wave height exceeded 6 m, 50% of the vessels left anchorage before significant wave height achieved about 5.5 m.

Figure 10. Number of vessels at anchor as percentage of the initial number of anchored vessels vs. significant wave height during an increasing storm according to data in ATSB (2008)

4 It is noted that the agreed seaway conditions of the Regional Stockholm Agreement (SOLAS, Part B, Res. 14) for the assessment of the damage stability of RoPax ships in coastal waters, specify a JONSWAP spectrum with a significant wave height of not more than 4.0 m in European waters.
Similar conclusions follow from the interviews of ship masters. Figure 11: 50% of the ship masters prefer to leave coastal areas before wind increases to Beaufort 8 and significant wave height achieves 5.0 m.

![Figure 11. Wind force (top) and significant wave height (bottom) during leaving coastal areas (○) and during encountering steering and propulsion problems (●) from interviews of ship masters](image)

The scatter between the wave heights relevant for manoeuvrability in coastal areas from different sources is not really surprising if we take into account that manoeuvrability performance depends to a large extent on characteristics of the vessel and on the operational experience and practices of the ship master. Therefore, benchmarking of the existing fleet with respect to the new criteria appears as the most rational way to define the standard wave height, for several reasons:

1. It is impossible to design efficient ships for the worst possible storms that can be encountered even in coastal areas, nor it is necessary as ships can escape extreme weather conditions. The standard wave heights should be defined in such a way that the majority of the existing vessels fulfil the requirements, because, first, the benchmarking will reflect the established operational practices, which are important for manoeuvrability in general and, especially, for manoeuvring in heavy weather, and, second, because the present safety level with respect to manoeuvrability-related accidents in heavy weather is considered satisfactory, Ventikos et al. (2014).

2. Sea routing and heavy weather avoidance have a very strong influence on the encountered weather conditions. Both have been significantly improved over the last years, which is reflected in design and operational practices and should be taken into account by regulations.

3. The criteria proposed by SHOPERA address relevant parameters and characteristics of the ship engine, propulsion and steering systems for manoeuvrability in adverse conditions, but they are significantly simplified to remain practicable and thus should not be confused with operational guidance. For example, these criteria cannot say what particular manoeuvres are possible in particular adverse conditions. On the other hand, because these criteria take into account relevant ship characteristics, they can be fine-tuned to reproduce differentiation between safe and unsafe existing vessels. In this sense, the absolute values of the selected standard environmental conditions used with each of the criteria are not relevant; the actual aim relevant is the fine-tuning of the outcome of the assessment.

In SHOPERA, dedicated case studies were undertaken concerning all ship types considered in the EEDI regulations; results are presented in the Chapter Case Studies.
Wind Speed

The influence of wind forces on propulsion and steering ability in seaway is comparable to the influence of the time-average wave forces for ships with a large windage area, such as container vessels and pure car and truck carriers, and is less important, but not negligible, for vessels with moderate windage area, such as bulk carriers and tankers, Shigunov (2015). For practical assessment, it is convenient to use a unified wind speed-wave height relationship (perhaps different for the open sea and coastal areas) rather than use wind speed as an additional standard. The problem in the derivation of such a unified relation is that the relation between wind speed and wave height strongly depends on the fetch (i.e. the length of water surface over which a given wind has blown), wind duration and relation between the wind sea and swell (i.e. waves generated distant weather systems and not by the local wind). Because these factors depend on location, the relation between the wind speed and wave height is location dependent, even when considered in a statistical sense.

The well-known semi-empirical formula by Bretschneider for the wind sea (taken from Michel, 1999),

\[ h_s = 0.243 \frac{v_w^2}{g} \left(0.011 \sqrt{gF/v_w} \right), \]

where \( F \), \( m \), is the fetch length, and wind speed \( v_w \) is assumed at 10 m height above the free surface, gives for the unlimited fetch (open sea) an expression \( h_s = 0.0248v_w^2 \), or

\[ v_w = 6.354 \sqrt{h_s}, \]

denoted as Unlimited Fetch in Figure 12. This figure shows also a recommendation for the wind speed-wave height relationship for fully developed seas in the open areas according to NATO (1983), denoted as STANAG 4194, and hindcast data for two open-sea locations, West Shetland (generated by Oceanweather Inc. for the period from 1988 to 1998) and South-East of Iceland (generated by MET Norway for the period from 1955 to 2009, denoted SE Iceland). Both these locations are characterised by severe wind and are strongly affected by swell, representing typical North Atlantic met-ocean climate.

The semi-empirical relation (2) agrees well with the hindcast data for the both locations and provides slightly conservative estimation of the required wind speed for a given significant wave height, which might be due to the presence of swell in the hindcast data, which increases wave heights at moderate wind speeds and has less influence at greater wind speeds. The recommendation NATO (1983) agrees well with the semi-empirical formula at moderate wind
speeds, but under-estimates wave heights at wind speeds greater than 12 m/s, thus leading to more conservative wind speed for given wave height in the relevant region of significant wave heights.

Formula (2) is recommended by SHOPERA for the open sea.

For coastal areas, the influence of limited fetch for offshore wind can be very significant. Figure 13 shows wind speed as a function of significant wave height for 10, 20 and 30 miles fetch in comparison with the relation (2) for unlimited fetch (denoted as Unlimited Fetch). For comparison, the wind speed-wave height relationship is shown also according to the following sources:

- 2013 Interim Guidelines for Determining Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions (denoted 2013 Guidelines);
- SHOPERA accident statistics described in section 2.3 (denoted Accidents);
- Hindcast data for a North Sea location off Dutch coast (simulated by Oceanweather Inc. for the period from 1964 to 1995, denoted Hindcast SNS).

![Image](https://edocs.imo.org/Final Documents/English/MEPC 70-INF.33 (E).docx)

The accident data shows a considerable number of accidents in strong wind and under-developed waves; in such conditions, wind force at a given significant wave height increases considerably compared to eq. (2). The hindcast data for the south coast of North Sea agrees well with accident data in the relevant region of significant wave heights, but shows significantly smaller wind speeds in low to moderate seaways. The 2013 Interim Guidelines provide a good estimation for the wind speed in more severe seaways, but under-predict the wind speed in moderate to severe conditions. As a recommendation, agreeing with both accident data and hindcast in the relevant region of significant wave heights, and also providing a fair average of the accident data in low to moderate sea states, the following formula is proposed for coastal areas (shown as Proposal in Figure 13):

\[
v_w = 9 \cdot h_s^{0.44}.
\]  

(3)

Other Sea State Parameters

In severe to extreme sea states, the influence of swell is usually negligible compared to the wind sea, whereas in small to moderate seaways, the influence of swell may be significant. Figure 12 shows that for the significant wave heights relevant in the assessment of manoeuvrability in adverse conditions, the influence of swell is small, therefore, a unimodal spectrum can be assumed for simplicity.
For the open sea, it is feasible to assume a situation of a ship weather-vaning for a prolonged time until the storm finishes, i.e. a developed storm situation is relevant for the assessment of the weather-vaning ability in the open sea. For a developed sea state, the Bretschneider spectrum (also referred to as a two-parameter Pierson-Moskowitz spectrum or a two-parameter ITTC spectrum) is generally recommended,

$$S_{\zeta\zeta} = \frac{5}{\omega_p^2} \frac{h^2}{\pi^4} \exp\left(-\frac{20\pi^4}{\omega_p^2 \omega^4}\right),$$

where $T_p$, $s$, is the wave period corresponding to the modal wave frequency $\omega_p$, rad/s, and $\omega$, rad/s, is the wave frequency.

For coastal waters, assumed scenario, following from the practice and confirmed by the interviews of ship masters undertaken by SHOPERA, the assumed scenario is that ship masters do not remain near the coast in a growing storm until it escalates, but either search for shelter or leave to the open sea. Therefore, the feasible scenario to be applied with the steering and propulsion criteria is a developing storm. For a developing storm a general recommendation is to use the JONSWAP spectrum with the peak parameter of 3.3, i.e. as used in the 2013 Interim Guidelines for the evaluation of ship manoeuvrability in coastal areas,

$$S_{\zeta\zeta} = \frac{\alpha g^2}{\omega^2} \exp\left(-\beta \frac{\omega^4}{\omega_p^4}\right) \gamma^a,$$

where $\alpha = \exp\left(-\left(\omega - \omega_p\right)^2/(2\sigma_p^2\sigma^2)\right)$, $\sigma = 0.07$ if $\omega \leq \omega_p$ and $\sigma = 0.09$ if $\omega > \omega_p$, $\beta = 5/4$, and the peak parameter $\gamma = 3.3$.

As a realistic assumption, directional spreading of wave energy with respect to mean wave direction is recommended; as the spreading function, $\cos^2$-spreading was used in SHOPERA. An assessment of steering and propulsion abilities in short-crested waves with $\cos^2$-wave energy spreading in comparison with assessment in long-crested irregular waves for a VLCC tanker and 14000 TEU containership, Figure 14, shows that assuming long-crested seaway makes assessment results negligibly to moderately conservative, thus performing assessment in long-crested waves is also acceptable, as it is more practicable for designers.
Figure 14. Ratio of required delivered power to available delivered power (y axis) depending on significant wave height (x axis) for VLCC tanker (top) and 14000 TEU containership (bottom) from propulsion ability assessment (left) and steering ability assessment (right) in seaway with long-crested (blue lines) and short-crested (red lines) waves.

The range of characteristic wave periods (for clarity, peak wave period $T_p$ will be used) used in the assessment has a significant influence on the assessment results. For the propulsion ability criterion, as well as for the weather-vaning criterion, the upper (long waves) boundary of the used peak wave periods defines whether and how much of the added resistance peak is taken into account, whereas the lower boundary (short waves) is important for larger, especially blunt, vessels for which a significant part of added resistance comes from short wave components. For the steering ability criterion, external excitation increases with increasing wave frequency, therefore, it is important how the lower boundary (short waves) of the peak wave periods is defined.

Note that the recommended spectra are applicable in the range of peak wave periods $T_p$, s, from about $3.6h_s^{0.5}$ to about $5.0h_s^{0.5}$, marked in Figure 15 as $T_{p\text{min}}$-JONSWAP and $T_{p\text{max}}$-JONSWAP, respectively. The 2013 Interim Guidelines use the range of the peak wave periods from 7.0 (marked as $T_{p\text{min 2013 Guidelines}}$) to 15.0 s. Figure 15 shows also the most likely peak wave periods from measurements for two locations, West of Scotland and Belgium coast, and the theoretical maximum storm steepness boundary, Michel (1999), marked as Max. Steepness, $T_s = 8\sqrt{h_s/g}$ or, for JONSWAP spectrum, $T_p = 3.282\sqrt{h_s}$.

The lower boundary of peak wave periods used in the 2013 Interim Guidelines, 7.0 s, is slightly conservative, because it crosses the theoretical maximum storm steepness boundary in the relevant range of significant wave heights. The upper boundary, 15.0 s, although theoretically possible, is unnecessary large, because such large wave periods are not critical for propulsion or steering ability.

Figure 15. Peak wave periods recommended for the assessment
As the lower boundary of peak wave periods (short waves),

\[ T_p^{\min} = 3.6h_s^{0.5} \]  

(6)

seems appropriate: this and larger peak wave periods are assumed suitable for the JONSWAP wave spectrum; besides, the theoretical maximum storm steepness boundary is not violated. For the upper boundary of peak wave periods,

\[ T_p^{\max} = 5.0 \cdot h_s^{0.5} \]  

(7)

(or slightly higher) can be used, as this will cover the peak wave periods important for added resistance.

3 Assessment Procedures

3.1 General

The general assessment concept proposed by SHO|PERA is to allow free choice of assessment procedures of different complexity (similarly to 2012 Interim Guidelines), ranging from simple empirical formulae to advanced assessment procedures, so that the designer can select the most suitable procedure depending on the particular design needs. Simple assessment procedures are sufficient for the majority of conventional vessels, whereas more accurate assessment procedures and evaluation methods are required for cases with large uncertainties, such as innovative propulsion and steering solutions, which are intended to be promoted by the EEDI regulations.

SHO|PERA proposes three alternative assessment procedures:

- **Comprehensive Assessment** allows the best accuracy, solving coupled nonlinear motion equations. Still, the designer does not have to use tedious/expensive evaluation methods for different assessment components, but can choose between numerical, experimental or empirical methods for different elements. This type of assessment is anyway necessary for ships with innovative propulsion and steering arrangements.
- **Simplified Assessment**, a first-principle assessment with reduced number of considered situations and reduced complexity of motion equations, also allowing choosing between experimental, numerical or empirical methods to evaluate force components, and having complexity of a spreadsheet calculation.
- **Sufficient Propulsion and Steering Ability Check** is based on pure empirical formulae to define the required installed power as a function of main ship parameters (deadweight, block coefficient, windage area, rudder area, engine and propulsion type), of a complexity of a pocket calculator.

3.2 Comprehensive Assessment

Compliance with the IMO Manoeuvrability Standards, *IMO (2002)*, is demonstrated in full-scale trials, which is impossible for ship manoeuvrability assessment in adverse weather conditions. Alternatively, the proposed criteria (weather vaning, steering and propulsion abilities) can be evaluated, in principle, directly in transient model experiments with self-propelled ship models in simulated irregular waves and wind, for all required combinations of wave directions and periods. This is, however, presently unfeasible for practical purposes for several reasons: First, providing reliable statistical predictions in irregular seaway requires repeating tests in multiple long realisations of each seaway, which is too expensive. Besides, few facilities exist worldwide which are able to perform such tests, which makes such tests impractical for routine
design and approval. Third, verification of such tests by the Administration is impossible (unless the test program is repeated), which makes this approach impractical for approval. Finally, results of such tests very much depend on the time history of steering, which causes too large variability and uncertainty of test results, which therefore cannot be reliably verified especially in marginal cases (i.e. cases near the failure boundary, which are the actual cases of interest in approval). Alternative to such model tests, direct numerical simulations of transient manoeuvres in irregular seaway, are not mature enough yet for routine design and approval, *ITTC Manoeuvring Committee (2008).* The approach proposed by SHOPERA is based on separate evaluation of different acting forces (waves, wind, propeller, rudder etc.) using simple model tests, numerical simulations or empirical formulae, and combination of the defined forces in a simple numerical model. Whereas the resulting procedure is based on first principles and takes into account all relevant physics, it is at the same time:

- verifiable by Administrations or Recognised Organisations,
- based on technology presently available in the industry,
- inexpensive and as accurate as presently practicable,
- flexible, in that designers and administrations are free to choose alternative methods (experimental, numerical or empirical) depending on designer needs,
- open for updates when new numerical or experimental methods are developed, without the need to revise the Guidelines.

The Comprehensive Assessment procedure proposed by SHOPERA is based on neglecting oscillatory forces and moments due to waves and thus considering only time average forces and moments, assuming that the time scale of such oscillations is shorter than the time scale of manoeuvring motions. This effectively reduces the evaluation of manoeuvrability criteria to a solution of coupled motion equations in the horizontal plane under the action of *time-average* wave-induced forces, as well as wind forces, calm-water forces, rudder forces and propeller thrust. Projecting forces on the *x*- and *y*-axes and moments on the *z*-axis of the ship-fixed coordinate system, Figure 62, leads to a system of equations, converging to a steady state described by the following system (note that achieving converged solution can be realised in different ways, including time-domain simulation):

\[
\begin{align*}
X_s + X_w + X_d + X_R + T(1-t) & = 0 \\
Y_s + Y_w + Y_d + Y_R & = 0 \\
N_s + N_w + N_d - Y_R l_R & = 0
\end{align*}
\]

Indices *d*, *w*, *s*, and *R* denote, respectively, wave, wind, calm-water and rudder-induced forces and moments; *T* is propeller thrust. The coordinate system has an origin *O* in the main section at the water plane; *x*, *y*- and *z*-axes point towards bow, starboard and downward, respectively (positive rotations and moments with respect to *z*-axis are clockwise when seen from above). The ship sails with the speed *v_s*; its heading deviates from the course by the drift angle *β*. The mean wave and wind directions are specified by angles *β_w* and *β_w*, respectively (0, 90 and 180° for waves and wind from the north, east and south, respectively); rudder angle *δ* is positive to port; *l_R* is the lever of the yaw moment due to rudder. A converged solution, described by system (8)-(10), provides the required propeller thrust (from which, advance ratio *J*, rotation speed *n* of the propeller and required *P_D* and available *P_D* delivered power are found), drift angle *β* and rudder angle *δ*.

