A Novel Decision Support Methodology for oceangoing vessel collision avoidance

Panagiotis Mizythras, Christos Pollalis, Evangelos Boulougouris*, Gerasimos Theotokatos

Maritime Safety Research Centre, Department of Naval Architecture, Ocean & Marine Engineering, University of Strathclyde, Glasgow G4 0LZ, United Kingdom

Abstract

The wider use of electronic devices in shipping has led to the introduction of new navigation control systems and decision support tools for collision avoidance. The application of these systems improves the data utilisation and allows for the prediction of ship’s performance in various operational conditions. In this study, a decision support methodology for collision avoidance of oceangoing vessels is developed, taking into account both the ship’s manoeuvrability and propulsion system performance whilst employing a new formulation for the estimation of the collision probability indicator. An integrated model that simulates the ship’s manoeuvrability and propulsion system performance is employed to predict the required ship’s hull and propulsion plant dynamic response. The integrated model couples a 3-DOF manoeuvring model with a mean value engine model, providing a fast but accurate prediction of ship and her propulsion system characteristics during specific manoeuvring scenarios. The derived ship trajectories populate a database that is employed as input to the developed decision support for investigating various encounter situations depending on the target ship’s initial position, approach angle, trajectory and speed. The developed decision support provides the collision probability indicator as function of the ordered rudder angle and engine speed as the available control options to avoid the collision. This study provides support to the officer of the watch to make decisions on the ship and propulsion system control parameters during encountering situations, thus contributing

* Corresponding Author, e-mail address: evangelos.boulougouris@strath.ac.uk
to the safer maritime operations.

26

**Keywords**: Collision avoidance; navigation safety; trajectory and propulsion system simulation; control systems; predictive decision support system.

1 Introduction

1.1 Background

Safety and integrity of marine vessels against hazards should be maintained during the ship course planning process. Under this perspective, the International Maritime Organization (IMO) proposes the application of various navigation systems (e.g. bridge navigational watch alarm (BNWAS), automatic identification systems (AIS) and electronic chart display and information (ECDIS)) as support tools to the officers on the watch (OW), (IMO, 1974). The main aim of these systems is to provide the necessary data for the safe ship’s course planning, situation awareness and the minimisation of possible risks during ship sailing. Additionally, IMO has introduced the International Regulations for Preventing Collisions at Sea (COLREGS) to provide guidance on the actions that should be taken to avoid a collision incident (IMO, 1972). Although the COLREGS rules give priority to all the sailing ships’ obedience to prevent collision accidents, they do not provide precise actions to the OOW depending on the ship’s manoeuvrability and the propulsion system performance.

Despite the progress in navigational systems and regulations, marine accidents still occur (Eliopoulou and Papanikolaou, 2007; Schröder-Hinrichs et al., 2012; Karahalios, 2014). In fact, the latest overview of marine accidents and casualties that was published by the European Maritime Safety Agency (EMSA, 2017) showed that the contact and collision situations represent 34% of all navigational casualties during the period 2011-2016, whilst the percentage of accidents due to loss of control during navigation is even higher. Another important outcome of this survey is that the main type involved in marine accidents is cargo ships (43%), with 60% of the accidents being attributed to human erroneous actions.

The situation awareness in case of collision avoidance is essential. Based on the outcomes of the research conducted by Chauvin et al. (2008), the majority of OOW with low experience have wrong
perception of the data that should be used in order to avoid collision, which leads to underestimation, overestimation or even ignorance of the possible collision risk. Moreover, the impact of the human error in maritime systems due to the limited interpretation and perception of the collected data has been investigated in various studies (Harrald et al., 1998; Antão and Soares, 2008; Ćorović and Djurović, 2013; Yildirim et al., 2017; Abdushkour et al., 2018; Sotiralis et al., 2016), revealing the influence of human actions to the ship’s navigation. Thus, the development of a decision support system (DSS) tools fusing the input data from the installed navigation sensors is crucial for the reduction of the collision risk during ship navigation.

Calvert (1960) presented the necessary manoeuvring actions that a ship should perform to avoid collisions at sea. Based on this approach, Hollingdale (1961) established a mathematical framework that should be adopted in order to investigate the collision avoidance manoeuvres. Regarding the different approaches that may be followed for the ship’s collision avoidance, Statheros et al. (2008) conducted a detailed analysis of the existing concepts, classifying the available technologies and techniques and identifying the main areas that had been investigated. An effort to categorise the available course planning and collision avoidance models based on the course needs and the purpose of each model was presented by Wang et al. (2017a).

Considering the collision avoidance as a highly complex problem, the application of a series of optimisation algorithms were proposed for the course planning, taking into account the COLREGS convention guidelines as well as the vessels’ relative speed and distance. The applied techniques include the use of fuzzy theory (Agrawal and Dolan, 2015; Shu et al., 2014; Lee and Kim, 2004; Liang and Cai, 2016; Wen et al., 2016), artificial neural network methods (ANN) (Zhu et al., 2001; Liu et al., 2006; Zhao and Zhang, 2010) and various optimisation methods (Tsou and Hsuen, 2010; Tsou et al., 2010; Gang et al., 2016; Weifeng and Wenya, 2016; Montewka et al., 2010) for the selection of the optimal course planning taking into account the surrounding vessels navigational parameters.

Various hybrid versions of the aforementioned methods were also proposed by a number of researchers. Kolendo et al. (2011) and Tsou (2016) focused on the identification of the optimal course by using evolutionary algorithms based on the predicted areas of danger (PAD), whilst Perera et al. (2012) implemented constraints to the ANN technique to predict the ship’s navigation course and
1.2 Collision avoidance techniques

The prediction of a collision between the own ship (the ship to be navigated) and the target(s) (vessel(s) or physical obstacles to be avoided) in its route, is one of the main concerns for maritime safety, considering the increase of world’s fleet size and the upcoming introduction of the autonomous surface vehicles (ASVs) and their impact to the navigational safety (Wróbel et al., 2017). The collision risk is prescribed also in the COLREGS regulations, referring that all available means should be taken into consideration for its assessment. Thus, a collision probability indicator (CPI) was introduced in the pertinent literature to quantify the collision risk probability, whereas various methods have been proposed for its estimation.