The evaluation of steering ability and propulsion ability criteria is performed as follows:

- According to the steering ability criterion, the ship should be able to overcome environmental forces to start or continue course change in waves and wind from any direction. To evaluate this criterion, the ratio of the required brake
power $P_B$ to the available brake power $P_{av}$ is computed along the line $[\delta = \delta_{max}]$; the maximum of the ratio $P_B/P_{av}$ should not exceed 1.0.

- According to propulsion ability criterion, the ship should be able to keep speed of at least 6.0 knots in waves and wind from any direction. To evaluate this criterion, the ratio of the required brake power $P_B$ to the available brake power $P_{av}$ is computed along the line $v_s = 4.0$ knots; the maximum of the ratio $P_B/P_{av}$ should not exceed 1.0.

Figure 16 shows examples of converged solutions and application of the steering and propulsion criteria in polar coordinates ship speed (radial) – seaway direction (circumferential, head waves and wind come from the top): along line A, the required delivered power is equal to the available delivered power, line B corresponds to the required advance speed (here 4.0 knots), and line C limits the highlighted area, in which the required steering effort exceeds the available one (here, rudder angle exceeds 25°). The left plot illustrates a seaway in which the vessel fulfils both criteria (line A does not cross lines B and C); in the middle plot, the installed power is marginally sufficient to provide advance speed of 4.0 knots in head seaway, where line A crosses line B; in the right plot, the installed power is marginally sufficient for steering in nearly beam seaway, where line A crosses line C.

The advantage of the proposed Comprehensive Assessment, and the main difference from the Comprehensive Assessment in the 2012 Interim Guidelines is that the different effects (wind, waves, calm water, rudder, propeller and engine) can be measured or computed separately, if necessary with different methods (experimental, numerical or empirical). Note that even if model tests or complex numerical computations are used for some of contributions, they are done in stationary setups under well-controlled conditions and combined in a simple mathematical model.

3.3 Evaluation Methods for Components of Forces and Moments

The terms of the equation system (8)-(10) can be defined with different methods: empirical formulae, numerical methods or model experiments. The methods that can be applied are described in Table 8.
Table 8. Methods for evaluation of components in Comprehensive Assessment procedure

<table>
<thead>
<tr>
<th>Elements</th>
<th>Components</th>
<th>Model Tests</th>
<th>Numerical Methods</th>
<th>Empirical Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm-water</td>
<td>X, Y, N</td>
<td>steady-drift tests</td>
<td>double-body steady-drift tests</td>
<td>empirical formulae</td>
</tr>
<tr>
<td>Time-average wave forces</td>
<td>X, Y, N</td>
<td>drift forces in regular waves at different speeds and headings</td>
<td>potential methods, CFD for drift forces in regular waves</td>
<td>empirical formulae</td>
</tr>
<tr>
<td>Wind forces</td>
<td>X, Y, N</td>
<td>static wind tunnel tests</td>
<td>CFD for static wind forces</td>
<td>empirical formulae</td>
</tr>
<tr>
<td>Rudder forces</td>
<td>X, Y</td>
<td>steady towing tests working</td>
<td>CFD simulations with rotating propeller</td>
<td>empirical methods</td>
</tr>
<tr>
<td>Open-water propeller characteristics</td>
<td>T, J, (n_p), (P_D)</td>
<td>open-water propeller tests</td>
<td>potential methods, CFD for open-water propeller simulations</td>
<td>propeller series</td>
</tr>
<tr>
<td>Engine</td>
<td>(P_B^{aw})</td>
<td>static model (engine diagram)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Because the proposed assessment procedure allows definition of different forces separately, using different (experimental, numerical or empirical) methods, an important question is how much freedom we have in the definition of each force component. Table 9 shows the percentage of the change of the required installed power to fulfil propulsion and steering ability requirements due to changes of each force or moment component in turn by 10% at significant wave height of 5.5 m, obtained with the Comprehensive Assessment (maximum values over several ships of different types are shown). The figures mean, for example, the following: a change of the \(x\)-calm water force by 10% changes the required installed power by 3.0%.

Table 9. Percentage change of required installed power due to change of components of forces and moments

<table>
<thead>
<tr>
<th>Contributions</th>
<th>(x)-force</th>
<th>(y)-force</th>
<th>(z)-moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm-water</td>
<td>3.0</td>
<td>3.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Wind</td>
<td>2.5</td>
<td>1.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Wave</td>
<td>3.8</td>
<td>3.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Rudder</td>
<td>1.5</td>
<td>3.4</td>
<td>-</td>
</tr>
</tbody>
</table>

The table shows that the most important contributors (bold) are the time-average \(x\)- (added resistance) and \(y\)-forces, calm-water \(x\)- and \(y\)- forces and \(z\)-moment and lateral rudder force. For these forces, the error of about 15% leads to the error in the definition of the required power of 5%.

Opposite to the transient manoeuvring tests in simulated wind and irregular waves, the proposed procedure relies on measurements of separate forces in well-controlled steady conditions. For calm-water, wind, rudder and propeller forces, such experiments are well established and can be done in many facilities world-wide (note that calm-water resistance and propulsion characteristics, including open-water propeller characteristics and hull-propeller interaction coefficients can be taken from the model tests that are required for EEDI verification anyway). However, measurement of the time-average wave forces requires advanced measurements in a seakeeping basin, therefore, cannot be used routinely.

Numerical methods are presently available, in principle, for the same forces (calm-water, wind, rudder and propeller) as well; however, their use in regulatory assessment needs a significant effort of administrations and recognised organisations. The availability of numerical methods for time-average wave forces is one of the most critical issues: the absence of suitable numerical methods for added resistance led the removal of numerical methods from the 2013 Interim Guidelines. Development and validation of numerical methods for time-average wave
forces and moments was one of the major tasks of SHOPERA. Model test measurements of such forces were done for three ship models (a 14000 TEU container vessel, a VLCC tanker and a RoRo) for various ship speeds and wave directions and periods (with particular emphasis on short waves); results of these measurements were used for an international benchmarking of the available numerical methods for time-average wave forces. The results of this benchmarking (will be published elsewhere) show a significant progress of numerical methods in the last years and indicate the principal availability of numerical methods for regulatory purposes, if applied correctly.

Especially important for the practical implementation of any practical procedure is the availability of empirical methods for different force components. In addition to the well-established empirical methods for wind forces, Blendermann (1993), Fujiwara et al. (2006), extensive validation studies were carried out together with the project from Japan for calm-water reactions and rudder forces in propeller race, which indicate availability of such empirical methods for the practical use; however, designers and Administrations should ensure that empirical methods are used within their applicability limits. Again, empirical methods for the time-average wave forces and moments have required particular attention and the significant progress achieved in the project will be reported elsewhere.

An important aspect of propulsion and steering in adverse conditions is a correct description of the engine under high load. Note that frequently used wrong assumptions (e.g. constant torque or constant rotation rate of the engine) lead to strongly misleading results. In SHOPERA, air/surge limits of diesel engines (two- and four-stroke) were verified and recommendations were provided for practical assessment procedures.

3.4 Simplified Assessment

Principles

The aim of the development of the Simplified Assessment was to have a simple enough procedure for routine use by Administrations by reducing the number of calculations (solution cases) as well as the number of terms in motion equations (8)-(10), while keeping all relevant physics. In particular, the Simplified Assessment addresses the same criteria as those enforced in the Comprehensive Assessment (weather-vaning, steering and propulsion). The simplified procedures for steering ability (ability to start or continue course change in any seaway direction) and propulsion ability (ability to keep a minimum advance speed in all seaway directions) were proposed in Shigunov et al. (2014). Below, they are summarised; more details can be found in Appendices 9 and 10. Appendix 11 contains a particular simplified procedure for propulsion ability assessment, where choices for some elements were specified in agreement with the project carried out in Japan and which is going to be proposed as a part of the Draft Revised Guidelines for Determining Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse conditions.

Simplified Steering Ability Assessment

The starting point is system (8)-(10), solved for all relevant forward speeds and all seaway directions to check that the ship is able to start or continue course change in seaway from any direction. Note that for the steering ability, both the steering system and propulsion (which influences steering ability) are required and should be integral parts of the assessment: e.g. ships with powerful propulsion may have a smaller rudder, whereas ships with weaker propulsion may compensate this with larger or more effective steering devices. Results of Comprehensive Assessment for many ships show that the dimensioning condition for the installed power, i.e. the condition at which the ratio of the required to available delivered power is maximised along the line of maximum steering effort (further referred to for brevity as critical
condition for steering) is close to beam seaway, Figure 16, right. Note that from experience, as well as from the results of Comprehensive Assessment for many ships, critical conditions for steering occur most frequently in stern quartering waves, like in Figure 16, middle; however, in such situations the required power is less than the required power defined by the Propulsion Ability, i.e. by the crossing point of lines A and B. When the Steering Ability is dominating for the definition of the installed power, i.e. when line A crosses line C, the critical conditions are always close to beam seaway situations. This allows reducing the evaluation of the time-average wave and wind forces to beam seaways.

The second simplification stems from the observation that the levers of time-average wave and wind yaw moment are negligible compared to the lever of the calm-water yaw moment in critical conditions for steering, see details in the Appendix.

Note that the simplifications made restrict the Simplified Steering Ability assessment to the vessels with conventional steering devices arrangement at the stern (including azipods); vessels equipped with azipods at the bow require Comprehensive Assessment.

As a result, the system of equations (8)-(10) reduces to one equation:

\[ X_s + X_w^90 + X_d^90 + X_R + T(1-t_H) = 0 \]

and one check:

\[ Y_R \geq -b\left(Y_w^90 + Y_d^90 \right) \]

where

\[ b = N\prime/\left(N\prime + 0.5Y\prime \right). \]

To define the components of forces and moments \( X_s, X_w^90, Y_w^90, X_d^90, Y_d^90 \) and \( X_R \) in the Simplified Assessment of Steering Ability, any of the methods used in the Comprehensive Assessment can be applied; in addition, application of simplified empirical formulae seems suitable for this assessment level. Such formulae and their validation are given in Appendix.

Simplified Propulsion Ability Assessment

The starting point is the system of equations (8)-(10), which has to be solved for all relevant forward speeds and all possible seaway directions to demonstrate that the ship is able to keep forward speed of at least 6.0 knots in seaway from any direction. Noting that bow seaways are most critical for required power at a given speed (Figure 16, middle plot), it is enough to consider only seaways from 0 to about 60° off-bow in the assessment. Further, neglecting the influence of drift on the required thrust and required power allows omitting equations (2) and (3). Thus only eq. (1) needs to be considered, and only in head waves:

\[ X_s + X_w + X_d + X_R + T(1-t_H) = 0 \]

However, it is important to keep in mind that the time-average longitudinal force due to waves \( X_d \) should be taken as the maximum force in mean wave directions between 0 and 60° off-bow.

The contributions \( X_s, X_w, X_d \) and \( X_R \) can be found using any method from the Comprehensive Assessment (empirical, numerical or experimental). However, it seems logical to allow using also simpler approximations for these terms in the Simplified Assessment, which are provided in Appendix.
3.5 Sufficient Propulsion and Steering Ability Check

The simplest assessment procedure, *Sufficient Propulsion and Steering Ability Check*, is based on pure empirical formulae to define the required installed power as a function of main ship parameters. The formulae proposed below are based on the application of the comprehensive propulsion and steering assessment procedures to over 400 bulk carriers, tankers, containerships and general cargo vessels equipped with two-stroke low-speed diesel engines, a fixed-pitch propeller and a conventional rudder. For each ship, the maximum significant wave height was found, at which the required brake power is equal to the available brake power, separately for steering and propulsion criteria. Based on these results, MCR was approximated as empirical formulae of $h_s$, for each combination of main ship parameters, and then, the required installed power was found that satisfies the standard significant wave heights for propulsion and steering proposed in section 4.3.

The resulting empirical formulae are, for propulsion ability requirement

$$MCR = 0.21 \cdot C_B^{0.5} \cdot L_{pp}^2,$$

where $MCR$, kW, is the required installed power in terms of the maximum continuous rating of the engine, and for the steering ability requirement

$$MCR = 0.15 \cdot c_R \cdot L_{pp}^2,$$

where $c_R = L_{pp} \cdot T_m / (50 \cdot A_R^*)$, and $A_R^* = \min(2A_R / 3, A_R^0)$.

Figure 17 compares these empirical formulae with the results of comprehensive assessment; ideally, the Sufficient Propulsion and Steering Ability Check should provide the same or slightly more conservative results than the Comprehensive Assessment. Testing of the proposed formulae by all interested stakeholders and its validation are required to approve / improve them; it should be noted that these formulae are suitable only for vessels equipped with two-stroke low-speed diesel engines, a fixed-pitch propeller and a conventional rudder; for other tapes of the engine, propulsion and steering the simplified or comprehensive assessment should be used.

Figure 17. Required MCR according to Sufficient Propulsion and Steering Ability Check (y axis) in comparison to required MCR according to Comprehensive Assessment (x axis) for propulsion ability (left) and steering ability (right) requirements
3.6 Engine and Propulsion

Engine Model

The available delivered power on the propeller \( P_D^{av} \), W, can be calculated as

\[
P_D^{av} = \eta_s \eta_g P_B^{av} - P_{PTO}.
\]

The assumptions used in the project for the non-dimensional shaft efficiency, non-dimensional gear efficiency and power take-off were \( \eta_s = 0.98 \), \( \eta_g = 1.0 \) for directly connected engines and \( \eta_g = 0.98 \) for single-stage geared engines, and \( P_{PTO} = 0.0 \) W in emergency situations; these values can be used as default, unless less conservative parameters are available from the manufacturer.

Within the comprehensive and simplified assessment procedures, a steady engine model can be used to define \( P_D^{av} \) as a function of the engine rotation rate, defined by the engine diagram. Figure 18 shows an example of the engine diagram for a two-stroke low-speed turbocharged diesel engine, the type used on the majority of modern merchant ships. The horizontal axis corresponds to the rotation speed as percentage of rotation speed at the maximum continuous rating (MCR), and the vertical axis shows shaft power as percentage of MCR (note logarithmic scales used for both axes).

![Figure 18. Diesel engine diagram](https://edocs.imo.org/Final Documents/English/MEPC 70-INF.33 (E).docx)

Line 1 corresponds to the maximum rotation speed (minimum rotation speed limit, or idle limit, corresponding to 25%-30% of the nominal rotation speed, is not shown).

Curve 2 is called the light propeller curve and corresponds to resistance and propulsion characteristics of a clean hull and propeller in calm water. Along this line, shaft power is defined by the hull resistance curve, open-water propeller characteristics and hull-propeller interaction coefficients. Curve 3 is referred to as the heavy propeller curve, and is assumed in design as propeller curve corresponding to fouled hull in heavy weather. This curve corresponds to shifting the light propeller curve upwards by a sea margin up to point M; point M corresponds to MCR and is the layout point for the engine.
In the assessment of the sufficiency of the installed diesel engine for manoeuvrability in adverse conditions, it is necessary to take into account that the maximum continuous output of a diesel engine is bounded, depending on its rotation speed, by several limits:

- **Power limit**, line 4, at the maximum rotation rates. At the power limit, maximum power continuously provided by the engine is constant and equal to MCR.
- **Maximum torque limit** (also called **maximum mep limit**), line 5, defined by the shafting system bearing strength, at the moderately reduced rotation rates. At the maximum torque limit, torque is constant and thus the maximum engine output is proportional to rotation speed.
- **Surge limit** (also called **air limit**), line 6, at low rotation rates. To the left of line 6, the engine will lack air from the turbocharger for the combustion process. Surge limit depends on the turbocharging technology used; thus, manufacturer data should be referred to for its exact definition.