The main method to estimate the CPI is the calculation of the distance to the closest point of approach (DCPA) and the time to the closest point of approach (TCPA) (Lee and Rhee, 2001). An alternative method is to introduce safety zones for collision risk assessment, initially proposed by Hara et al. (1990). Based on this approach, Szlapczynski (2006) proposed the establishment of a ship domain that contains ellipses for the identification of different collision risk levels, which was further developed in order to determine the safe manoeuvre course taking into consideration the manoeuvrability of the vessel (Szlapczynski and Krata (2018), Szlapczynski et al. (2018)). By coupling the CPI concept with the safety zones, Miyake et al. (2017) analysed manoeuvres from recorded AIS data and evaluated the collision probability by setting four degrees of collision risk areas using the relative ships’ distance and azimuth for their boundaries’ definition. Moreover, a vessel conflict ranking operator index was developed (Zhang et al., 2015b; Zhang et al., 2016), taking into account the ship size, relative position, speed and orientation for the collision probability estimation. A simple real-time risk assessment for maritime traffic surveillance was proposed by Zhen et al. (2017), identifying the encountered vessels and ranking them according to the estimated CPI. The connection of the collision probability with the location and time was suggested by Goerlandt and Kujala (2011) as a method to identify the expected consequences and provide the collision risk level. Huang and van Gelder (2020) proposes an improved time-varying collision risk (TCR) measure that reflects the dangerous level of the approaching ships.
and the difficulty of avoiding collisions.

Studies on the application of sensors and their adaptation in collision avoidance systems were also performed, as a way to improve the existing AIS installed on-board ships (Kang et al., 2010). Inspired by the Air-borne Collision Avoidance Systems (ACAS), Baldauf et al. (2011) proposed a situation-dependent model to assess the collision probability, introducing alarm thresholds to minimise the human factor impact. Concerning the automation control of ASVs, a rule-based repairing algorithm (Campbell et al., 2014) and the velocity obstacles (VO) method were applied (Kuwata et al., Woo and Kim, 2016; Huan et al., 2018) to develop an automatic obstacle avoidance system using the CPI for the selection of the optimal course and taking into account the IMO COLREGS regulations. Zhang et al. (2015a) presented a distributed anti-collision decision support system, for proposing the course or speed change to each vessel in multi-ship encounter situations. Taking into account the marine environment uncertainties for the prediction of vessels’ trajectories, a methodology for the estimation of the collision probability was proposed by Perera et al. (2015) investigating ship’s manoeuvrability under stochastic state conditions. Ożoga and Montewka (2018) demonstrated a concept of a decision support system based on the multi-Automatic Radar Piloting Aid (MARPA) that provides to the navigator information on safe headings estimating the degree of navigation hazard.

The preceding research efforts focused on the selection of the course that will minimise the collision risk probability without considering the manoeuvrability or the speed change of the vessel. The integration of a manoeuvring model and a collision avoidance model was initially presented in Curtis (1986), where an overtaking situation was investigated. Following this research, Zhang et al. (2012) used a simple manoeuvring model for the estimation of the ship’s yaw rate and the definition of a restricted area in an anti-collision decision-making system. This model estimated the course that the own and the target vessels should follow in order to keep the minimum safe distance between them, neglecting the change of speed during manoeuvring. Taking into account the ship’s manoeuvrability, a methodology to identify the desired ship’s yaw rate was presented in (Xue et al., 2008; Xue et al., 2011); the potential field theory was employed to estimate the planned course in real-time through rudder’s proportional-integral-derivative (PID) controller assuming that the engine’s speed remains constant during the planned course. Furthermore, a decision support system named ‘HiCASS’ was tested and
evaluated in real sea conditions, taking into account the collision risk and using a manoeuvring model for the heading angle estimation and course prediction (Kim et al., 2015). Moreover, the importance of the vessel’s manoeuvrability was acknowledged also in the studies presented by Montewka et al. (2014).

An alternative approach to the course planning using manoeuvring models was the Model Predictive Control (MPC) technique that was presented by Yan and Wang (2012), using the ship’s surge force and the yaw moment to control the actual trajectory of the vessel based on a provided trajectory as reference. Based on that model, different non-linear approaches of the MPC model were tested, taking into account the collision avoidance situation (Wang et al., 2015; Abdelaal et al., 2016; Eriksen and Breivik, 2017).

A different approach on the control actions that should be taken into account in case of collision was suggested by He et al. (2017); where a quantitative model was developed for the estimation of first time-in-point of closer-quarters (FTCS) and immediate danger (FTID) situations. Inspired by the local reactive obstacle avoidance approach that was reported in Tang et al. (2015), Moe and Pettersen (2016) and Zhang et al. (2017) proposed the usage of robust path-following models, which is similar to the MPC technique, coupling manoeuvring models with obstacle recognition algorithm and control prediction. Although the hydrodynamic damping terms were included in these innovative concepts, the influence of engine response in dynamic conditions was not considered during ship manoeuvres, assuming that the engine speed and the propeller’s performance remained unchanged.

Efforts on the investigation of propulsion system’s influence on the ship’s collision avoidance were performed by Yongqiang and Chen (2010) and Johansen et al. (2016), who developed a model that estimates the speed and rudder commands that should be provided to the engine control system during collision avoidance manoeuvres. Although these studies included the propulsion system in the collision avoidance techniques, the control parameters used for the ordered engine speed were not able to represent the performance and response of the ship’s propulsion system during manoeuvres. Additionally, the influence of the own vessel’s speed to the prediction of DCPA and TCPA was considered by Wang et al. (2017b), using a manoeuvring model to predict the selected rudder angle during collision avoidance scenario, neglecting the ordered engine speed.

Taking into consideration the safe and secure navigation of the vessels, which is one of the main objectives of the “e-Navigation” strategy that is adopted by the IMO (IMO, 2007), additional efforts
were pursued by researchers to develop a scheme that will allow the optimisation of course planning and the reduction of the traffic conjunction and collision accidents (Denker et al., 2016), and a technology that will identify the safe and dangerous navigational sectors and support the OOW in making correct decisions (TotemPlus, 2014). Furthermore, the NDSS-NAVDEC was developed, consisting of numerous modules that focus on the collection of data from shipboard and alternative resources, and the analysis assessment of the navigational situation of the own vessel (Pietrzykowski et al., 2012; Borkowski, 2014; Borkowski, 2017). This system proposes admissible (safe) course and course sectors as well as speed, which allows for taking over the target ship at a predefined safe distance. An alternative decision support on the assessment of the internal and external factors impact to the OOW recognition of the degree of navigation of danger was presented in (IMO, 2015). Through these developments, the necessity of the inclusion of decision support systems into the “e-Navigation” strategy (IMO, 2013) is noted, taking into account the collected data and predicting the path of the vessel.

1.3 Current research challenges

It can be deduced from the preceding literature review that a wide variety of methods are used in collision avoidance DSSs taking into account various parameters for the estimation of the CPI and the selection of the ship’s optimal course. However, the performed literature review reveals the following challenges:

- Few studies adopt the vessel’s manoeuvrability in the course planning, which increases the uncertainty of the proposed control options. Even in the cases that the manoeuvring model was included in the existing DSS tools, the employed models focused mainly on the ship’s yaw and surge motions.

- The main proposed action that can be implemented as a collision avoidance control technique is the rudder angle change, assuming that any change to the ordered engine speed will provide a delayed ship course change or it will not affect the vessel’s trajectory. Thus, the influence of the propulsion system to the collision avoidance manoeuvres was not investigated in depth.
The impact of the sea depth and the uncertainty of the target vessel’s position were not considered in the pertinent literature.

Mainly the DCPA and the TCPA are considered for the CPI estimation, neglecting the time that the two vessels remain within the DCPA risk zones.

The majority of the developed methods focused on the selection of the optimal course and they cannot be described as actual DSSs, which must provide alternative options to the OOW.

Recent developments in the “e-Navigation” strategy indicate the interest of the maritime industry to methods and plans that will be able to manage the collected data, predict the vessel’s path and support the OOW’s decisions.

This study aims to provide a more comprehensive methodology for the development of a collision avoidance decision support system (DSS) that considers both the ship manoeuvrability and the propulsion system characteristics, thus addressing the identified research challenges. This decision support system (DSS) output include the available solutions and control options that can be selected to avoid any possible collision during the own vessel’s navigation. Moreover, a new formulation is proposed for the calculation of the collision probability indicator (CPI), whilst the dynamic response of the ship’s propulsion system during collision avoidance manoeuvres is taken into account for the first time.

The remaining of this study is structured as follows. In Section 2, the functionality of the proposed collision avoidance decision support system is presented, describing the employed main control parameters and the proposed formulation for the CPI calculation. Section 3 includes the description of the investigated three encounter situations for a large ocean-going vessel. The derived results of the investigated situations are presented and discussed in Section 4. Finally, conclusions and proposals for future studies are outlined in Section 5.

2 Decision support system

According to Simon (1977), a decision-making process includes the following four phases: intelligence, design, choice and implementation-review. Based on the decision support system
definition (Filip et al., 2017), the main purpose of a DSS is to “relax the limits and constraints, which may be met in solving complex decision problems”, focusing mainly on the first two phases. Thus, the development of a collision avoidance decision support system requires the definition of the objectives that the system aims to solve, as well as the description of any assumptions and boundaries. The main objective of the DSS proposed in this study is the support of the OOW to make decisions in case of an encounter situation of the own vessel with a target vessel/obstacle. In this section, the definition of the studied hypothesis principle is described. Moreover, the main control parameters and the proposed formulation for the CPI calculation are discussed.

2.1 Study principle definition

During navigation, the OOW should identify and assess the potential collision risk probability from the surrounding obstacles (physical objects or target vessels) and proceed to the necessary actions and manoeuvres that will amend the ship’s planned course in order to avoid the collision. The methodology presented in this study mainly focuses on the identification of the control options that the OOW should consider to avoid the collision, using the calculated CPI as the measure to assess the control options that provide the safest manoeuvring scenario.

Existing AIS data provide the estimation of the TCPA and DCPA based on the current speed and distance between the own and the target vessels ignoring the impact of the own vessel’s speed alteration during manoeuvring or the estimated collision risk probability of alternative manoeuvres. Thus, the usage of the own vessel’s propulsion system model to assess possible alternative scenarios, which can be selected by the OOW to avoid the collision, improves the course prediction accuracy and, consequently, the estimation of the TCPA and DCPA that are used for the CPI calculation. Moreover, considering that there is an increase of the collision risk close to coastal areas, the sea depth is introduced as an input parameter in the developed DSS, thus improving the accuracy of the own ship trajectory, which in turn improves the calculated CPI confidence. Consequently, the complexity and the number of control parameters that should be taken into consideration for the proposed collision avoidance system increases.

For the development of the DSS, the following constraints and assumptions were considered:
The developed DSS investigates encounter situations with a single object (target vessel on a predefined course or obstacle) and calculates the CPI for various combinations of the control actions that may be selected from the OOW. Additionally, the results of this DSS provide valuable feedback to the navigation system in order to detect near-miss collisions.

Any influence of the target vessel’s surrounding flow field to the hydrodynamic derivatives of the own vessel’s manoeuvring model is neglected. This assumption is valid only in case of a relatively large distance between the own ship and the obstacle, assuming that the radiated waves created from one ship do not affect the hydrodynamic forces applied to the other vessel.

The CPI is calculated taking into account the actions that should be followed by the own vessel as they are described by COLREGS rules 13 to 17 (IMO, 1972), considering good visibility.

The initial location and azimuth \(d_{rel}(t=0)\) and \(\theta_{pos,rel}(t=0)\), respectively), as well as the initial speed magnitude and azimuth of the target vessel \(V_{tar} \) and \(\theta_{V,rel}(t=0)\), respectively), are provided as input in the DSS, assuming that they remain constant. The acquisition of these data is recommended, based on the existing shipboard systems according to the SOLAS.

The DSS calculates the CPI for specific manoeuvring scenarios. Each scenario is selected according to the most commonly performed manoeuvres by the OOW to avoid the collision.

The return to the original course is not investigated in this study, setting as the main purpose of the control actions that should be followed to avoid a target ship or an obstacle. It is assumed that the OOW may return to the original course without a problem, after passing a performed collision avoidance manoeuvre.

The own and the target vessels sail at open sea under calm weather conditions. Thus, the forces and moments induced by wind and currents affect the own and the target vessels in a similar way. Results from previous studies (Kao et al., 2007) demonstrated that this assumption is reasonable, with low effect to the calculated CPI.

The metacentric height for the own ship is considered sufficiently high, rendering any effects of the heeling moments due to the ship’s manoeuvres negligible.
The main objective of the developed DSS is to calculate the CPI by employing the ordered rudder angle and engine speed as control options. Due to the infinite number of possible manoeuvring combinations, specific manoeuvring scenarios are defined to provide the ship trajectories, which are stored in a database that provides input to the developed DSS. This approach (using a database instead of physical or data-driven models) is computationally time effective. Thus, it can be adopted in future developments to enable the use of the proposed decision support system for ship applications. The outcomes of the proposed DSS in conjunction with the application of the COLREGS rules 13 to 17 should be considered beneficial for the OOW to make decisions on avoiding any potential collision scenarios. Moreover, the proposed DSS constitutes a custom-made solution that takes into account the actual manoeuvrability characteristics of the own vessel.