Diesel engine is controlled by changing pressure in cylinders; **constant mean effective pressure** (mep) lines are the lines parallel to line 7, which corresponds to the mep limit of 100%; along these lines, shaft power is proportional to the rotation speed, and, correspondingly, the torque is constant.

Line 8 is the engine **overload limit**: whereas the area between lines 2, 4, 5 and 6 is available for continuous operation in adverse conditions or during manoeuvres without time limitation, the area between lines 4, 5, 6 and 8 is available for overload running for limited periods (1 hour per 12 hours); this area should be considered not available for manoeuvring in adverse conditions.

Due to increased resistance in adverse conditions or during manoeuvres, line 2 shifts upwards, for example, up to line 9, and the maximum engine output is defined by the intersection point A of line 9 with one of the engine limit curves 5 or 6. At low added resistance, e.g. in normal operation in low to moderate sea states, maximum torque line 5 is relevant, whereas for propulsion and manoeuvring in heavy weather, i.e. at a greater added resistance, surge limit line 6 becomes the limiting curve.

In any case, it is important to take into account that the available shaft power in adverse conditions is reduced compared to MCR.

**Other Types of Engine and Propulsion**

SHOPERA has performed case studies for vessels with various types of engine and propulsion besides the low-speed two-stroke diesel engine working directly on a controlled-pitch propeller. Although in the practical approval, verified manufacturer data describing engine limit curves and propeller characteristics should be used, a summary of approaches used to consider other types of the engine and propulsion in the SHOPERA case studies is given below for information:

- For 4-stroke diesel, the air-surge limit curve is much more restrictive than the air-surge limit curve for 2-stroke engines. In SHOPERA, measurement data were used for 4-stroke diesels.
- For a diesel-electric propulsion, it was assumed that the power output of an electric motor is independent from the rotation speed, i.e. the output of the engine was assumed constant at all rotation speeds. In emergency situation, 100% of MCR can be considered as the maximum available power.
• For a vessel equipped with a controlled-pitch propeller, it was assumed that the propeller operates at a constant rotation rate, and the pitch of propeller blades was varied to adjust the propeller to the actual forward speed and required thrust.

Propeller Model and Hull-Propeller Interaction

The propeller thrust $T$ was found from the equilibrium equation in the x-direction (1). Using the known thrust, the advance ratio $J$ was found from the nonlinear equation $T = \rho u_a^2 D_p^2 K_T(J)/J^2$ using known open-water propeller characteristic $K_T(J)$ and the propeller advance speed $u_a$. From the found advance ratio $J$, the torque coefficient $K_Q(J)$ was found using the open-water propeller characteristic. After that, the propeller rotation speed $n_p$ was found from the equation $n_p = u_a/(J D_p)$ and then the required delivered power to the propeller was calculated as $P_D = 2\pi n_p^2 D_p^4 K_Q(J)$. The open-water propeller characteristics can be defined using methods summarized in Table 8.

4 Case Studies

4.1 Introduction

It is not realistic and not necessary to design ships for operation in the worst possible storms that can be theoretically encountered, when considering ship's economy and the fact that ships can nowadays timely avoid such stormy conditions by improved weather forecasts and satellite information systems. The standard operational wave heights of ships should be defined in such a way that the majority of the existing vessels fulfil the related requirements, because, first, present design and operational practices cannot be changed abruptly, for example, because of the introduction of EEDI and, second, the present safety level with respect to manoeuvrability-related accidents in heavy weather is satisfactory, Ventikos et al. (2014). Notably, to similar conclusions comes a study by IACS, EE-WG 1/4 (2010), Table 1, which identifies rather mild standard wave heights for weather-vaning (wind speed up to 21 m/s and significant wave height up to 5.4 m) and advance speed (up to Bft 8 at 6.0 knots advance speed) requirements.

Therefore, benchmarking of the existing fleet with respect to the herein proposed new criteria appears as the most rational way to define standard wave heights in relation to implementation of the EEDI requirements. Such an approach was also used in the IACS studies on minimum power requirements and led to the environmental conditions in the 2013 Interim Guidelines: wind speed 15.7 m/s at significant wave height 4.0 m for ships with $L_{pp}=200$ m to 19.0 m/s and 5.5 m, respectively, for $L_{pp}=250$ m and greater.

Therefore, case studies were undertaken in SHOPER A concerning all ship types considered in the EEDI regulations.

4.2 Comparison between Criteria

The weather-vaning ability was treated using a simplified criterion, as the ability of the ship to keep position in bow to bow-quartering seaway; this simplification follows from the observation that the ship (with the traditional steering devices at the stern) will not be able to keep heading under the action of environmental forces if the forward speed is not sufficiently large, because of significantly reduced manoeuvring reactions on the hull and steering force on the rudder. Figure 19 compares marginal significant wave heights according to comprehensive propulsion assessment (x axis, note that here 4.0 knots advance speed was used) with marginal significant wave heights according to the comprehensive position keeping (y axis)
assessments for bulk carriers, tankers and container vessels. Obviously, marginal wave heights for position-keeping are consistently greater than those for 4.0 knots propulsion; the deviation between results decreases with increasing ship size, according to Froude law. Note, however, that the marginal wave heights according to these assessments are very well correlated, which means that for norming, one of the criteria is redundant. Before making the final choice, a comparison with assessment based on other weather-vaning criteria would be useful, e.g. with the more comprehensive "heading recovery" criterion proposed by the project conducted in The Netherlands.

Figure 20 compares marginal wave heights according to comprehensive propulsion assessment (x axis, here, 6.0 knots advance speed was used) with marginal wave heights according to steering assessment (y axis) for bulk carriers (BC), tankers (TA), general cargo vessels (GC) and container ships (CV). The marginal wave heights according to these two criteria are also correlated to some degree, however, with significantly more spreading than for the position keeping vs. propulsion. It can be concluded that fulfillment of the propulsion ability requirement at a certain marginal significant wave height guarantees fulfillment also of the steering ability requirement at a marginal significant wave height of about 1.0 m smaller. The difference becomes slightly greater than 1.0 m at the propulsion marginal significant wave heights above about 5.5 m, which are, perhaps, not relevant anyway. Note, however, that this correlation between the propulsion and steering abilities stems from the fact that the steering systems of the considered ships are properly dimensioned according to other requirements, e.g. IMO Manoeuvrability Standards (2002).
4.3 Definition of Standard Wave Heights Using Comprehensive Assessment

One of the aims of the Case Studies was to provide recommendations for the standard wave heights using Comprehensive Assessment. This study was done as follows: first, a sample of representative vessels was selected; after that, the Comprehensive Assessment of Propulsion and Steering Abilities was applied to find the marginal wave height (separately for Propulsion and Steering and for different ship types and sizes); finally, a fit of the determined marginal wave heights vs. \( L_{pp} \) was done to define the standard wave height per ship type and overall for all ship types; note that the marginal wave heights were considered separately for the Propulsion and Steering Abilities.

To select representative vessels, several series of designs were generated:

1. Series of bulk carriers and tankers along the defined boundary lines \( \text{MCR}(L_{pp}) \), which exclude a certain percentage of vessels with lower power. As the "bottom line", a line corresponding to the limit of 5% of the low-powered vessels was used; besides, 10%, 20% and 30%-lines were defined and series of ships were generated. For comparison, low-power series were generated also for container ships and general cargo vessels. These series were generated using the IHS-FairPlay data for each of the considered vessel types.

2. Series of bulk carriers and tankers along the lines \( \text{MCR}(L_{pp}) \) corresponding to vessels that fulfill marginally the requirements of EEDI implementation Phase 1, 2 and 3.

3. Series of bulk carriers and tankers along the Minimum Power Lines according to the 2013 Interim Guidelines, Res. MEPC.232(65), as amended by Res. MEPC.255(67) and MEPC.262(68).

These series of bulk carriers and tankers are shown in graphs of \textit{length between perpendiculars} \( (L_{pp}, x \text{ axis}) \) vs. \textit{installed power} \( \text{(MCR, y \text{ axis})} \) together with the FairPlay data in Figure 21 to Figure 23; Figure 24 shows container ships and general cargo vessels which were used for comparison.

![Figure 21](https://edocs.imo.org/Final Documents/English/MEPC 70-INF.33 (E).docx)
Figure 22. Series (solid lines) of bulk carriers (left) and tankers (right) marginally fulfilling requirements of EEDI implementation Phase 2 (lowest line) and 1 (top line) vs. FairPlay database (grey points)

Figure 23. Series (solid lines) of bulk carriers (left) and tankers (right) marginally fulfilling requirements of (updated) Minimum Power Lines of 2013 Interim Guidelines

The marginal significant wave heights obtained with Comprehensive Propulsion and Steering assessment are shown in Figure 25, left and right plots, respectively, for the bulk carriers and tankers with the installed power corresponding to the 5% of low power vessels of the FairPlay database. Results for low-power container ships and general cargo vessels are shown for comparison. Bulk carriers and tankers look very similar with respect to the marginal wave heights and are significantly below container ships.

Figure 24. Series of container ships (left) and general cargo vessels (right) selected for comparison (red circles) with bulk carriers and tankers along low-power boundary of IHS FairPlay database
Figure 25. Marginal significant wave heights for bulk carriers (BC) and tankers (TA) with installed power corresponding to the 5% of low power vessels of HIS FairPlay database according to Comprehensive Propulsion (left) and Comprehensive Steering (right) assessments; results for low-power container vessels (CV) and general cargo (GC) vessels are shown for comparison.

Figure 26 shows marginal significant wave heights for bulk carriers and tankers with an installed power corresponding to 20% of low power vessels of FairPlay database. The results indicate that, if only the propulsion ability is taken into account, bulk carriers and tankers with a power at about the 20% MCR line of the FairPlay database are slightly above the current standard ($h_s=5.5$ m at $L_{pp}=250$ m); Steering Ability appears to be more critical, i.e. it corresponds to lower marginal wave heights than Propulsion Ability.

Figure 27, Figure 28 and Figure 29 show marginal significant wave heights for bulk carriers and tankers marginally satisfying the requirements of EEDI implementation Phase 3, 2 and 1, respectively. The results show that if only propulsion ability is taken into account, the current standard $h_s=5.5$ m at $L_{pp}=250$ m is fulfilled by Phase 1-compliant tankers and bulk carriers and, marginally, by Phase 2 compliant tankers and bulk carriers.
Figure 27. Marginal wave heights for EEDI-Phase 3 compliant bulk carriers (BC) and tankers (TA) according to Comprehensive Propulsion (left) and Comprehensive Steering (right) assessments.

Figure 28. Marginal wave heights for EEDI-Phase 2 compliant bulk carriers (BC) and tankers (TA) according to Comprehensive Propulsion (left) and Comprehensive Steering (right) assessments.

Figure 29. Marginal wave heights for EEDI-Phase 1 compliant bulk carriers (BC) and tankers (TA) according to Comprehensive Propulsion (left) and Comprehensive Steering (right) assessments.

Figure 30 shows the marginal significant wave heights according to comprehensive propulsion and steering abilities assessments for bulk carriers and tankers, which marginally satisfy the Minimum Power Lines of 2013 Interim Guidelines.
Figure 30. Marginal wave heights according to Comprehensive Propulsion (left) and Steering (right) Abilities assessment for bulk carriers (BC) and tankers (TA) marginally compliant with Minimum Power Lines of 2013 Interim Guidelines

Based on the obtained marginal wave heights for bulk carriers and tankers, and requiring that the standard wave height for the propulsion ability assessment is equal to the standard wave height according to the 2013 Interim Guidelines of 5.5 m for vessels with $L_{pp}=250$ m, the following can be proposed:

$$h_s = \min(2.2 + L_{pp}/75, 5.5).$$

or the standard wave heights can be set equal to those (slightly less conservative for vessels of $L_{pp} < 250$ m) in the 2013 Interim Guidelines.

To define standard wave heights for the steering ability assessment, it was assumed that, on the average, the same percentage of vessels from the total number of vessels used should fail the steering ability assessment as the propulsion ability assessment (for the individual vessels, one or the other requirement can be dominating). This led to the following function:

$$h_s = 2.0 + L_{pp}/100.$$

One observation from these results is that the marginal wave heights are ship size-dependent: larger vessels are able to fulfill both propulsion and steering requirements at greater significant wave heights than smaller vessels. This is understandable physically; in principle, ship size dependent standard wave heights may be acceptable from the pragmatic point of view: because consequences of accidents are greater for larger vessels, acceptable probability of accidents should be lower for larger vessels. Besides, ship size-dependent standard wave height would reflect existing design and operational practices: smaller vessels, obviously, do not operate in storms of the same severity as larger vessels. Note that standard wave heights in the 2013 Interim Guidelines are also ship-size dependent, however, this is a subject of ongoing discussion.

Another observation from Figure 25 is that the marginal wave heights differ, partly substantially, between different ship types; this will be discussed in the next section, including results also for other ship types besides bulk carriers, tankers, container ships and general cargo vessels.

A final note concerns the possibility of contradiction between fulfilling the proposed requirements to manoeuvrability in adverse weather conditions and the possibility to fulfill EEDI requirements, which are progressively strengthening from Phase 1 to Phase 3. It is interesting to note that whereas the selected low-power general cargo vessels and container carriers satisfy the standard wave heights corresponding to the 2013 Interim Guidelines and, at the
same time, easily fulfil the requirements to Phase 3 of EEDI implementation (as presently formulated), the selected bulk carriers and tankers, marginally satisfying standard wave heights of the 2013 Interim Guidelines, are able to marginally fulfil requirements of Phase 2 of EEDI implementation, but not the requirements of Phase 3.

Note, however, that standard wave heights can be adjusted to the marginal wave heights of Phase 3-compliant bulk carriers and tankers, i.e. effectively, slow-steaming designs; whether such vessels can be considered as representative vessels of fleet in service requires a prolonged discussion with all interested stakeholders.

4.4 Comparison between Ship Types using Simplified Assessment

The simplified assessment of propulsion and steering ability is more conservative than the comprehensive assessment, therefore, it was not applied to define the standard wave heights. On the other hand, it can be used to compare performance of vessels of different types with respect to EEDI requirements, when selected vessels of different types have comparable performance with respect to manoeuvrability in adverse conditions.

In this study, vessels of different types were selected, which have the same marginal wave heights (computed using simplified assessment procedure) as bulk carriers and tankers, marginally compliant with the requirements of either Phase 1, 2 or 3 of EEDI implementation, and it was analysed, requirements of which EEDI phase can these selected vessels satisfy. The analysis shows that the general cargo vessels satisfy either the same EEDI phase as the bulk carriers and tankers with the same marginal wave heights (this concerns old designs of general cargo vessels), to "higher" Phases; all other vessel types (Cruise Vessels, LNG and Gas Carriers, RoRo Cargo and RoPax) achieve significantly "higher" phases of EEDI implementation than bulk carriers and tankers if they have comparable marginal wave heights with respect to manoeuvrability in heavy weather.

Figure 31 illustrates these conclusions by showing marginal significant wave heights according to simplified propulsion (left) and simplified steering (right) abilities assessment for bulk carriers, tankers, container vessels, general cargo vessels, LNG and gas carriers, RoRo cargo vessels, reefers and RoPax vessels. In each plot, only vessels satisfying requirements of a certain EEDI implementation phase are shown: Phase 3 denotes vessels, satisfying requirements of Phase 3, Phase 2, vessels satisfying requirements of Phase 2, but not showing vessels satisfying Phase 3 requirements etc.

Note that absolute values of the marginal wave heights in Figure 31 are not relevant, because they correspond to a more conservative, simplified assessment procedures, than the comprehensive assessment used in the previous section. However, relative differences between different ship types are correctly reproduced; they show that for each phase, bulk carriers and tankers show remarkably similar marginal significant wave heights, which are lowest over all ship types. Container vessels demonstrate high marginal wave heights due to high installed power; passenger vessels (RoPax and cruise vessels) show significantly higher marginal wave heights than other vessel types due to advanced propulsion and steering systems (twin screw, diesel-electric main propulsion, controlled pitch propeller, pods).