The coordinate system that is used in this study is shown in Fig. 1. The main input parameters are the relative azimuth angle, the distance between the own and the target vessels, the initial engine speed of the own vessel, as well as the target vessels’ speed and course direction. Taking into account the database with the potential courses of the own vessel in different manoeuvring scenarios, the DSS calculates the CPI, which are presented in plots as a function of the control parameters. This provides useful support to the OOW, who should decide the required control actions during collision avoidance manoeuvres.
The development of the proposed DSS is based on two phases as presented in Fig. 2. In the first phase, the DSS is parameterised and prepared for the specific own vessel. Taking into account the own vessel characteristics and selecting the manoeuvring scenarios (input), an integrated ship manoeuvring/propulsion system model is used to predict the path of the own vessel at predefined manoeuvring scenarios. This model couples the ship propulsion system submodel and the ship manoeuvring sub-model (the latter is based on three degrees of freedom (3-DOF) equations). The output of this coupled model is further processed using geometric representation techniques (Data Processing) and subsequently the derived parameters are stored in a database, which provides input to the developed DSS. By this way, the developed DSS can predict with acceptable accuracy and low computational effort all the possible paths of the own vessel for the considered manoeuvring scenarios. The final step of the DSS is the CPI calculation at different manoeuvres (output) by using the ordered rudder angle and the engine speed as control options and taking into consideration the position and velocity of the target object, the initial conditions and the sea depth (input). A detailed description of the DSS sub-
systems and the applied methods is presented in the following sections.

Fig. 2. Flow diagram of the DSS setup and CPI evaluation process.

2.2 Own ship trajectories prediction

During navigation, the main available options to amend the planned course are by controlling the vessel’s speed and the rudder angle. Hence, the developed DSS uses the ordered engine speed and the rudder angle as the main control parameters to determine the desired ship trajectory with the aim to
reduce the CPI. In order to investigate the impact of the own vessel’s ordered engine speed alteration to the ship’s manoeuvrability, the integrated ship manoeuvring-propulsion system model is used to estimate the position and speed of the own ship for various manoeuvring scenarios. The coupling of a propulsion system and manoeuvring sub-models allows the investigation of the complex dynamics that take place in the propulsion system-hull-sea system during ship manoeuvres.

The detailed description of the integrated manoeuvring-propulsion system model is presented in a previous authors’ study (Mizythras et al. 2017), where the model was validated against ship trials data and tested for various case studies including manoeuvring in shallow water conditions. The propulsion system sub-model employs a Mean Value Engine Model (MVEM) for modelling the ship main engine coupled with the shafting system and propeller dynamics; thus it is capable of representing the dynamic response of the ship propulsion system. The ship manoeuvring submodel employs a 3–DOF to predict the ship course and speed. The integrated model was developed in the MATLAB® software.

The MVEM was initially proposed by Woodward and Latorre (1984) to predict the engine performance by using thermodynamic principles. Hence, this approach was adopted in many studies to estimate the marine Diesel engine performance (Schulten and Stapersma, 2003; Alegret et al., 2015; Theotokatos, 2010). The technical characteristics of the vessel’s main engine and propulsion system components are provided as input to the model. Additionally, the ordered speed is forwarded to a proportional-integral controller for the identification of injected fuel mass flow rate into the engine cylinders.

The mathematical model that was proposed by Sano and Yasukawa (2008) is used to solve the horizontal plane 3-DOF equations system for the own ship, taking into account the hydrodynamic coefficients, referring to added masses and yaw added moment of inertia, and the manoeuvring derivatives and assuming that the centre of gravity is adequately low. The surge and sway added masses, as well as the added moment of inertia in the yaw direction, are calculated according to the Motora’s charts (Motora, 1960). The impact of the shallow water to the hydrodynamic derivatives, the added moment of inertia and mass coefficients, as well as to the ship’s resistance is modelled using the methods described by Ankudinov et al. (1990), Li And Wu (1990) and Furukawa et al. (2016).

At each computational step, the new position of the vessel and the velocities of the own vessel are
estimated using the 3-DOF equations system. Taking into account the derived velocities, the propeller
torque coefficient is calculated and provided to the propulsion system sub-model. Thence, taking into
account the propeller torque and speed demand as well as the engine ordered speed, the propulsion
system sub-model estimates the new engine speed and propulsion system performance parameters. The
propeller characteristics, as well as the flow interaction coefficients (e.g. wake factor), are updated at
every time step and they are shared between the two sub-models, as it is illustrated in the flowchart
presented in Fig. 3.

Fig. 3. Flow diagram for the integrated model structure including the ship manoeuvring and
the propulsion system simulation sub-models.

The selection of this integrated model improves the accuracy on the estimation of the own vessel’s
speed during various manoeuvres comparing with the manoeuvring model employed in the literature.
The accurate estimation of the vessel’s speed is necessary for effective support on collision avoidance, considering that the encounter situation must be predicted with sufficient accuracy. Furthermore, the own vessel speed prediction during the complete ship manoeuvre reduces the uncertainty of the CPI prediction.

The application of complex time-domain tools in real-time applications is impractical due to the increased computational cost that is required for the evaluation of each possible scenario that will be selected by the OOW. The identification of possible manoeuvring scenarios and the development of a response surface (described by simpler mathematical equations) with the available trajectories for the own ship constitutes an effective method for reducing the computational cost of the developed DSS, thus rendering its usage feasible in ship applications.

For that purpose, two possible manoeuvring scenarios are investigated. The first one focuses on the zig-zag manoeuvre, which is the most common manoeuvre that the own vessel usually performs to overtake or avoid collision during head-on or crossing situations. In such manoeuvres, the own ship initially turns to the starboard or port side and subsequently continues sailing on a path parallel to the original course. The second one includes the change of the vessel’s heading angle to a desired value.

The investigated manoeuvres allow for avoiding collisions in all the three encounter situations that are described by COLREGS rules 13 to 17 as depicted in Fig. 4. The area A of this figure corresponds to the head-on situations, in which the own vessel must turn to the starboard side. The areas B1 and B2 correspond to the own vessel crossing situations. In case where the target vessel is approaching from the B2 area, the own vessel must turn to her starboard side; otherwise she should stand-on. Finally, the areas C1 and C2 represent overtaking situations of the own vessel. In such cases, the target vessel should take the appropriate actions to keep out of the way of the own vessel, which is being overtaken.
Fig. 4. Ship encounter situations according to the COLREG requirements.