An important consideration is the possibility of contradiction between fulfilling the proposed requirements to manoeuvrability in adverse weather conditions and the need to fulfil EEDI requirements, which are progressively strengthening from Phase 0 to Phase 3. Note that all vessel types, with exception of bulk carriers and tankers can fulfil the requirements to Phase 3 of EEDI implementation, as presently formulated, and at the same time satisfy the requirements of the proposed criteria for manoeuvrability in adverse weather conditions with the proposed standards. On the other hand, bulk carriers and tankers, if they satisfy the
proposed standards, are able to fulfil marginally requirements of Phase 2, of EEDI implementation. Note, however, that standard wave heights can be lowered to include also Phase 3-compliant bulk carriers and tankers (which are, effectively, slow-steaming vessels); whether such vessels can be considered as representative vessels of fleet in service should be a subject of discussion with all interested stakeholders.

Figure 31. Marginal significant wave heights according to simplified propulsion (left) and simplified steering (right) abilities assessment for bulk carriers (BC), tankers (TA), container vessels (CV), general cargo vessels (GC), LNG and gas carriers (GAS), pure car and truck carriers (PCTC), RoRo cargo (ROROC), reefers and RoPax vessels, satisfying requirements of EEDI Phase 3 (denoted Phase 3), Phase 2 (denoted Phase 2; not showing vessels satisfying Phase 3 requirements), Phase 1 (denoted Phase 1; not showing vessels satisfying Phase 2 and 3 requirements) and Phase 0 (denoted Phase 0; not showing vessels satisfying Phase 1, 2 and 3 requirements).

A final note concerns the question whether the standard wave heights should depend on ship type. On the one hand consequences of accidents, as well as operational practices, differ between different ship types, especially between passenger and cargo vessels. Besides, the revealed differences in the marginal wave heights between different ship types reflect
established design and operational practices, which should not be drastically changed by new regulations, assuming that the present level of safety satisfactory. Both these arguments are in favour of correspondingly different standard wave heights per ship type. On the other hand, the revealed difference in the manoeuvring characteristics in heavy weather reflects, obviously, different requirements to the operational performance of the propulsion and steering systems of ships of different types, not related to safety. Obviously, reaching a conclusion regarding ship type-dependency of standard wave heights requires a prolonged discussion with all interested stakeholders.

5 Optimisation

A ship needs to be optimized for cost effectiveness, operational efficiency, improved safety and comfort of passengers and crew, and, last but not least, for minimum environmental impact (minimization of risk of accidental oil outflow, engine emissions etc.). Many of these requirements are clearly conflicting and a decision regarding the optimal ship design needs to be made, based as far as possible on rational criteria and procedures. This is the case of the problem which the SHOPER A project is dealing with: Environmental concern was the reason behind the introduction of the EEDI requirements by the IMO a few years ago. One way of fulfilling the demanding requirements of the EEDI regulation, is the reduction of speed of future ships. This would result however in under-powered designs, raising questions regarding the ability of these designs to operate safely in adverse weather conditions. The challenge of identifying the more suitable path between the conflicting requirements of reducing greenhouse emissions and at the same time maintaining adequate safety of ships in adverse sea conditions is the main objective of the SHOPER A project. To this end, a specific work package is foreseen in SHOPER A for the development of a multi-objective optimization procedure, in which a ship's performance is assessed holistically, thus, looking for the minimum powering requirement to ensure safe ship operation in adverse seaway/weather conditions, while keeping the right balance between ship economy, efficiency and safety of the ship and the marine/air environment. More specifically, the objective of this workpackage of the SHOPER A project, is:

To integrate validated software tools for the hydrodynamic/manoeuvrability assessment of ships in adverse seaway/weather conditions into a ship design software platform and set-up of multi-objective optimization procedures in which ship's performance is assessed holistically, thus, looking for the minimum powering requirement to ensure safe ship operation in adverse seaway/weather conditions, while keeping the right balance between ship economy, efficiency and safety of the ship and the marine/air environment.

The planned optimization studies shall be implemented in two phases:

- The first phase consists of a Global Optimization, aiming to identify most favourable combinations of main dimensions, form parameters and other integrated characteristics of the ship, including powering and manoeuvring devices, for the selected operational profile. These studies should be carried out applying as far as possible simplified methods, developed in previous work packages of the project.
- The second phase consists of a Detailed Optimization, including hullform details. These studies should be carried out applying refined and more accurate methods than those used for the global optimization.
5.1 Parametric Model for the Global Optimization of RoPax Ships

The parametric model for the RoPax ships, developed within the NAPA software, is quite generic and can be used for the design of RoPax ships of small, medium or large size. Once NAPA is called by the optimization software, the parametric design methodology is automatically executed and the following basic tasks are elaborated:

1. Hullform development
2. Resistance and propulsion estimations
3. Development of internal layout
4. Weights estimation – Definition of Loading Conditions
5. Evaluation of transport capacity (lanes length, number of cars/trucks, payload)
6. Evaluation of Stability Criteria and other Regulatory Requirements
7. Assessment of Building and Operational Cost, Annual Income and Selected Economic Indices
8. Evaluation of Energy Efficiency Design Index (EEDI)
9. Evaluation of hydrodynamic/manoeuvring performance in adverse seaway/weather conditions

The first step of the parametric design procedure is the development of the hullform. The resulting hullforms are typical of modern twin-screw RoPax vessels with fine fore-bodies and buttock-flow sterns. The definition grid of representative hullform of a small RoPax ship, developed by the parametric model, is shown in Figure 32.

![Figure 32: Typical hullform (fore and aft parts), developed by the parametric model](image)

The development of the vessel’s internal layout starts with the definition of the watertight subdivision below the main car deck. The number of car decks and the type of vehicles carried on each of them (mix of private cars and trucks) are specified by a series of user-defined parameters, in accordance with the size of the vessel. A number of upper decks are then generated, providing the necessary area for the accommodation of passengers and crew, according to the passengers transport capacity specified by the user and the required crew number. The model of the internal arrangement of accommodation spaces is rather coarse; however, it is ensured that ample room for public spaces and cabins for passengers and crew and for the required service spaces is provided. The internal layout of a small RoPax is presented in Figure 33.

![Figure 33: Internal layout of a small RoPax ship](image)
The calm water resistance and propulsion power were predicted with the Holtrop 1984 procedure. These predictions may be corrected using appropriate calibration factors provided by the user. Then, suitable diesel engine models are selected from a data base. The ship's light weight is decomposed in the following main weight categories: structural, propulsion, auxiliary, deck machinery and outfitting, electrical, piping, heating and air conditioning, accommodation and miscellaneous. For the main engines, the actual weight provided by the engine manufacturer is used. The calculation of the remaining weight groups is based on empirical formulae and appropriate weight coefficients. The vessel's maximum payload is determined by subtracting the light ship weight and the various DWT items (consumables, provisions, stores etc.) from the total displacement. A series of typical loading conditions are then created, for which the intact stability assessment is performed based on the requirements of IMO Resolution A.749. Suitable NAPA macros for the assessment of damage stability are also implemented, but they were not applied during the optimization studies presented below, in order to keep the calculation time in reasonable limits. The assessment of propulsion and manoeuvring performance of the ship in adverse weather conditions is performed applying the assessment procedure developed by the SHOPER A project for Scenario 2: “Escape from coastal area in gale condition”. The financial evaluation of the shipbuilding investment is based on the calculation of the Net Present Value.

5.2 Global Optimization of two RoPax Ships

As already mentioned, the developed parametric model is quite generic, and has been applied for the design and optimization of RoPax ships of various sizes. In the following, results obtained from the optimization of a small and a relatively larger vessel will be presented. The objective of these studies was to maximise the Net Present Value of the owner's investment, while ensuring compliance with safety regulations, EEDI Phase I or Phase II requirements and the SHOPER A criteria for manoeuvrability in adverse weather conditions, as well as various operational constraints such as draught and trim constraints for the various loading conditions, upper limit on building cost, lower limits on DWT and lanes length requirements, constraints on the average truck weight etc.

Optimization of a small RoPax Ship

The small RoPax ship is designed for operation between Piraeus and the island of Crete, with a roundtrip length of 320 sm, a transport capacity of 1,200 passengers, 200 private cars and 21 trucks and a service speed of 23.8 kn. For the above operational scenario, several studies have been performed with the optimization tool available in NAPA (i.e. the Optimization...
Manager), using Genetic Algorithms. The results presented in the following were obtained by using the main dimensions as follows: Length BP from 105 m to 115 m, Beam from 18 m to 20 m and Design Draught from 5 m to 5.4 m.

Scatter diagrams of NPV vs. DWT and Propulsion Power are shown in Figure 34 and Figure 35. Only feasible designs are shown in these and the following diagrams, while the starting point of the optimization (the original design) is marked by a cross. A negative relationship between NPV and DWT is shown in Figure 34. This is because the freight rate of trucks was assumed to be constant, irrespectively of their weight. This way, ships capable of carrying the same number of trucks, but of increased mean weight, are penalised because of their increased propulsion power requirements, whereas at the same time they are not receiving any credit for their increased DWT capacity.

The obtained results indicated that compliance with the EEDI Phase II requirement was quite demanding for this study, as most of the unfeasible designs (not shown here) failed to satisfy this criterion. At the same time, only two designs were identified, marginally fulfilling the EEDI Phase III requirement. Scatter diagrams of the calculated margins with respect to the EEDI Phase II and Phase III are plotted in Figure 36. The EEDI margin is herein defined as the required EEDI minus the attained value. Therefore, a positive margin indicates a design complying with the corresponding phase, while designs with negative margin are failing to comply with the requirement. A plot of the calculated margin with respect to the EEDI Phase III requirement versus NPV is plotted in Figure 37. The results shown in this diagram indicate that increased NPV is associated with improved performance with respect to EEDI. It is anticipated that systematic hullform and propeller optimizations, installation of energy saving devices and waste heat recovery systems, or other technological advances might help the designers to improve the performance of future ships, without the need of (significant) compromises with respect to service speed. However, with the current parametric model, it was found that, in order to obtain a significant number of designs in compliance with EEDI Phase III requirement, the design speed should be reduced down to 21.6 kn, a reduction that would have a significant impact on the specified operational scenario. For the design speed of 23.8 kn, four Wärtsilä 9V32 engines were selected for all ships presented herein. For the reduced speed of 21.6 kn, these engines were replaced by four Wärtsilä 9L26 engines. As a result, compliance with EEDI Phase III requirement was achieved by a number of design alternatives (see Figure 38).

In contrast to what was observed in the case of tankers and bulk carriers, compliance with the SHOPERA propulsion criterion in adverse weather conditions was easily achieved. The same conclusion was derived by all optimization studies for RoPax ships that were carried out, regardless of their size. This of course was not an unexpected result, since RoPax ships are highly powered in comparison with other types of ships of equal displacement. Even the designs with reduced service speed of 21.6 kn, complying with EEDI Phase III, had enough power to ensure adequate manoeuvrability in adverse weather conditions. Calculations performed with only one propeller in operation (in order to verify redundancy of the propulsion system), and assuming a 30% reduction of the propeller thrust to account for ship motions, unsteady conditions and propeller racing, indicated that all feasible designs were able to achieve 12 kn at bow waves with a significant wave height of 4.0 m (see Figure 39). The propulsion criterion plotted in this figure corresponds to the ratio of the required to the available propulsion power; therefore, values less than 1.0 indicate compliance with the criterion.
In the following, results obtained from the optimization of a relatively larger vessel will be presented. The ship is designed for operation between Piraeus and the island of Rhodes, with a roundtrip length of 514sm, a transport capacity of 1,800 passengers, 640 private cars and 130 trucks and a service speed of 27kn. For the above operational scenario, several studies have been performed with the optimization tool available in NAPA (i.e. the Optimization Manager), using Genetic Algorithms. The results presented in the following were obtained by varying the main dimensions as follows: Length BP from 155 m to 165 m, Beam from 25.2 m to 27.2 m and Design Draught from 6.1 m to 6.5 m.
Scatter diagrams of NPV vs. DWT and Propulsion Power are shown in Figure 40 and Figure 41 (only feasible designs are included). The starting point of this optimization (the original design) in this and the following diagrams is marked by a cross. The negative relationship between NPV and DWT that was observed in the results for the small RoPax is shown also in this case. Once again, the obtained results indicate that compliance with the EEDI Phase II requirement was quite demanding, as most of the unfeasible designs (not shown here) failed to satisfy this criterion. None of the obtained designs was able to fulfil the Phase III requirement. Scatter diagrams of the calculated margins with respect to the EEDI Phase II and Phase III are plotted in Figure 42.

Compliance with the SHOPERA propulsion criterion in adverse weather conditions was easily achieved also for this vessel. Calculations performed with only one propeller in operation, and assuming a 30% reduction of the propeller thrust to account for ship motions, unsteady conditions and propeller racing, indicated that all feasible designs were able to achieve 12 kn at bow waves with a significant wave height of 6.5 m (see Figure 43).

5.3 Parametric Model for the Global Optimization of Tankers and Bulk Carriers

Different parametric models have been developed for the Global Optimization of Tankers and Bulk Carriers. However, since there are significant similarities between them, a common description will be provided for the sake of brevity while important differences will be referenced. Both parametric models have been elaborated by NTUA in the CASD software NAPA. The parametric models are quite generic, and can be used for the design ships of various sizes.
Once NAPA is called by the optimization software, the parametric design methodology is automatically executed and a series of basic tasks are elaborated. The first step of the parametric design procedure is the development of the hullform. The hullform is created by a piecewise linear transformation of a given original hull. A representative hullform, corresponding to an Aframax tanker, developed by the parametric model is shown in Figure 44. The next step is the development of the vessel's internal layout. A series of surfaces are created (decks, transverse and longitudinal bulkheads) along with the corresponding compartments, which are subsequently combined in the so called "ship model". A rather coarsely modelled superstructure is added to the main hull. The internal layout up to the main deck of a large Crude Oil Carrier, created by the parametric model is presented in Figure 45. This is an example of a design with corrugated bulkheads, however the optimization studies for a SUEZMAX and a VLCC presented below have been performed using planar bulkheads.

The procedure continues with the preliminary resistance and powering calculations. The prediction of the vessel's resistance and calm water propulsion power are performed by applying the well-known Holtrop 84 procedure. Each optimization study is carried out for one particular main engine, specified by the user. Given the engine power and RPM, the optimal propeller is identified, and the ship's speed is calculated. The calculation of the light weight of the ship is based on empirical formulae, specifically developed for each ship type and size. A series of typical loading conditions are then created, for which the intact stability assessment
is performed based on the requirements of IMO Resolution A.749. Damaged stability calculations are also implemented, but they were used only for tanker ships. For bulk carriers, damaged stability calculations are based on the probabilistic concept and they quite time consuming; therefore they have been omitted in these studies in order to keep the calculation time between reasonable limits. Other macros have been developed for the calculation of the Oil Outflow Index in case of tanker ships. The assessment of propulsion performance of each design alternative in adverse weather conditions is performed applying the assessment procedure developed by the SHOPER project for Scenario 2: "Escape from coastal area in gale condition". The financial evaluation of a shipbuilding investment is based on the calculation of the Net Present Value.

Optimization of a SUEZMAX Tanker

In the following, results obtained from the optimization of a SUEZMAX tanker will be presented. The ship is assumed to operate between Sidi Kerir and Aghioi Theodoroi, with a roundtrip length of 1,048 sm. The ship will be fitted with a main engine delivering 18,660 kW MCR at 91 RPM. The results presented in the following were obtained by varying the main dimensions as follows: Length BP from 240 m to 291 m, Beam from 44 m to 52 m and Design Draught from 15 m to 17.4 m.