The main control parameters for the development of the ship trajectories response surface in both manoeuvring scenarios are the engine speed ordered at the beginning of the manoeuvre, the initial engine rotational speed, the sea depth over draught ratio and the rudder’s angle. For the second manoeuvring scenario, the ordered heading angle is used as an additional control parameter. For both scenarios, it is assumed that the ship main engine can operate at overload running conditions, as the engine manufacturer allows such operation for a limited time period (typically 1 hour every 24 hours) (MAN B&W, 2000).

Considering that the rudder angle is zero after the completion of these two manoeuvring scenarios, it is necessary to investigate the restoration of the balance in the propulsion system. Therefore, both acceleration and deceleration manoeuvres are studied, using only the ordered engine speed as the control option. The impact of the propulsion system response to the vessel’s speed during acceleration manoeuvres was presented and discussed in (Mizythras et al., 2018). The combination of the trajectories for the preceding scenarios provides an accurate method for the estimation of the ship’s actual position and speed during manoeuvring.
2.3 Rudder controller

The first reference to the steering controller was made by Minorsky (1930), proposing the application of a PID controller for the dynamic control of the rudder angle to achieve the desired ship heading angle. A method to control the rudder angle is combined with the ship manoeuvring submodel to predict the ship manoeuvrability characteristics under the specific conditions of the manoeuvres considered in this study. This method focuses on the computation of the yaw angle that the rudder should turn to perform the selected manoeuvre as delineated in the following paragraphs.

The zig-zag manoeuvre is performed in three stages (Fig. 5a). The first stage corresponds to the rudder turning to the ordered angle till the vessel’s yaw angle becomes equal or greater than the ordered rudder angle. The second stage includes the rudder turning to the opposite direction in order to restore the vessel to her initial heading angle. The final stage includes a procedure for the vessel’s course correction in order to minimise the absolute value of the yaw rate and angle, and restore the initial vessel’s heading angle. This procedure includes the rudder turning from a positive to a negative value of the ordered angle, depending on the change of the yaw rate. To determine the yaw angle at which the third stage begins, the Newton-Raphson’s iterative method (Venkateshan and Swaminathan, 2004) is implemented, setting as an objective to achieve zero vessel’s heading angle at the end of the manoeuvre.

The change of heading angle manoeuvre is performed in two stages (Fig. 5b). The first stage includes the rudder turning to the ordered rudder angle, whilst the second stage includes the correction of the vessel’s yaw angle and rate, considering the ordered vessel’s heading angle. An iterative process is followed for the computation of the yaw angle at which the second stage commences.
In this study, the Aframax crude oil tanker studied in Mizythras et al. (2017) is used as the own ship for the estimation of the required DSS input parameters. The validation of the integrated model for this vessel ensures that sufficient accuracy is achieved on the estimation of vessel’s trajectory and speed profile during turning manoeuvres. Simulation runs were performed for the control parameters values that are presented in Table 1, generating 144 and 768 different combinations of zig-zag and heading angle change manoeuvres, respectively. The average computational time for each manoeuvring scenario was 1200 s, obtained on 3.6GHz i7-4790 CPU with 8 GB RAM. The acceleration/deceleration manoeuvres in zero heading angle are investigated considering the following control parameters: (a) the initial engine speed; (b) the ordered engine speed, and; (c) the vessel’s initial speed. The last control parameter is considered in order to simulate the propulsion system response in cases where the ship operates with varying resistance (in various resistance curves), which is the case at the end of a turning or zig-zag manoeuvre.

<table>
<thead>
<tr>
<th>Control parameter</th>
<th>Zig-zag manoeuvre</th>
<th>Heading angle change manoeuvre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea depth/Draught (-)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Very Shallow (sea depth<1.2D_
own) |
| Shallow (sea depth<1.4D_
own) |
| Deep (sea depth>1.4D_
own) |
<table>
<thead>
<tr>
<th>Initial engine speed (°)</th>
<th>40% MCR speed</th>
<th>60% MCR speed</th>
<th>80% MCR speed</th>
<th>100% MCR speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordered engine speed (°)</td>
<td>40% MCR speed</td>
<td>60% MCR speed</td>
<td>80% MCR speed</td>
<td>100% MCR speed</td>
</tr>
<tr>
<td>Ordered rudder angle (degrees)</td>
<td>±10</td>
<td>±20</td>
<td>±35</td>
<td></td>
</tr>
<tr>
<td>Ordered heading angle (degrees)</td>
<td>–</td>
<td>±5</td>
<td>±30</td>
<td>±60</td>
</tr>
</tbody>
</table>

The output of each simulation run includes the own vessel’s trajectory, the required yaw angle at which the adjustment of the own vessel’s course should begin, the initial and final values of the vessel’s speed as well as the manoeuvre duration. The derived trajectory points are non-dimensionalised by using the own vessel’s length. It must be noted that the target vessel’s trajectory is also estimated taking into account her initial speed and direction. Considering the vast number of data that are required for the generation of the own ship trajectories response surface (which is stored in the DSS database), a B–spline approximation is selected to describe the vessel’s trajectory. The number of control points, required for the estimation of the own vessel’s trajectory, is selected after a parametric analysis, the results of which are presented in Fig. 6 for a specific heading angle change manoeuvre. It was deduced that seven control points provide good compromise between the solution accuracy and the computational cost. The selection of additional control points increases the computational cost of the present method without any significant accuracy improvements. Hence, the database stores the non-dimensional coordinates of the seven points of the B-spline function for every combination of the considered control parameters and for each manoeuvring scenario. This approach improves also the computational cost of the DSS, whilst reducing the amount of the required input data.
Fig. 6. Investigation on the optimal number of required control points for the own ship trajectory approximation.

2.4 Collision probability indicator calculation methodology

A number of techniques for the collision probability estimation taking into account the minimum distance between the courses of the two ships and the required time for the two ships to approach in this distance are reported in recent studies (Liang and Cai, 2016; Wen et al., 2016; Gang et al., 2016; Zhen et al., 2017; He et al., 2017). The main approach for the collision probability evaluation is the definition of a domain around the own vessel, the size of which depends on the minimum distance that should be kept between the own and the target vessels (Kao et al., 2007). The size and the shape of this domain vary in the pertinent literature, depending on the vessel’s type, speed, size, OOW’s discretion and data uncertainty on the target ship’s position (Zhang, J. et al., 2012; Zhang, J. et al., 2015). However, the main parameter that is ignored in the collision probability estimation in these studies is the duration that the own and the target vessels sail within each other’s domain during a collision avoidance manoeuvre. If both vessels sail within the risk domain, the navigational characteristics (heading angle of each vessel and their relative speeds) may jeopardize the navigational safety and result in a collision.
To address the preceding challenges, this study proposes a more accurate formulation for the collision probability indicator (CPI) calculation based on the following considerations: (a) the definition of safety domains around both the own and the target vessels, which are divided in specific risk zones; (b) the introduction of an uncertainty factor for their definition, and (c) the consideration of the dynamic location and speed of the own vessel. Moreover, the proposed CPI forms a single indicator, which, for each manoeuvring scenario, takes into account the minimum distance between the vessels, the required time for both vessels (own and target) to approach to the corresponding distance, the vessels heading angles, and the time duration that one vessel sails within the domain of the other. Hence, the CPI is calculated by using the following equation, which was proposed in Ezzati et al. (2004):

\[ CPI = 1 - \prod_{k} (1-w_kP_k) \]  

where \( w_k \) and \( P_k \) denote the weighting factors and the probabilities for each considered category \( k \). The calculation of the probabilities \( P_{DCPA}, P_{TCPA}, \) and \( P_{TD} \) for DCPA, TCPA and time duration (TD) of ships’ domain intersection are provided below in this section.

The definition of the employed weighting factors improves the parameterization of the DSS, providing the option to the OOW or the DSS developer to classify the quality of each probability and thus control the impact of each individual probability to the CPI calculation. Analysis of the weighting factors impact to the risk estimation is provided in Section 4.2. The developed technique for the CPI calculation is developed on the basis that the vessels are in a near miss situation and the own vessel has to take immediate actions to avoid a collision.

For the calculation of the preceding probabilities and CPI, an elliptical domain is defined around the vessel boundaries as presented in Fig. 7, which was initially proposed by Szlapczynski (2006). This domain is considered for both vessels (own and the target) and takes into account the uncertainty of the target vessel’s shape. The definition of the elliptical shape is selected as the simplest and most suitable geometric shape that can fit to the ship boundaries. Five different risk zones are defined, whereas the collision risk probability is considered zero outside of the defined ship safety domain. The size of the highest risk zone (risk zone 5) is selected as an ellipse that is able to circumscribe the vessel’s water plane area. As the vessel’s water plane has different shape than an ellipse, the major and minor axes of the elliptic domain corresponding to the risk zone 5 are equal to 55% and 62.5% of the vessel’s length.
and breadth respectively. Hence, the highest risk zone includes the entire vessel’s water plane. The size of the lowest risk zone (outer boundary of the ship safety domain) is calculated by using the following equation:

$$s_{ship} = s_{min} + (s_{max} - s_{min}) \frac{V_{ship}}{V_{max}}$$

(2)

where $V_{ship}$ denotes the ship’s speed; $s_{ship}$ denotes the lower risk zone size; $s_{min}$ is the minimum limit of the $s_{ship}$ that is defined to be three times the ship’s size; $s_{max}$ is the maximum limit of the $s_{ship}$ that is calculated as a function of the ship’s design speed ($V_{max}$) and the time that is required to maintain the clearance between the two vessels.

The clearance is usually determined by experience (Kim et al., 2015). In this study, the minimum safe distance is defined as the distance that the vessel could cover within 2 minutes, in safe navigational conditions. In case where the target vessel’s speed is unknown, the maximum speed corresponding to the target ship type can be selected for the identification of the target’s ship safety domain.

The distribution of the risk zones within the ship safety domain depends on the uncertainty of the locations of both vessels and the ship manoeuvring model accuracy. In this study, the risk zones size is determined by using a positive parameter that defines the uncertainty of the zone distribution as illustrated in Fig. 8. In cases of low uncertainty, the high risk zones are shifted closer to the ship boundaries. When the uncertainty is high, the high risk zone may cover the entire ship safety domain.

The derivation of the uncertainty level impact on the estimation of the risk zone’s size is provided in Appendix A.

Fig. 7. Risk zones in the domain around vessel’s boundaries.
Consi... 

Considering the risk zones for both the own and the target vessels, the next step is the development of a mesh for the navigation area that will be used for the investigated ships manoeuvring scenarios simulation, and thus, the CPI calculation. Taking into account the time that is required for the own vessel to perform each investigated manoeuvre, the distance that the own and the target vessels sail during this time and the defined risk zones size, the required navigation area size is estimated. In order to check the intersection of the defined risk zones, a mesh is generated on this navigation area. If there is no intersection of the own and the target vessels’ risk zones, the DCPA probability is set to zero. In other cases, the DCPA probability for each mesh panel is calculated as the product of the attributed DCPA probability for each vessel. The DCPA probability at each time step is estimated as the maximum value of the intersected risk zones products, according to the following equation:

$$P_{DCPA,abs}(t_i) = \max\left\{P_{DCPA,own}(t_i), P_{DCPA,target}(t_i)\right\}$$  \hspace{1cm} (3)

As the collision risk depends on the directions of the own and the target vessels, an additional variable accounting for the relative location of the own and the target vessels is considered in the DCPA probability calculation. Therefore, the DCPA probability calculated by employing Equation (3) is
corrected considering the relative angle between the own and the target vessels’ velocity vectors. If the
velocity vectors are not parallel, the $P_{DCPA}$ increases up to the next probability level according to the
following equation:

$$P_{DCPA,azi}(t_i) = 1 + c_{RZ} \sin \left( \theta_{coll,rel}(t_i) \right)$$

(4)

where $c_{RZ}$ is the ratio of the current over the next probability level and $\theta_{coll,rel}(t_i)$ is the relative
collision angle as presented in Fig. 1, which is calculated by using the following equation:

$$\theta_{coll,rel}(t_i) = \left| 180^\circ - \varphi_{own}(t_i) - \theta_{V,rel}(t=0) \right|$$

(5)

where $\varphi_{own}$ is the yaw angle of the own vessel and $\theta_{V,rel}$ the relative angle of vessels’ speed vectors
at the beginning of the manoeuvre.

Thus, the overall DCPA probability at each time step $t_i$ is calculated by using the following equation:

$$P_{DCPA,i}(t_i) = P_{DCPA,abs}(t_i) P_{DCPA,azi}(t_i)$$

(6)

The final DCPA probability is calculated according to the following equation as the ratio of the
maximum value of the $P_{DCPA,i}$ derived by Equation (6) and the product of the maximum risk zones
numbers (equal to 25):

$$P_{DCPA} = \begin{cases} \max \left( \frac{P_{DCPA}(t_i)}{25} \right), & P_{DCPA}(t_i) \neq 0 \\ 0, & P_{DCPA}(t_i) = 0 \end{cases}$$

(7)

The TCPA probability ($P_{TCPA}$) is calculated as the ratio of the time that the first intersection of risk
zones occurs and the manoeuvre duration, according to the following equation:

$$P_{TCPA} = \begin{cases} \frac{t_i \left( \max \left( P_{DCPA,i} \right) \right)}{t_{sim}}, & P_{DCPA,i}(t_i) \neq 0 \\ 0, & P_{DCPA,i}(t_i) = 0 \end{cases}$$

(8)

Lastly, the probability of the time duration (TD) of the ships’ domains intersection is also calculated.