A scatter diagram of NPV vs. DWT is shown in Figure 46. In contrast to the RoPax ships, in the case of cargo ships a strong positive relationship between NPV and DWT is shown. The calculated margins with respect to the EEDI Phase 0, Phase I and Phase II are plotted in Figure 47. The obtained results indicate that compliance with the EEDI Phase I requirement was easily achieved, while no design was found complying with Phase II. In order to comply with the SHOPER propulsion criterion, the ship must have enough power to achieve a forward speed of 6 kn at bow waves with a significant wave height of 5.5 m. As shown in Figure 48, all vessels comply with the criterion, with the larger margin obtained by some of the smaller ones, with DWT values bellow 166 kt. However, even in the other end of the DWT range some designs were found with a propulsion criterion bellow 0.85. A scatter diagram of EEDI margin vs. the propulsion criterion is shown in Figure 49.
Optimization of a VLCC Tanker

In the following, results obtained from the optimization of a VLCC tanker will be presented. The ship is assumed to operate between Ras Tanura and Singapore, with a roundtrip length of 7,402 sm. The ship will be fitted with a main engine delivering 29,439 kW MCR at 76 RPM. The results presented in the following were obtained by varying the main dimensions as follows: Length BP from 300 m to 341 m, Beam from 55 m to 65 m and Design Draught from 19 m to 23 m.

A scatter diagram of NPV vs. DWT is shown in Figure 50. The same strong positive relationship between NPV and DWT observed for the SUEZMAX is shown also by the VLCC. The calculated margins with respect to the EEDI Phase 0, Phase I and Phase II are plotted in Figure 51. The obtained results indicate that compliance with the EEDI Phase I requirement was achieved by a number of designs, even with a quite small margin. No design was found complying with Phase II. Compliance with the SHOPERA propulsion criterion is shown in Figure 52. It is interesting to note that the best performance with respect to the propulsion criterion is shown by some designs with a DWT around 335kt and not by the smaller ones. A scatter diagram of EEDI margin vs. the propulsion criterion is shown in Figure 53.

Optimization of a 37,000t Bulk Carrier

Results obtained from the optimization of a 37,000t bulk carrier will be presented next. The ship is assumed to operate in a roundtrip length of 2,900 sm. The ship will be fitted with a main engine delivering 6,900 kW MCR at 129 RPM. The results presented in the following were obtained by varying the main dimensions as follows: Length BP from 168 m to 195 m, Beam from 25 m to 30.4 m and Design Draught from 8.9 m to 11 m.
Figure 52. Propulsion Criterion vs. DWT

Figure 53. EEDI Phase I, II, III Margin vs. DWT

Figure 54 shows NPV vs. DWT. Scatter diagrams of the calculated margins with respect to the EEDI Phase 0, Phase I and Phase II vs. DWT are plotted in Figure 55. EEDI Phase 0 requirement was fulfilled by all design alternatives. In addition, Phase I was also easily fulfilled, while several designs were found complying with Phase II. In order to comply with the SHOPERA propulsion criterion, the ship must have enough power to achieve a forward speed of 6 kn at bow waves with a significant wave height of 4.0 m (wave height corresponding to ships with an LBP not exceeding 200 m). Compliance with the SHOPERA propulsion criterion is shown in Figure 56. As shown in this figure, the larger margin is obtained by some of the smaller ships, with DWT values around 38 kt. However, even in the other end of the DWT range some designs were found with a propulsion criterion below 0.85. A scatter diagram of EEDI margin vs. the propulsion criterion is shown in Figure 57.
Optimization of a 58,600t Bulk Carrier

The ship is assumed to operate in a roundtrip length of 2,900 sm. It will be fitted with a main engine delivering 9,020 kW MCR at 125 RPM. The results presented in the following were obtained by varying the main dimensions as follows: Length BP from 180 m to 207 m, Beam from 29 m to 32.25 m and Design Draught from 10.2 m to 12.3 m.

A diagram of NPV vs. DWT is shown in Figure 58. Scatter diagrams of the calculated margins with respect to the EEDI Phase 0, Phase I and Phase II vs. DWT are plotted in Figure 59. EEDI Phase 0 requirement was fulfilled by all design alternatives. In addition, Phase I was also fulfilled by a series of designs, while no designs were found complying with Phase II. Compliance with the SHOPERA propulsion criterion is shown in Figure 60. As shown in this figure, the larger margin is obtained by some ships, with DWT values around 51 kt. A scatter diagram of EEDI margin vs. the propulsion criterion is shown in Figure 61.

![Figure 58. NPV vs. DWT](image1)
![Figure 59. EEDI Phase I, II, III Margin vs. DWT](image2)
![Figure 60. Propulsion Criterion vs. DWT](image3)
![Figure 61. EEDI margin vs. Propulsion Criterion](image4)

6 References


EE-WG 1/4 (2010) Minimum required speed to ensure safe navigation in adverse conditions, submitted by IACS
IMO (2002) Standards for ship manoeuvrability, Res. MSC.137(76)
IMO (2012) Interim Guidelines for Determining Minimum Propulsion Power to Maintain the Manoeuvrability of Ships in Adverse Conditions, MSC-MEPC.2/Circ.11
IMO (2013) Interim guidelines for determining minimum propulsion power to maintain the Manoeuvrability in adverse conditions, IMO Res. MEPC.232(65)
MAIB (1996) Report on the investigation into the grounding of the passenger ro-ro ferry Stena Challenger on 19 September 1995, Blériot-Plage, Calais, Marine Accidents Investigation Branch
MAIB (2012a) Report on the investigation of windlass damage, grounding and accident to person on the ro-ro ferry Norcape, Firth of Clyde and Troon, Scotland, on 26-27 November 2011, Marine Accidents Investigation Branch
MEPC 62/5/19 (2011) Reduction of GHG emissions from ships - Consideration of the Energy Efficiency Design Index for New Ships. Minimum propulsion power to ensure safe manoeuvring in adverse conditions, Submitted by IACS, BIMCO, CESA, INTERCARGO, INTERTANKO, WSC
MEPC 64/4/13 (2012) 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
MEPC 64/INF.7 (2012) Background information to document MEPC 64/4/13, Submitted by IACS
MEPC (2014) EU Project "Energy Efficient Safe SHip OPERAtion" (SHOPERA), Paper MEPC 67/INF.14 submitted by Germany, Norway and United Kingdom
Shigunov, V. (2015) Manoeuvrability in adverse conditions, Proc. 34th Int. Conf. on Ocean, Offshore and Arctic Engineering OMAE2015, St. John's, Newfoundland, Canada; Paper Nr. OMAE2015-41628
Ventikos, N., Koimtzoglou, A., Louzis, K. and Eliopoulos, E. (2014) "Database of ships and accidents" and "Risk analysis of accidents related to manoeuvring in adverse weather conditions", SHOPERA D1.3, D1.4, NTUA

https://edocs.imo.org/Final Documents/English/MEPC 70-INF.33 (E).docx
IACS, 2001, Standard Wave Data, International Association of Classification Societies, Recommendation No.34.
Appendix 1. Coordinate System, Symbols and Definitions

Coordinate System

The coordinate system used in the Explanatory Notes is shown in Figure 62. The origin O of this coordinate system is located in the main section at the water plane; x-, y- and z-axes point towards bow, starboard and downward, respectively. Positive rotations and moments with respect to z-axis are clockwise when seen from above. Main wave and wind directions are 0, 90 and 180 degree, respectively, for waves and wind from head, steering board and following directions, respectively.

![Figure 62. Coordinate system and definitions](https://edocs.imo.org/Final Documents/English/MEPC 70-INF.33 (E).docx)

Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>wave amplitude</td>
</tr>
<tr>
<td>A_w</td>
<td>wet hull surface</td>
</tr>
<tr>
<td>A_F</td>
<td>forward projected area above water plane</td>
</tr>
<tr>
<td>A_L</td>
<td>lateral projected area above water plane</td>
</tr>
<tr>
<td>A_R</td>
<td>submerged projected rudder area</td>
</tr>
<tr>
<td>A_R^2</td>
<td>rudder area within the propeller slipstream</td>
</tr>
<tr>
<td>B</td>
<td>moulded waterline breadth</td>
</tr>
<tr>
<td>C_B</td>
<td>block coefficient of ship</td>
</tr>
<tr>
<td>C_F</td>
<td>friction coefficient</td>
</tr>
<tr>
<td>C_Th</td>
<td>propeller loading coefficient</td>
</tr>
<tr>
<td>D</td>
<td>seaway spreading function</td>
</tr>
<tr>
<td>D_p</td>
<td>propeller diameter</td>
</tr>
<tr>
<td>J</td>
<td>advance coefficient of propeller</td>
</tr>
<tr>
<td>h_s</td>
<td>significant wave height</td>
</tr>
<tr>
<td>k</td>
<td>form factor</td>
</tr>
<tr>
<td>K_T</td>
<td>propeller thrust coefficient</td>
</tr>
<tr>
<td>K_Q</td>
<td>propeller torque coefficient</td>
</tr>
<tr>
<td>L_oa</td>
<td>overall length of ship</td>
</tr>
<tr>
<td>L_pp</td>
<td>ship's length between perpendiculars</td>
</tr>
<tr>
<td>L_wa</td>
<td>waterline length</td>
</tr>
<tr>
<td>N</td>
<td>projection of moments on z-axis</td>
</tr>
<tr>
<td>n_p</td>
<td>rotation speed of propeller</td>
</tr>
<tr>
<td>n_MCR</td>
<td>rotation speed of propeller at MCR engine loading</td>
</tr>
<tr>
<td>P_D</td>
<td>required delivered power</td>
</tr>
<tr>
<td>P_D^W</td>
<td>available delivered power on propeller</td>
</tr>
<tr>
<td>P_B</td>
<td>required brake power</td>
</tr>
<tr>
<td>P_B^W</td>
<td>available brake power</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>P&lt;sub&gt;PTO&lt;/sub&gt;</td>
<td>power take-off</td>
</tr>
<tr>
<td>S&lt;sub&gt;W&lt;/sub&gt;</td>
<td>m&lt;sup&gt;2&lt;/sup&gt;s/rad&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>T</td>
<td>N</td>
</tr>
<tr>
<td>T&lt;sub&gt;d&lt;/sub&gt;</td>
<td>m</td>
</tr>
<tr>
<td>T&lt;sub&gt;p&lt;/sub&gt;</td>
<td>s</td>
</tr>
<tr>
<td>t&lt;sub&gt;H&lt;/sub&gt;</td>
<td>-</td>
</tr>
<tr>
<td>u&lt;sub&gt;a&lt;/sub&gt;</td>
<td>m/s</td>
</tr>
<tr>
<td>u&lt;sub&gt;s&lt;/sub&gt;</td>
<td>m/s</td>
</tr>
<tr>
<td>V</td>
<td>m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>v</td>
<td>m/s</td>
</tr>
<tr>
<td>v&lt;sub&gt;MCR&lt;/sub&gt;</td>
<td>m/s</td>
</tr>
<tr>
<td>v&lt;sub&gt;s&lt;/sub&gt;</td>
<td>m/s</td>
</tr>
<tr>
<td>v&lt;sub&gt;w&lt;/sub&gt;</td>
<td>m/s</td>
</tr>
<tr>
<td>v&lt;sub&gt;wr&lt;/sub&gt;</td>
<td>m/s</td>
</tr>
<tr>
<td>v&lt;sub&gt;R&lt;/sub&gt;</td>
<td>m/s</td>
</tr>
<tr>
<td>w</td>
<td>-</td>
</tr>
<tr>
<td>X</td>
<td>N</td>
</tr>
<tr>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>α</td>
<td>degree</td>
</tr>
<tr>
<td>β</td>
<td>degree</td>
</tr>
<tr>
<td>β&lt;sub&gt;s&lt;/sub&gt;</td>
<td>degree</td>
</tr>
<tr>
<td>β&lt;sub&gt;ε&lt;/sub&gt;</td>
<td>degree</td>
</tr>
<tr>
<td>δ</td>
<td>degree</td>
</tr>
<tr>
<td>δ&lt;sub&gt;max&lt;/sub&gt;</td>
<td>degree</td>
</tr>
<tr>
<td>ε</td>
<td>degree</td>
</tr>
<tr>
<td>η&lt;sub&gt;δ&lt;/sub&gt;</td>
<td>-</td>
</tr>
<tr>
<td>η&lt;sub&gt;ε&lt;/sub&gt;</td>
<td>-</td>
</tr>
<tr>
<td>μ = β&lt;sub&gt;ε&lt;/sub&gt; - β</td>
<td>degree</td>
</tr>
<tr>
<td>ρ</td>
<td>kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>ρ&lt;sub&gt;a&lt;/sub&gt;</td>
<td>kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>ω</td>
<td>rad/s</td>
</tr>
</tbody>
</table>

Indices:
- ' non-dimensional coefficients of corresponding forces and moments
- d time-average wave-induced forces and moments
- R rudder forces and moments
- s calm-water forces and moments
- w wind forces and moments

**Physical Constants**

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water density</td>
<td>ρ</td>
<td>1025.0 kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Air density</td>
<td>ρ&lt;sub&gt;a&lt;/sub&gt;</td>
<td>1.2 kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Water kinematic viscosity</td>
<td>ν</td>
<td>1.3 × 10&lt;sup&gt;-6&lt;/sup&gt; m&lt;sup&gt;2&lt;/sup&gt;/s</td>
</tr>
</tbody>
</table>
Appendix 2. Validation of Evaluation Methods

Test matrix

One of the most important gaps in the state of the art of ship hydrodynamics before the project was the absence of validated numerical and empirical methods for the computation of time-average wave forces and moments, including the added resistance in waves. Although some measurements were available for the longitudinal component of such forces, both at zero and non-zero speeds, most data were available for head waves only; virtually no systematic measurements were freely available for the added resistance in oblique waves, as well as for the side drift force and yaw drift moment on ships, especially for non-zero forward speed.

Second, providing experimental data for the validation of advanced methods or simplified models for rudder forces in propeller race, not sufficiently available yet in the open literature, were also aim of the experimental studies.

Finally, validation of the proposed criteria for maneuvering in waves (weather-vaning, steering and propulsion) can be done using direct transient simulations of maneuvers in waves in time domain. However, such simulation methods themselves require validation by comparison with experiments; in the open literature, only limited amount of such experimental results is available.

To close this gap a test matrix was defined, which specifies test conditions and values to be measured; summarizing, the following model tests were performed in deep and shallow water to provide validation data for the developed numerical models:

- Time-average wave forces including added resistance in regular waves;
- Added resistance in irregular waves;
- Propulsion and speed loss in regular waves;
- Rudder forces in regular waves;
- Rudder forces in propeller race at high propeller loading;
- Turning circle in regular waves;
- Zig-zag maneuvers in regular waves.

Three vessel types of significantly different hydrodynamic characteristics were selected to provide a sufficiently broad variety of hull geometries for the validation of numerical tools: a VLCC tanker, a post-panamax container ship and a RoPax ferry. For the former two vessels, the shiplines are publicly available, namely, KVLCC2 tanker designed by MOERI and the Duisburg Test Case (DTC) container vessel designed by the Institute of Ship Technology, Ocean Engineering and Transport Systems (ISMT) at the University of Duisburg-Essen. For the RoPax vessel, data are confidential and cannot be disclosed to the public. However, the Ropax results were used for validation of numerical tools by SHOPERA partners. The hull surface images of the vessels are shown in Figure 63; the main particulars are summarized in Table 10.

Figure 63. Geometry of VLCC tanker KVLCC2, 14000 TEU container ship DTC and RoPax

Table 10. Main particulars of vessels used in tests
Validation of Time-Average Waves Forces

The effects of various characteristics of ship's hull form on the added resistance of ships in waves were investigated to derive new empirical formulae for the time-average wave forces, including added resistance, based on best fitting of available experimental data for different types of hull forms. Extensive validations of the proposed empirical formulae were carried out for different types of ships and in comparison with other empirical methods as well as more advanced approaches. In the comparative calculations presented below, four methods were tested:

- The STA2 method [1], denoted as STA2(MARIN);
- The herein proposed empirical formula, denoted as NEW (NTUA-SDL, simplified);
- Potential theory 3D panel code calculations based on work [2], namely a far field method of NTUA-SDL based on Maruo's theory [3] in combination with a correction for short waves acc. to Tsujimoto et al [4], which corresponds to the "theoretical method" defined in ITTC's guidelines [1], herein denoted as "Far Field Method, corrected". For S60 hulls, excessive overestimation of added resistance was observed in previous studies [5], hence an extra correction for the peak values was applied.