If the speeds of the own and the target vessels are similar, the collision risk probability increases,
considering the longer duration that both vessels are exposed to such a risky situation. The TD
probability is calculated as function of the time period that the own and the target vessels’ domains are
intersected, according to the following equation:

$$P_{TD} = \begin{cases} \frac{t_i \left( \max \left( \min \left( P_{DCPA,i} \right) \right) \right) - t_i \left( \min \left( \max \left( P_{DCPA,i} \right) \right) \right)}{t_{sim}}, & P_{DCPA,i}(t_i) \neq 0 \\ 0, & P_{DCPA,i}(t_i) = 0 \end{cases}$$

(9)
3 Case studies

The developed DSS investigates the following three main vessel encounter cases: head-on, overtaking and crossing situations. It is assumed that the investigated encounter situations take place in deep sea water. During crossing situations, it is assumed that the target vessel is approaching the own vessel from her starboard side. The relative size of the target vessel and the initial conditions for the simulation for each situation are presented in Table 2. The results of the developed DSS for the investigated cases are provided in Figs. 9–12, presenting the calculated CPI for each combination of the control options.

Table 2. Initial conditions of investigated case studies

<table>
<thead>
<tr>
<th>Investigated encounter situation</th>
<th>(A) Head-on</th>
<th>(B) Overtaking</th>
<th>(C) Crossing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea depth</td>
<td>Deep water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target vessel length, L_{tar} [-]</td>
<td>92% L_{own}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target vessel breath, B_{tar} [-]</td>
<td>91% B_{own}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial relative distance, d_{rel}(t=0) [-]</td>
<td>8.5 L_{own}</td>
<td>5 L_{own}</td>
<td>6.5 L_{own}</td>
</tr>
<tr>
<td>Initial relative azimuth, θ_{pos,rel}(t=0) [degrees]</td>
<td>0</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Own vessel Initial speed V_{own}(t=0) [knots]</td>
<td>9</td>
<td>13.30</td>
<td>13.30</td>
</tr>
<tr>
<td>Target vessel Speed V_{tar}(t=0) [knots]</td>
<td>11.67</td>
<td>5.83</td>
<td>8.75</td>
</tr>
<tr>
<td>Target vessel Speed azimuth θ_{v,rel}(t=0) [degrees]</td>
<td>180</td>
<td>0</td>
<td>-70</td>
</tr>
</tbody>
</table>

The main purpose of the developed DSS is to provide an estimation of the collision risk in terms of the CPI depending on the available control options. The plots of Fig. 9 employ the ordered rudder angle and the ordered engine speed on their horizontal and vertical axes, respectively, whereas the CPI contours are presented (the maroon colour indicates areas of the highest CPI values, whilst the dark blue colour indicates areas with the lowest CPI values). The highest CPI values correspond to the cases where the control actions result in the ship turn to the starboard or the portside directions that are not allowed according to the COLREGS rules 13 to 17.

The plots presented in Figs. 10–12 employ the ordered rudder angle in their radial coordinate, the ordered heading angle in their azimuth coordinate and the CPI contours (in the same colour scale as Fig. 9). Moreover, these plots correspond to various values of the ordered engine speed (as percentage
of the engine speed at the MCR point). The results of these figures provide support to the OOW on the impact (in terms of CPI) that various control actions could cause for the three investigated scenarios. Recommended control actions (or combinations of actions) can be identified considering the areas of lowest CPI resulting in safe manoeuvring avoiding collisions.

Fig. 9. Calculated CPI as a function of the ordered rudder angle and engine speed for the zig-zag manoeuvre scenario in the investigated (a) head-on, (b) overtaking and (c) crossing situations.
Fig. 10. Calculated CPI as a function of the ordered rudder angle, heading angle and engine speed for the heading angle change manoeuvre scenario in the investigated head-on situation.

In cases where the target vessel sails from the starboard side of the own vessel (according to parameters provided in Table 2), the derived results of Fig. 9(a) indicate the engine speed and the rudder angle (considering the blue area) that should be ordered to perform a collision avoidance zig-zag manoeuvre. For zig-zag manoeuvre in the investigated crossing situation (Fig. 9(c)), the own vessel should turn to the starboard direction and pass aft of the target vessel, avoiding the collision. The selection of a lower ordered engine speed or the increase of the rudder angle to the starboard direction reduces the CPI. However, the engine deceleration is not considered as the first option by the OOW in such manoeuvring scenarios, whereas the rudder turning to the starboard option may be considered as
the optimal solution in this manœuvring scenario.

Fig. 11. Calculated CPI as a function of the ordered rudder angle, heading angle and engine speed for the heading angle change manœuvre scenario in the investigated overtaking situation.

In the investigated head-on and overtaking situations (Fig. 9(a–b)), the selection of a rudder angle over the value of 10 degrees in zig-zag manœuvre considerable reduces the CPI. For reduced ordered engine speed values, the CPI increases in the head-on situation and decreases in the overtaking situation. Especially in head-on situations, the deceleration of the own vessel increases the probability of the intersection with the target vessel’s safety domain due to the high value of TCPA probability and the
small distance between the own and the target vessels. The CPI achieves its lowest values only in the cases where the highest ordered engine speed and rudder angle are selected as control options. On the contrary, the CPI in overtaking situations increases when the ordered engine speed increases because of the greater TCPA probability when the own vessel approaches faster the target vessel.

Fig. 12. Calculated CPI as a function of the ordered rudder angle, heading angle and engine speed for the heading angle change manoeuvre scenario in the investigated crossing situation.

The results for the heading angle change manoeuvre in the considered head-on situation presented in Fig. 10 demonstrate the effect of the small distance between the own and the target vessels resulting in areas with high or considerable values of CPI. In addition, low ordered engine speed results in higher
CPI values. For the investigated heading angle change manoeuvre in the overtaking situation, it is deduced from the results presented in Fig. 11 that the calculated CPI is extremely low for most the control options with the ship turning in the starboard direction. Considerable to high CPI values are obtained for the case where the vessel does not turn continuing in her original course. The highest CPI values are obtained for cases where the control options are not allowed according to the COLREGS rules 13 to 17. Lastly, the investigation of the heading angle change manoeuvre in the crossing situation demonstrates that the CPI exhibits its highest values if the ship turns to the portside heading angles as this is not allowed by the COLREGS.