Figure 64 to Figure 66 show the results obtained by the above methods and experimental data for 3 different ship types, namely the Series 60 (C_B= 0.70), the KVLCC2 tanker and the S175 container ship. In the comparisons, JS1…JS6 correspond to hypothetical irregular seas JONSWAP spectra, for which the mean added resistance was estimated by use of the standard spectral analysis technique.
Figure 65. Prediction of added resistance in regular and irregular waves, KVLCC2 ship, Fn=0.142

Figure 66. Prediction of added resistance in regular and irregular waves, S175 ship, Fn=0.20

An extensive study on second order forces in regular waves was also performed by field methods. Quadratic response amplitude operators (RAOs) for the forces were compared with experimental results for two different ship types, see Figure 67 and Figure 68. The ratio between wave and ship length was varied from 0.2 to 2.5. Thus, both, relatively short waves and long waves were considered. The time-average waveforces were normalized as follows:

\[
C_{aw} = \frac{F - R_{\text{calm}}}{\rho g (B/L) A} \quad \text{and} \quad C_{aw} = \frac{F_y - F_{y,\text{calm}}}{\rho g (B/L) A}.
\]

\(R_{\text{calm}}\) denotes the calm water resistance and \(F_{y,\text{calm}}\) the calm water sway force.

Figure 67. Computed and measured surge forces in head waves for DTC and KVLCC2
Validation of Methods for Rudder Forces

Several semi-empirical methods for the forces on full-spade and semi-spade rudders in propeller race were developed and tested, based on the approach described in Brix (1993). In addition, a model was developed for the forces acting on podded drives during manoeuvring.

Figure 69 to Figure 79 show selected validation results, demonstrating a fair agreement between the semi-empirical methods, experiments and viscous CFD methods for the rudder forces in uniform flow and in the propeller slip stream.

Figure 68. Computed and measured time-average sway wave force in oblique waves from 60° direction and surge force in oblique wave from 30° direction at zero speed for DTC

Figure 69. Free stream characteristics of spade rudder with rounded tip, \( \Lambda = 2 \), \( R_n = 2.25 \cdot 10^6 \) vs. measurements by Whicker & Fehliner (1958)

Figure 70. Free stream characteristics of spade rudder with sharp-edged tip, \( \Lambda = 2 \), \( R_n = 2.72 \cdot 10^6 \); measurements by Whicker & Fehliner (1958)

Figure 71. Comparison with CFD results of lift coefficient on panamax container ship semi-spade rudder in free stream, \( \lambda = 40.0 \), \( \Lambda = 1.48 \), \( R_n = 56.22 \cdot 10^6 \)

Figure 72. Comparison with CFD results of drag coefficient on panamax container ship semi-spade rudder in free stream, \( \lambda = 40.0 \), \( \Lambda = 1.48 \), \( R_n = 56.22 \cdot 10^6 \)

https://edocs.imo.org/Final Documents/English/MEPC 70-INF.33 (E).docx
Figure 73. Forces on multipurpose ship spade rudder in propeller slip stream vs. model test data, $\lambda = 24.091$, $\Lambda = 1.62$, $C_{th} = 2.278$

Figure 74. Lift force on post-panamax container ship semi-spade rudder in propeller slip stream vs. model test, $\lambda = 41.364$, $\Lambda = 1.68$, $C_{th} = 0.937$

Figure 75. Drag on semi-spade rudder of post-panamax container ship in propeller slip stream vs. CFD, $\lambda = 41.364$, $\Lambda = 1.68$, $C_{th} = 0.937$

Figure 76. Lift force on KVLCC2 semi-spade rudder in propeller slip stream vs. model test, $\lambda = 58.0$, $\Lambda = 1.61$, $C_{th} = 2.76$

Figure 77. Comparison of semi-empirical models by SHOPERA and JASNAOE with model test for side force vs. rudder angle for bulk carrier semi-spade rudder in propeller slip stream at $C_{th} = 6.8$ (left) and 15.8 (right)

Figure 78. Comparison of semi-empirical models by SHOPERA and JASNAOE with CFD for side force on container ship full-spade rudder in propeller slip stream vs. $C_{th}$ at forward speed 4 knots and rudder angle of 10° (left) and 20° (right)
Validation of Maneuvering Simulations in Calm Water and in Waves

Validation of the proposed criteria for maneuvering in waves (weather-vaning, steering and propulsion) can be done using direct transient simulations of maneuvers in waves in time domain. To do this, such simulation methods themselves require validation by comparison with experiments. In the open literature, few such experimental results are available. In [6] the results of maneuvering predictions for the two similar tankers KVLCC1 and KVLCC2 were presented at the SIMMAN 2008 workshop using CFD methods. Note that the free surface was not taken into account in this study.

The results for the turning circle maneuver of KVLCC1 with a rudder angle of 35° can be seen in Figure 80, left. The red line shows the benchmark data obtained by full scale trials of MARIN. The green line depicts the predicted motion calculated with an empirical model by MARIN. The blue line presents the prediction by a CFD solver, which captures the experimental ship path very well. Only selected results of the SIMMAN08 workshop are shown in the graph.

In the SIMMAN 2014 workshop similar maneuvering predictions were repeated, this time using the KRISO container ship (KCS) and considering the free surface by applying a level set technique during the virtual captive model tests [7]. The results are shown in Figure 80, right. The numerical prediction (blue) agrees fairly with the benchmark data obtained with free maneuvering trials performed by MARIN.

Figure 80. Numerical simulations (blue) vs. experiments; SIMMAN 08 (left) and 14 (right) workshops
For the comparison with the conducted maneuvering experiments for the DTC container ship, a complete set of calm water maneuvering coefficients was computed using RANS-CFD simulations. Figure 81 shows the predicted turning circle (blue), which agrees fairly well with the free running experiment to the starboard side. The green line is the mirrored free running test to port, whose steady turning diameter is substantially smaller than the one to starboard. This difference between the two tests has still to be clarified and may be related to the fitting of the twisted rudder.

Turning circle maneuvering tests were performed at different ship speeds in regular waves of different heights and headings. The nonlinear equations of motion for six degrees of freedom or, alternatively, four degrees of freedom, were solved in time domain. The hydrodynamic coefficients for calm water reactions were computed using virtual PMM tests with viscous field methods. For the turning circle tests in regular waves, the rudder angle was put to 35° starboard when the first wave crest was encountered midships. Turning circle tests were performed in regular waves of height 2 m, period 12.5 s with the initial heading from head. The computed and measured trajectories for the DTC and S175 container ships agree fairly well with the experiments, Figure 82.

Figure 81. Computed (blue) and measured trajectories of DTC turning circle in calm water

Figure 82. Computed vs. measured trajectories of a turning circle of DTC container ship in regular head waves (left) and computed vs. measured trajectories of turning circle for S175 container ship in regular head wave (right)
References

1. ITTC, "Recommended Procedures and Guidelines, Speed and Power Trials, Part 2 Analysis of Speed/Power Trial Data, 7.5-04 -01-01.2, Effective Date 2012, Revision 00," ITTC, 2012.
Appendix 3. Benchmarking of Time-Average Wave Forces & Moments

Introduction

An open blind international benchmark study has been organized by SHOPERA using for validation selected tank test results, which were obtained within the SHOPERA project, while some benchmark test data were made available from experimental studies in Japan. The aim of this benchmark study was to assess the accuracy/reliability of current numerical simulation methods on calculating the mean second order forces/moment and simulating the maneuverability of a ship in waves of varying complexity; simplified formulas, potential flow methods, motion simulators and viscous field methods, were compared with each other and with model tests for selected cases. As the employed methods were of varying complexity and capability, their robustness in predicting was expected accordingly to be of mixed quality.

Qualified institutes from both inside and outside SHOPERA consortium that have been established as developers of relevant simulation methods and computer programs were invited to demonstrate the performance of their software on the prediction of the mean second order forces and maneuverability of ships sailing in waves. The participating institutes dispose independently developed codes and have published relevant results in peer reviewed scientific journals and conferences in the past, thus their participation in this benchmark study suggested that they adequately represent the current state of art in the field.

The study was announced to potential participants in November 2015. Initially a total of thirty-eight (38) participants showed their interest in contributing to the benchmark study. On 15 December 2015, Part I of the specifications of the SHOPERA International Benchmark Study were circulated to the participants; it referred to a first series of tests of DTC containership for which relevant experimental data were available to the study coordinator from a series of tests carried out within the SHOPERA research project. The Part II of the study data, which referred to the tests of the KVLCC2 tanker ship were made available on 22 December 2015 through the SHOPERA website (www.shopera.org/benchmark-study/). An updated, enhanced version of the document “Specification, Part II: The KVLCC2 Case Study” was uploaded on the SHOPERA web site on 05 February 2016. The templates for submitting study results were released in the end of January 2016.

According to the set initial plan, the participants should submit their numerical/simulation results by 10 Mar 2016 to the study coordinator. Eventually sixteen (16) independent participants submitted simulation results, Table 11. The comparative experimental data were not known to the study participants, hence it can be concluded that the present benchmark assessment was based on a solid foundation and allowed an assessment of the genuine capabilities of benchmarked codes.

The submitted simulation results were analyzed by the benchmark study coordinator and compared with corresponding model experimental data to conclude on the accuracy and efficiency of the methods. The outcomes of the study were presented at a public workshop on April 15, 2016, Lloyds Register, London (see http://www.shopera.org/benchmark-study/eedings/presentations of the workshop).

---

5 It is acknowledged that some additional qualified institutes with relevant background have not participated in the present benchmark study, due to a variety of reasons. However, it is believed that the overall conclusions of the present study are not affected by this.

6 Inherently, the experimental data were known to the institutions in charge of the model experiments and the organizers of the present benchmark study.
Table 11. Final list of participants in the benchmark study

<table>
<thead>
<tr>
<th>Institution</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Aalto University</td>
<td>Finland</td>
</tr>
<tr>
<td>2 American Bureau of Shipping</td>
<td>USA</td>
</tr>
<tr>
<td>3 Chalmers University</td>
<td>Sweden</td>
</tr>
<tr>
<td>4 Germanischer Llyod</td>
<td>Germany</td>
</tr>
<tr>
<td>5 Hiroshima University</td>
<td>Japan</td>
</tr>
<tr>
<td>6 Indian Register of Shipping</td>
<td>India</td>
</tr>
<tr>
<td>7 MARIN/CRS</td>
<td>Netherlands</td>
</tr>
<tr>
<td>8 MARINTEK</td>
<td>Norway</td>
</tr>
<tr>
<td>9 National Technical University of Athens — Ship Design Laboratory</td>
<td>Greece</td>
</tr>
<tr>
<td>10 Shanghai Jiao Tong University (Chen Si)</td>
<td>China</td>
</tr>
<tr>
<td>11 Shanghai Jiao Tong University (Wei Zang)</td>
<td>China</td>
</tr>
<tr>
<td>12 Seoul National University</td>
<td>Korea</td>
</tr>
<tr>
<td>13 Strathclyde University</td>
<td>UK</td>
</tr>
<tr>
<td>14 Technical University of Berlin</td>
<td>Germany</td>
</tr>
<tr>
<td>15 University of Duisburg-Essen</td>
<td>Germany</td>
</tr>
<tr>
<td>16 University of Zagreb</td>
<td>Croatia</td>
</tr>
</tbody>
</table>

The Subject Ships

Duisburg Test Case

The Duisburg Test Case (DTC) containership design is a modern post Panamax 14,000 TEU container vessel. It was developed by the Institute of Ship Technology, Ocean Engineering and Transport Systems (ISMT) of the University of Duisburg-Essen in collaboration with Germanischer Lloyd for benchmarking and validation of numerical methods; its lines and other characteristics are available to the public, see [XX]. The DTC CAD offset file was made available for download by the benchmark participants from the SHOPERA web site.

KVLCC2 ship

The KVLCC2 is a VLCC type tanker vessel, representing the second variant of a modern tanker design developed by the Korean Institute of Ship & Ocean Engineering (KRISO) with bulb bow and U-shaped stern lines, see [XX]). The hull lines have been exclusively developed for testing and benchmarking and this ship has been until now widely used benchmarks of international scientific committees, like ITTC and SIMMAN.

Added Resistance in Waves

For the added resistance of the DTC ship, 13 participants\(^7\) made 15 submissions, Figure 83; for the added resistance of KVLCC2 ship, 10 participants made 11 submissions, Figure 84. At higher speed in head waves, the spreading of results among the various methods and in comparison to the experimental data is moderate, while most methods seem to deliver results with good agreement with the experimental data. It should be herein noted that the test range of frequencies/wave lengths, extending to very short waves of \(\lambda/L \approx 0.2\) is quite demanding regarding uncertainties for both the experiments and computations.

\(^7\) Participants’ coding (P1...P21) is randomly chosen (keeping the anonymity of the originators of the benchmark results). It is understood that 2 of the 16 participants submitted more than one set of results by alternative methods; also, one set of the depicted results refers to the comparative experimental data (marked by the star \(\star\) symbol), whereas one participant provided numerical results for a wider range of frequencies (marked by a dotted green line).
The following notations are used in the Figures with the benchmark results:

\[\tilde{\omega} = \sqrt{\frac{L_{pp}}{A_W}}, \quad C_{AW} = \frac{-F_x - R_T}{\rho g (B^2 / L_{pp}) A_Z^2}, \quad C_{AY} = \frac{F_y}{\rho g (B^2 / L_{pp}) A_Z^2}, \quad C_{MZ} = \frac{M_z}{\rho g B^2 A_Z^2}\]

Colored symbols are used as identifiers for the type of used code (category method):

- Cyan: Empirical formula;
- Red: Strip theory (quasi 2D) method;
- Green: Boundary element (3D Panel) method;
- Blue: RANSE method.

At lower speeds in head waves, Figure 85 and Figure 86, the spreading among the numerical results gets larger, and the deviation from experimental results is also significant. The quality of the numerical predictions by some methods is poor, but several others are satisfactory. It should be noted that range of tested scenarios refers to a great extent to the short waves region, where the physics of the problem gets very complicated for both the numerical and experimental methods (breaking waves, viscous effects, etc.).

For oblique waves, Figure 87 and Figure 88, tank tests have been conducted only for low speeds and 60 deg heading. In general, a relatively good agreement has been observed for the DTC ship, whereas for the KVLCC2 ship the performance is similar.
Results of Calculation of Drift Forces and Moments

For the mean side force and yaw moment of the DTC ship, 10 participants made 13 submissions. For the KVLCC2 ship, 8 participants made 9 submissions.

The convergence of results on the drift force in the transverse direction is general good, while the results for the mean yaw moment are less satisfactory. This may have been expected, as the yaw moment is the combined effect of forces both in the longitudinal and the transverse direction, and any discrepancy in the mean force in the longitudinal direction trivially leads to unsatisfactory results in the mean yaw moment. Figure 89 shows the predicted mean side force for DTC and KVLCC2 ships in bow quartering and beam waves, the corresponding longitudinal forces of which are presented in Figure 87 and Figure 88. The performance of the various methods is similar to that observed in the previous tests.
Conclusions

The objectives of the SHOPERA international benchmark study on the performance of numerical simulation tools for the prediction of mean second forces/moment and manoeuvrability of ships in waves were fully met. The good international participation from both inside and outside the SHOPERA consortium enabled the assessment of representative results and reliable conclusions about the current state of the art of the study field.

The benchmark study concerned two large ships, the DTC containership and the KVLCC2 tanker, which are both well over 300m in terms of length. For such large ships, the encountered waves in actual sea conditions are mostly 'short', namely $\lambda/L < 0.5$, where the benchmark study focused on. The study delivered a good insight into the predictability of complicated hydrodynamic phenomena on the basis of experimental and numerical studies. It provided also valuable benchmark data to the international scientific community for future research on a subject with strong scientific and engineering background linked to international maritime regulations. Some essential aspects of the subject were noticed and should be further studied in the future. In particular, examining the numerical simulation results in comparison to model experimental data, the following may be concluded:

1. The predictability of the added resistance is generally decent to good. The performance of the tested methods is better for moderate speeds and worsens with decreasing speed. Also, the agreement is better for the tested full type ship (KVLCC2) than for the DTC containership hull form.
2. The predictability of the second order forces/moments (drift forces and yaw moment), is generally worse than for the added resistance and again worse for the DTC ship than the KVLCC2 ship.
3. For the maneuverability simulations, the behaviour of various employed numerical methods is not consistent. Despite the large spreading among the numerical methods and deviation from experimental results, some methods, performing well in one case, were not good for another case, thus conclusions could not be drawn, except for some qualitative effects of the impact of incoming waves.
4. The overall impression of the submitted results based on strip theories was not satisfactory. This is mainly due to its insufficiency in accounting the 3D and end effects (bow and stern) of the hull form, which are significant in the present study subject.
5. BEM methods implementing various theories performed as category of methods best in the present benchmark due to their essential merits: comparatively easy to use, when the code is properly programmed and validated and with decent results for non-extreme designs and loading/environmental conditions.
6. A reliable assessment of CFD/RANS methods was not possible due to limited participation and some delivered odd results. This may be attributed to improper use of codes (meshing etc.), allowing the conclusion that CFD codes are highly dependent on their usage, rather than on the physics of the studied problem or the code itself.
7. There was also one empirical method participating in the benchmark study by submitting results on the prediction of added resistance. For the studied cases, the empirical method delivered good results, showing a promising performance.
Some additional general comments may be concluded:

a. **Limitations of the numerical methods**: CFD tools are highly dependent on the end-users' skills (background, experience with the type of problem, etc). In general, however, the quality of predictions is solely dependent on the code developer's know-how and the code user's experience.

b. **The particularity of hull form**: The scattering of the numerical results is more serious for the DTC ship than for the KVLCC2 ship. This can be credited to the effect of their hull form. The DTC ship disposes a relatively small draft (in comparison with other main particulars), an extended bulbous bow close to the free surface and a transom stern with long overhang near the calm water free surface. It is well known that for these are two critical issues, namely, an emerging bulbous bow and immersing transom stern, with the associated complex wave phenomena and rapid change of the wetted part of the ship. Potential flow, paneling methods are not performing well in these conditions due to their essential limitations. However, even RANS methods are challenged under similar conditions and may fail, if not properly used.

c. **The tested waves**: As the size of the tested ships is large (>300m), representative sea states fall into the relatively short waves. In order to measure the small absolute values during model tests, quite steep waves were generated and tested. This may have created additional uncertainty in the benchmarked results, independently of the specific hull form. This uncertainty can only be partially controlled by using larger ship models for testing or applying full scale CFD simulations in future work.

d. **Uncertainty of experimental data**: The studied complex hydrodynamic phenomena put great challenges not only to numerical methods, but also to model experiments. This is obvious, when observing the spread of comparative model experimental data for similar conditions. This may be attributed to limitations of the used hardware, which is sometimes tested to its limits (e.g. measurement of very small force values of few Newtons), the inherent limitations of the size of tested ship models and generated scaled waves, the lack of repeatability of test measurements, etc.

**References**


Appendix 4. Details of Simplified Steering Ability Assessment

Background

The starting point is system (8)-(10), solved for all relevant forward speeds and all seaway directions to check that the ship is able to start or continue course change in seaway from any direction. Note that for the steering ability, both the steering system and propulsion (which influences steering ability) are required and should be integral parts of the assessment: e.g. ships with powerful propulsion may have a smaller rudder, whereas ships with weaker propulsion may compensate this with larger or more effective steering devices. Results of Comprehensive Assessment for many ships show that the dimensioning condition for the installed power, at which the ratio of the required to available delivered power is maximised along the line of maximum steering effort (further referred to for brevity as critical condition for steering) is close to beam seaway, Figure 16, right. (Note that from experience, as well as from the results of Comprehensive Assessment for many ships, the critical conditions for steering occur most frequently in stern quartering waves, like in Figure 16, middle; however, in such situations the required power is defined by the Propulsion Ability requirement, i.e. by the crossing point of lines A and B; when Steering Ability requirement is dominating for the definition of the installed power, i.e. when line A crosses line C, the critical conditions are always close to beam seaway situations.) This allows reducing the evaluation of the time-average wave and wind forces to beam seaways:

\[ X_s + X_w^{90} + X_d^{90} + X_R + T(1-t_H) = 0 \] (11)
\[ Y_s + Y_w^{90} + Y_d^{90} + Y_R = 0 \] (12)
\[ N_s + N_w^{90} + N_d^{90} - Y_R l_R = 0 \] (13)

The second simplification stems from the comparison of the levers of time-average wave and wind yaw moment with the lever of the calm-water yaw moment in critical conditions for steering. Introduce the levers of yaw moments as follows:

\[ l_s = N_s / Y_s, \quad l_w = N_w / Y_w, \quad l_d = N_d / Y_d, \] (14)

and rewrite eq. (13) using these definitions as

\[ l_s Y_s + l_w Y_w + l_d Y_d - Y_R l_R = 0 \] (15)

Express \( Y_s \) from eq. (12) as

\[ Y_s = -Y_w^{90} - Y_d^{90} - Y_R \] (16)

Introducing eq. (16) into eq. (15) leads to a combination of equations (12) and (13),

\[ Y_w^{90} (l_w - l_s) + Y_d^{90} (l_d - l_s) = Y_R (l_s + l_R) \] (17)

Analysis of the terms of converged solutions of the system (8)-(10) in the critical conditions for steering ability (i.e. forward speeds and seaway directions, for which \( p_o / p_0^{90} \) is maximum along the line \( \delta = \delta_{\text{max}} \), Figure 16, right) shows that

\[ l_s = L_{pp} / 2, \quad l_w << l_s, \quad l_d << l_s, \] (18)

Figure 90, thus eq. (17) can be simplified as

\[ Y_w^{90} (0 - l_s) + Y_d^{90} (0 - l_s) = Y_R (l_s + l_R) \], or

\[ Y_R = -b (Y_w^{90} + Y_d^{90}) \] (19)
where
\[ b = \frac{l_s}{l_s + l_R} \quad (20) \]

As a result, the system of equations (11)-(13) reduces to one equation
\[ X_s + X_{w0} + X_{d0} + X_R + T(1 - \eta_I) = 0 \quad (21) \]

Figure 90. Ratios of levers \( l_w / l_s \) (left) and \( l_d / l_s \) (right) in critical conditions for steering
(combinations of forward speeds and seaway directions for which \( P_u / R_0^w \) is maximum along the line \( \delta = \delta_{\text{max}} \)).

The solution of this equation (the maximum attainable speed and corresponding propeller rotation speed and thrust) defines the maximum available lateral steering force on the rudder \( Y_{\text{av}}^R \). This steering force should not be less than the required lateral steering force defined by eq. (19), \( Y_{\text{req}}^R = -b(Y_{w0}^0 + Y_{d0}^0) \). As an approximation, assume \( l_R \approx 0.5L_p \), then definition (20) simplifies to
\[ b = -l_s/\left(l_s + 0.5L_p\right), \quad (22) \]

which can also be written as
\[ b = \frac{Y_{l_s}}{Y_{l_s} + Y0.5L_p} = \frac{N_s}{N_s + 0.5Y L_p} = \frac{N_s'}{N_s' + 0.5Y'} \quad (23) \]

where \( Y' = Y/\left(0.5\rho L_p T_{\text{av}^2}\right) \), \( N' = N/\left(0.5\rho L_p^2 T_{\text{av}^2}\right) \) are the coefficients of calm-water side force and yaw moment, respectively; note that they depend only on drift angle \( \beta \).

To validate these approximations, Figure 91 compares the ratio of the required to available delivered power according to approximations (21), (22) with the same ratio from the Comprehensive Assessment for the 15 sample ships. In the Simplified Assessment, the value of \( b \) was taken from the Comprehensive Assessment, as the exact value \( b = N_s/\left(N_s + 0.5Y L_p\right) \) in critical conditions for steering ability. Figure 92 compares marginal significant wave height according to Simplified Steering Assessment (21), (22) with marginal significant wave height from Comprehensive Assessment for sample bulk carriers, tankers and container ships; according to Figure 91 and Figure 92, the approximation (21), (22) provides accurate to slightly conservative results.

Note that the simplifications made restrict the Simplified Steering Ability assessment to the vessels with conventional steering devices arrangement at the stern (including azimuths); vessels equipped with azimuths at the bow require Comprehensive Assessment.
Simplified Empirical Methods for Forces

In the Simplified Assessment of Steering Ability in Waves, any of the methods used in the Comprehensive Assessment can be applied to define the components of forces and moments. In addition, simplified empirical formulae can be used, that are given below.

Wind resistance in beam seaway $X_w$, N, can be calculated as

$$X_w = -0.5X'_w \rho_1 v^2 A_F$$

where $X'_w$ is the wind resistance coefficient that can be assumed $X'_w = 1.0$.

Lateral force due to beam wind $Y_w^{90}$, N, can be calculated as

$$Y_w^{90} = -0.5Y'_w \rho_2 A_L v^2$$

where $Y'_w$ is the lateral wind resistance coefficient that can be assumed $Y'_w = 0.9$.

The added resistance due to irregular short-crested beam waves $X_d^{90}$, N, can be calculated using methods from the Comprehensive Assessment procedure as the maximum value over all peak wave periods specified. Alternatively, a simple empirical formula

$$X_d^{90} = -380L_{pp} C_{f/d}^B (0.1 + Fr) h_s^2$$

can be used, where $Fr = v_s / \sqrt{g k_{pp}}$ is the Froude number. This formula was obtained from numerical computations with GL Rankine and spectral integration for JONSWAP spectrum with $\gamma = 3.3$ with cos$^2$-spreading, as a maximum over peak wave periods from 7.0 to 15.0 s. Comparison of results of this formula with numerical computations is shown in Figure 93 at the forward speed of 4.0 m/s.
The time-average lateral force due to irregular short-crested beam waves $Y_d^{90}$, N, also can be defined using numerical methods from the Comprehensive Assessment or, alternatively, calculated with the simple empirical formula

$$Y_d^{90} = -540L_{pp}h_2^2\left[1 + \left(\frac{T_p C_{pp}^{1-1/2}}{L_{pp}}\right)^5\right]$$

which was obtained from the results of calculations with GL Rankine, combined with spectral integration for JONSWAP spectrum with $\gamma = 3.3$ and $\cos^2$-spreading. Figure 94 compares results of this formula with numerical computations with GL Rankine followed by spectral integration.

The increase in rudder resistance $X_R$ in critical conditions for steering can be defined with any method (experimental, numerical or empirical from the Comprehensive Assessment); because $X_R$ implicitly depends on thrust, which is itself part of solution, this will require an iterative solution. Alternatively, a simple assumption $X_R = -t_R T$ can be used to avoid iterative solution of eq. (21). According to Comprehensive Assessment results for 15 vessels, $t_R = 0.18$ is recommended (note that rudder resistance part at zero rudder angle in calm water is included into the calm-water resistance $X_s$).

The coefficient $b$ in the formula for the required lateral steering force $Y_{req} = -b(Y_w^{90} + Y_d^{90})$ can be defined using a conservative assumption $b = 0.5$, following from the application of Comprehensive Assessment to 15 bulk carriers, tankers, container vessels and general cargo ships. A less conservative empirical formula for $b$ as a function of main ship characteristics would be useful.
Appendix 5. Details of Simplified Propulsion Ability Assessment

Background

The starting point is the system of equations (8)-(10), which has to be solved for all relevant forward speeds and all possible seaway directions to demonstrate that the ship is able to keep forward speed of at least 6.0 knots in seaway from any direction. Noting that bow seaways are most critical for required power at a given speed (Figure 16, middle plot), it is enough to consider only seaways from 0 to about 60° off-bow in the assessment. Further, neglecting the influence of drift on the required thrust and required power allows omitting equations (9) and (10). Thus only eq. (8) needs to be considered, and only in head waves:

\[ X_s + X_w + X_d + X_R + T(1-t_h) = 0 \]  \hspace{1cm} (24)

However, it is important to keep in mind that the time-average longitudinal force due to waves \( X_d \) in eq. (24) should be taken as the maximum force in mean wave directions between 0 and 60° off-bow.

The contributions \( X_s, X_w, X_d, X_R \) and thrust \( T \) in eq. (24) can be found using any method from the Comprehensive Assessment (empirical, numerical or experimental). However, it seems logical to allow using also simpler approximations for these terms in the Simplified Assessment.

For example, using semi-empirical models for the rudder resistance \( X_R \) from the Comprehensive Assessment will lead to an implicit dependence of \( X_R \) on the propeller thrust \( T \), requiring an iterative solution of eq. (24). To allow a simpler, non-iterative solution, assume \( X_R = -t_R T \), where \( t_R \) is an empirical constant. In bow-quartering waves, a significant rudder angle may be required for steering, which leads to \( t_R = 0.14 \) (based on Comprehensive Assessment for 15 vessels). This results in a simple non-iterative equation for the required thrust \( T \):

\[ T = -\frac{(X_s + X_w + X_d)}{(1-t_h-t_R)} \]  \hspace{1cm} (25)

where \( t_h \) is the thrust deduction on the ship hull.

Figure 95 compares results of the proposed simplified propulsion ability assessment procedure with the Comprehensive Assessment for 4 bulk carriers, 3 tankers and 4 container ships at \( h_s = 0 \) to 9.5 m. The plot shows the ratio of the required to available delivered power \( P_{av}/P_{Dav} > 1 \) according to the Simplified (y-axis) vs. Comprehensive (x-axis) Assessment. Figure 96 shows corresponding marginal significant wave height according to simplified vs. comprehensive propulsion ability assessment for sample bulk carriers, tankers and container ships. Figure 95 and Figure 96 indicate that the proposed Simplified Assessment procedure is sufficiently accurate to slightly conservative, especially for \( P_{av}/P_{Dav} > 1 \) (which is not relevant anyway).

Simplified Empirical Methods for Forces

In the Simplified Assessment of Propulsion Ability in Waves, any of the methods used in the Comprehensive Assessment can be applied to define the components of forces and moments. In addition, simplified empirical formulae can be used, that are given in this section.

Wind resistance in head wind \( X_w \), N, can be calculated as
\[ X_w = -0.5X_w \rho_a (v_s + v_w)^2 A_f \]

Figure 95. Ratio of required to available delivered power according to Simplified (y-axis) vs. Comprehensive (x-axis) Propulsion Ability Assessment for 4 bulk carriers (■, △, ▽, ●), 3 tankers (■, △, ▽) and 4 container ships (□, △, ▽, ○) in waves of significant wave heights from 0.0 to 9.5 m

where \( \rho_a \) is the air density, \( v_w \) is wind speed, \( A_f \) frontal windage area, and \( X_w \) is the head wind resistance coefficient, which can be defined with any methods (experimental, numerical or experimental) used in the Comprehensive Assessment or conservatively assumed as 0.9. The added resistance in irregular short-crested bow waves \( X_d \), N, can be calculated using methods from the Comprehensive Assessment procedure, combined with a spectral integration, as the maximum value over for wave headings from head waves up to 60° off-bow and all peak wave periods specified. Alternatively, the formula

\[ X_d = -83L_{pp} C_d^{1/3} (1 + \sqrt{Fr}) h_s^2 \]

can be used, where \( Fr = v_s / \sqrt{gL_{pp}} \) is the Froude number. This formula is based on computations with the software GL Rankine, followed by a spectral integration using JONSWAP spectrum with \( \gamma = 3.3 \) and \( \cos^2 \)-wave energy spreading and taken as maximum over mean wave directions 0 to 60° off-bow and peak wave periods from 7.0 to 15.0 s. Figure 97 compares results of this formula, y-axis, with numerical computations, x-axis, for 14 bulk carriers (BC), tankers (TA) and container vessels (CV).

Figure 96. Marginal significant wave height according to Simplified (y-axis) vs. Comprehensive (x-axis) Propulsion Ability Assessment for bulk carriers (BC), tankers (TA) and container ships (CV)

Figure 97. \( X_d \) in irregular short-crested waves according to empirical formula vs. numerical computations.
The increase in rudder resistance $X_R$ in bow-quartering waves can be defined with any method (experimental, numerical or empirical from the Comprehensive Assessment); alternatively, a simple assumption $X_R = -t_r T$ can be used in the Simplified Assessment. According to Comprehensive Assessment results, $t_r = 0.08$ is recommended (note that rudder resistance part at zero rudder angle in calm water is included into the calm-water resistance $X_s$).
Appendix 6. Propulsion Assessment Procedure agreed with Japan

SUPPLEMENTARY INFORMATION ON MINIMUM POWER ASSESSMENT PROCEDURE

1 Purpose

1.1 The purpose of annex 2 is to provide sufficient detail of the [Minimum Power Assessment] procedure of the draft revised Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions, so that all interested stakeholders are able to perform this assessment on a uniform basis.

2 Requirement

2.1 To satisfy the requirements of the [Minimum Power Assessment], the required brake power $P_B$ in the adverse conditions and at the forward speed defined according to the draft revised Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions should not exceed the available brake power $P_B^{av}$ in the same conditions:

$$P_B \leq P_B^{av}$$

2.2 The required brake power $P_B$ is calculated as

$$P_B = \frac{2\pi n_p Q}{\eta_s \eta_g \eta_R}$$

where

- $n_p$ (1/s) is the propeller rotation rate in the specified adverse conditions at the specified forward speed;
- $Q$ (N·m) is the corresponding propeller torque;
- $\eta_s$ is the mechanical transmission efficiency of the propeller shaft;
- $\eta_g$ is the gear efficiency; and
- $\eta_R$ is the relative rotative efficiency.

2.3 The available brake power $P_B^{av}$ in the specified adverse conditions at the specified forward speed is defined as the maximum engine output at the actual rotation speed, taking into account maximum torque limit, surge/air limit and all other relevant limits according to the engine manufacturer’s data.

3 Definition of propulsion point

3.1 The propeller rotation rate $n_p$ and the corresponding propeller advance ratio $J$ in the specified adverse conditions at the specified forward speed are defined from the propeller open-water characteristics by solving the following equation:

$$\frac{K_T}{J^2} = \frac{T}{\rho u_c^2 D_c^2}$$

where

- $K_T$ is the thrust coefficient of the propeller, defined from the propeller open-water characteristics;
\[ T \text{ (N)} \] is the required propeller thrust;
\[ \rho \text{ (kg/m}^3\text{)} \] is the sea water density, \( \rho = 1025 \text{ kg/m}^3 \);
\[ u_a \text{ (m/s)} \] is the propeller advance speed; and
\[ D_p \text{ (m)} \] is the propeller diameter.

3.2 The corresponding torque of the propeller is found as
\[ Q = K_Q \rho \eta_r^2 D_p^5 \]
where
\[ K_Q \] is the torque coefficient of the propeller, defined from the propeller open-water characteristics.

3.3 The propeller advance speed \( u_a \) is calculated as
\[ u_a = U(1 - w) \]
where
\[ U \text{ (m/s)} \] is the specified forward speed according to draft revised Guidelines; and
\[ w \] is the wake fraction.

4 Definition of required propeller thrust

4.1 The required propeller thrust \( T \) is defined from the equation:
\[ T = \frac{X_s + X_a}{1 - t} \]
where
\[ X_s \text{ (N)} \] is the resistance in calm-water at the specified forward speed including resistance due to appendages;
\[ X_a \text{ (N)} \] is the added resistance in seaway \( X_a = X_w + X_d + X_r \) including added resistance due to wind \( X_w \), added resistance due to waves \( X_d \) and added rudder resistance due to manoeuvring in seaway \( X_r \); and
\[ t \] is the thrust deduction taking into account suction force on the ship hull due to propeller thrust.

5 Definition of calm water characteristics

5.1 The following calm-water characteristics can be defined using the same methods as those allowed to determine the calm-water characteristics for EEDI verification:

.1 the calm-water resistance \( X_s \) at the specified forward speed \( U \);

.2 the propeller thrust deduction \( t \), wake fraction \( w \) and relative rotative efficiency \( \eta_r \); and

.3 the propeller open-water characteristics \( K_T(J) \) and \( K_Q(J) \).
6 Definition of added resistance

6.1 The added resistance in seaway $X_a$ is defined as maximum of the sum of added resistance due to wind, waves and rudder over wave headings $\mu$ from head sea $\mu = 0$ degree to 60 degree off-bow $\mu = 60$ degree.

7 Definition of wind resistance

7.1 The added resistance due to wind $X_w$ is calculated as

$$X_w = 0.5X'_w(\varepsilon)\rho_a v_w^2 A_F$$

where

- $X'_w(\varepsilon)$ is the non-dimensional aerodynamic resistance coefficient;
- $\varepsilon$ (degree) is the apparent wind angle;
- $\rho_a$ (kg/m$^3$) is the air density, $\rho_a = 1.2$ kg/m$^3$;
- $v_w$ (m/s) is the relative wind speed, $v_w = U + v_w \cos \mu$;
- $v_w$ (m/s) is the absolute wind speed, defined according to the draft revised Guidelines; and
- $A_F$ (m$^2$) is the frontal projected area of the ship.

7.2 The non-dimensional aerodynamic resistance coefficient $X'_w$ can be defined from wind tunnel experiments or using equivalent methods verified by the Administrations or Recognised Organisations. Alternatively, it can be assumed $[X'_w = 0.9]$.

8 Definition of added resistance due to waves

8.1 The added resistance due to irregular waves $X_d$ can be defined according to either

1. expression

$$[X_d = 83 \cdot L_{pp} \cdot C_B^{1.5} (1 + \sqrt{Fr}) h_s^2]$$

where

- $L_{pp}$ (m) is the length of the ship between perpendiculars;
- $C_B$ is the block coefficient at the actual condition of loading;
- $Fr$ is the Froude number, $Fr = U (gL_{pp})^{-0.5}$;
- $g$ (m/s$^2$) is the acceleration due to gravity, $g = 9.81$ m/s$^2$; and
- $h_s$ (m) is the significant wave height, defined according to the draft revised Guidelines.

This expression defines the maximum added resistance over wave directions from head waves to 60 degree off-bow.

2. or spectral method

$$X_d = 2 \int_0^\infty \int_0^{2\pi} \frac{X_d(U, \mu', \omega')}{{A^2}} S_{xx}(\omega') D(\mu - \mu') \, d\omega' \, d\mu'$$
where

\[ \frac{X_d}{A^2} \text{ (N/m}^2\text{)} \]

is the quadratic transfer function of the added resistance in regular waves and \( A \) is the wave amplitude;

\[ S_{\xi\xi} \]

is the seaway spectrum, defined according to the draft revised Guidelines;

\( D \)

is the spreading function of wave energy with respect to mean wave direction;

\( \omega' \) (rad/s)

is the wave frequency of component; and

\( \mu' \) (rad)

is the direction of the wave component.

If practicable, this method may be applied using head waves as the only one mean wave direction. In this case, the maximum added resistance over wave directions from head waves to 60 degree off-bow can be defined as the added resistance in head waves times the correction factor equal to [1.04].

8.2 The spreading function \( D(\mu) \) is defined according to the draft revised Guidelines. Alternatively, long-crested seaway can be assumed with \( D = 1 \); in this case, the resulting added resistance \( X_d \) is multiplied with the reduction factor [0.9] to take into account the short-crestedness of the actual seaway.

8.3 The quadratic transfer functions of added resistance in regular waves \( \frac{X_d}{A^2} \) can be defined from seakeeping experiments or using equivalent methods verified by the Administrations or Recognised Organisations. Alternatively, [the semi-empirical method specified in appendix] can be used.

9 Definition of added resistance due to rudder

9.1 The added resistance due to rudder \( X_r \) is simply calculated as

\[ X_r = [0.04] \cdot T, \text{ where } T \text{ is the propeller thrust.} \]

***
APPENDIX

SEMI-EMPIRICAL METHOD FOR QUADRATIC TRANSFER FUNCTIONS OF ADDED RESISTANCE IN REGULAR WAVES

The method for the calculation of the quadratic transfer functions of added resistance given in this appendix can be applied to wave directions from head to beam. Therefore, this method can be used to either

(a) Calculate the added resistance in short-crested irregular waves of the head mean wave direction. The resulting resistance should be multiplied with a factor \([1.04]\) to take into account higher added resistance in oblique wave directions; or

(b) Calculate the added resistance in long-crested irregular waves of the mean directions from head to 60 degree off-bow. The maximum value of the added resistance over 0 to 60 degree wave directions should be multiplied with a factor \([0.9]\) to take into account lower added resistance in short-crested waves.

The quadratic transfer functions of added resistance in regular head to beam waves \(X'_d = \frac{X_d}{A^2}\), N/m², can be calculated as a sum

\[X'_d = X'_{dM} + X'_{dR}\]

of \(X'_{dM}\), the component of added resistance due to motion (radiation) effect, and \(X'_{dR}\), the component of added resistance due to reflection (diffraction) effect in regular waves.

The expression of \(X'_{dM}\) is given as follows:

\[X'_{dM} = 4 \rho g \frac{B^2}{L_{pp}} a_1 a_2 \bar{\omega}^b e^{d_1 (1-\bar{\omega}^{d_1})}\]

where

\[
\bar{\omega} = \begin{cases} 
2.142 \sqrt{k_y y} \frac{L_{pp}}{L} \left[ 1 - \frac{0.111}{C_B} \left( \ln \frac{B}{d} - \ln 2.75 \right) \right] \frac{2(\cos \beta)}{3} (Fr + 0.62) & \text{for } Fr < 0.1 \\
2.142 \sqrt{k_y y} \frac{L_{pp}}{L} \left[ 1 - \frac{0.111}{C_B} \left( \ln \frac{B}{d} - \ln 2.75 \right) \right] \frac{2(\cos \beta)}{3} Fr^{0.143} & \text{for } Fr \geq 0.1 
\end{cases}
\]

\[a_1 = 60.3 C_B^{1.34} (4k_y y)^2 \left( \frac{0.87}{C_B} \right)^{-(1+Fr)\cos \beta} \left( \ln \frac{B}{d} \right)^{-1} \left( 1 - 2 \cos \beta \right) \] for \(\frac{\pi}{2} \leq \beta \leq \pi\)

\[a_2 = \begin{cases} 
0.0072 + 0.1676 Fr & \text{for } Fr < 0.12 \\
Fr^{1.5} \exp (-3.5Fr) & \text{for } Fr \geq 0.12 
\end{cases}
\]

for \(C_B > 0.75\)

\[b_1 = \begin{cases} 
11.0 & \text{for } \bar{\omega} < 1 \\
-8.5 & \text{elsewhere} 
\end{cases}
\]

\[b_1 = \begin{cases} 
11.0 & \text{for } \bar{\omega} < 1 \\
-8.5 & \text{elsewhere} 
\end{cases}
\]

\[d_1 = \begin{cases} 
566 \left( \frac{L_{pp}}{B} \right)^{-2.66} & \text{for } \bar{\omega} < 1 \\
-566 \left( \frac{L_{pp}}{B} \right)^{-2.66} \times 6 & \text{elsewhere} 
\end{cases}
\]

\[d_1 = \begin{cases} 
14.0 & \text{for } \bar{\omega} < 1 \\
-566 \left( \frac{L_{pp}}{B} \right)^{-2.66} \times 6 & \text{elsewhere} 
\end{cases}
\]

where
\[ \beta = \pi - \mu \] 
is the wave direction, \( \beta = \pi \) means head seas;
\[ \lambda \text{ (m)} \] 
is the length of the incident wave;
\[ B \text{ (m)} \] 
is the beam of the ship;
\[ d \text{ (m)} \] 
is the draft of the ship;
\[ k_{xy} \] 
is the non-dimensional radius of gyration of pitch;

The expression of \( X'_{dR} \) is given as follows:

\[ X'_{dR} = \sum_{i=1}^{4} X'_{dR}^{i} \]

where

\[ X'_{dR}^{i} \] 
is the added resistance due to reflection/diffraction effect of the \( S_i \) waterline segment, as shown in Figure.

Figure. Sketch of the waterline profile of a ship and related definitions

when \( E_1 \leq \beta \leq \pi \)
\[ X'_{dR}^{1} = \frac{2.25}{4} \rho g B \alpha_{d^*} \left\{ \sin^2 (E_1 - \beta) + \frac{2\omega_0 U}{g} \cos E_1 \cos (E_1 - \beta) - \cos \beta \right\} \left( \frac{0.87}{C_B} \right)^{(1+4\sqrt{Fr})f(\beta)} \]

when \( \pi - E_1 \leq \beta \leq \pi \)
\[ X'_{dR}^{2} = \frac{2.25}{4} \rho g B \alpha_{d^*} \left\{ \sin^2 (E_1 + \beta) + \frac{2\omega_0 U}{g} \cos E_1 \cos (E_1 + \beta) - \cos \beta \right\} \left( \frac{0.87}{C_B} \right)^{(1+4\sqrt{Fr})f(\beta)} \]

when \( 0 \leq \beta \leq E_2 \)
\[ X'_{dR}^{3} = -\frac{2.25}{4} \rho g B \alpha_{d^*} \left\{ \sin^2 (E_2 + \beta) + \frac{2\omega_0 U}{g} \cos E_2 \cos (E_2 + \beta) - \cos \beta \right\} \]

when \( 0 \leq \beta \leq E_2 \)
\[ X'_{dR}^{4} = -\frac{2.25}{4} \rho g B \alpha_{d^*} \left\{ \sin^2 (E_2 - \beta) + \frac{2\omega_0 U}{g} \cos E_2 \cos (E_2 - \beta) - \cos \beta \right\} \]

where
\[ \omega_0 \] 
is the frequency of the incident wave;
\[ \alpha_{d^*} \] 
is the draft coefficient, calculated as

\[ \alpha_{d^*} = \begin{cases} 
0 & \frac{\lambda}{L_{pp}} > 2.5 \\
1 - \exp \left[ -4\pi \left( \frac{d^*}{\lambda} - \frac{d^*}{2.5L_{pp}} \right) \right] & \frac{\lambda}{L_{pp}} \leq 2.5 
\end{cases} \]

where for \( S_1 \) and \( S_2 \) segments
\[ d^* = d \]
and for S₃ and S₄ segments

\[ d^* = \begin{cases} 
  \frac{d \left( 4 + \sqrt{|\cos \beta|} \right)}{5} & C_B \leq 0.75 \\
  \frac{d \left( 2 + \sqrt{|\cos \beta|} \right)}{3} & C_B > 0.75 
\end{cases} \]

\[ f(\beta) = \begin{cases} 
  -\cos \beta & \pi - E_1 \leq \beta \leq \pi \\
  0 & \beta < \pi - E_1 
\end{cases} \]
Appendix 7. List of Selected Publications by SHOPERA Consortium


Motorship Propulsion and Emissions Conference, 4-5 March 2015, Hamburg (Germany).


22. Shigunov, V., and Bertram, V., 2014, Prediction of added power in seaway by numerical simulation, 9th Int. Conf. on High-Performance Marine Vehicles HIPER 2014, Athens, Greece, 3-5 December


25. Shigunov, V., 2015, "Maneuvrability in adverse conditions," Proc. 34th Int. Conf. on Ocean, Offshore and Arctic Engineering OMAE2015, St. John’s, Newfoundland, Canada; Paper Nr. OMAE2015-41628