4 Discussion

The main outcome of the developed DSS is the CPI calculation as a function of the available control options, in specific the ordered rudder angle, heading angle and engine speed. Taking into account the propulsion system of the own vessel and its influence to the vessel speed and manoeuvring during navigation, the DSS provides valuable support to the OOW in order to assess each situation and select the appropriate combination of control options resulting in the optimal manoeuvring scenario for minimising the potential risk of collision. In order to assess the DSS performance, the influence of the own vessel’s control options and sea conditions to the final solution are described in this section.

4.1 DSS accuracy and computational time

The parameters that have been selected for the definition of the sea domain mesh affect the computational speed of the DSS tool. Setting as an objective the balance between efficiency and accuracy, a parametric investigation of the user-defined parameters is performed in the head-on situation that is described in Table 2. The main user-defined parameters include the mesh size and the size of the mesh elements, which are defined as a function of the own vessel’s length, as well as the simulation time. The simulation time is defined as the time that is required from the own vessel to complete each manoeuvring scenario \((t_{\text{man,sim}})\). The impact of the user-defined parameters to the computational time of the developed DSS is presented in Fig. 13, which provides plots of the DSS computational time of the considered head-on situation at various simulation times and mesh sizes, using three different grid element sizes. The performed analysis shows that the increase of the selected
simulation time increases the computational cost. For the case where the element size decreases from 5% to 1% of the own vessel length, the computational cost increases considerably. The increase of the safety domain size around the vessel has less influence on the computational cost because of the mesh technique that is selected for the DCPA probability calculation.

Fig. 13. Impact of domain mesh size and simulation time to the DSS computational cost.
An important parameter for the estimation of the intersection of the own and the target vessels’ risk zones is the size of mesh elements. The performed analysis demonstrates the influence of the considered element sizes on the computational cost of the performed simulation. The results in Table 3 present the average values and standard deviations of the calculated CPI for various element sizes, keeping constant the specific ordered engine speed, the domain size and the simulation time. Based on these results, the selection of an element size less than 2% of the own vessel’s length only slightly affect the accuracy of the final solution and the CPI distribution.

Table 3. Effect of mesh element size to the CPI calculation.

<table>
<thead>
<tr>
<th>Domain mesh element size</th>
<th>CPI average value</th>
<th>CPI standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 L&lt;sub&gt;own&lt;/sub&gt;</td>
<td>56.791</td>
<td>19.764</td>
</tr>
<tr>
<td>0.02 L&lt;sub&gt;own&lt;/sub&gt;</td>
<td>56.727</td>
<td>19.771</td>
</tr>
<tr>
<td>0.05 L&lt;sub&gt;own&lt;/sub&gt;</td>
<td>56.361</td>
<td>19.407</td>
</tr>
<tr>
<td>0.1 L&lt;sub&gt;own&lt;/sub&gt;</td>
<td>55.704</td>
<td>18.909</td>
</tr>
</tbody>
</table>

4.2 Influence of control options to the collision avoidance

The DSS provides a full description of the steps that the OOW should perform during a manoeuvre as well as the prediction of the CPI. In order to assess the prediction of the correct non-collision manoeuvre, Fig. 14 shows the possible manoeuvres that the own vessel may perform to avoid the studied head-on situation, the characteristics of which were provided in Table 2. When the combination of control options that results in an estimation of 100% CPI is selected, the collision is unavoidable (Fig. 14a). Although the collision is avoided with the selection of alternative control options (Fig. 14b and 14c), the calculated CPI values were greater than zero due to the initial small distance between the own and the target vessels, leading to an intersection of the safety domains for both vessels.
Fig. 14. Own and target vessels trajectories in the considered head-on encounter situation; (a) $\beta=0^\circ$ and $n_{ord}=90\%$MCR; (b) $\beta=25^\circ$ and $n_{ord}=90\%$MCR, and; (c) $\beta=10^\circ$ and $n_{ord}=50\%$MCR.

The definition of the CPI by Eq. (1) provides a quantitative prediction of the collision probability. The connection of the CPI values with the determined risk probability levels is presented in Table 4. If the selected manoeuvre leads to low CPI values, the navigation of both own and target vessel is considered safe. The risk probability level increases in case where the initial distance of the vessels is small or the selected manoeuvres lead to the intersection of higher level risk zones. In that case, the DSS indicates that immediate actions should be taken from the OOW, the target vessel course should be continuously monitored and the performed manoeuvre should be executed with great care. Moreover, the minimum value of the calculated CPI can be used as an indicator for the timing to implement the identified control actions. The increase of the minimum CPI value reduces the response time to implement the control action for avoiding the collision, as well as the control options that are available to the OOW to avoid the collision.

<table>
<thead>
<tr>
<th>Probability</th>
<th>CPI</th>
<th>Acceptance criterion options</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Identification of risk probability levels.
<table>
<thead>
<tr>
<th>level</th>
<th>percentage range</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0%-20%</td>
<td>The selected control options allow the safe navigation of the own vessel.</td>
</tr>
<tr>
<td>Medium</td>
<td>20%-50%</td>
<td>The target vessel’s course should be continuously monitored and following measures may be considered.</td>
</tr>
<tr>
<td>High</td>
<td>50%-85%</td>
<td>The collision manoeuvre should be performed urgently and with extreme caution. The corresponding control options may be selected only in case that there is no better alternative solution.</td>
</tr>
<tr>
<td>Very High</td>
<td>85%-100%</td>
<td>The selected control options lead to a collision.</td>
</tr>
</tbody>
</table>

The selection of the weighting factors is important for the CPI calculation according to Eq. (1). By increasing the weighting factors values for the TCPA and TD probabilities, the CPI values in the intermediates level (between 10% and 90%), however without affecting the CPI boundaries (minimum and maximum values), as demonstrated by the results presented in Fig. 15. Particularly, the increase of the TCPA weighting factor shifts the CPI distribution to higher values, whilst the contribution of the TD weighting factor depends mainly on the relative speed and heading angle of both vessels. The selection of the weighting factors should be performed with great care in order to avoid an overestimation of the CPI, especially in the cases where the initial distance between the two vessels is small and their relative speed is close to zero.

![Fig. 15. Effect of the weighting factors on the CPI calculation for the zig-zag manoeuvre scenario to avoid the crossing situation described in Table 2.](image)

(a) $w_{DCPA}=1$, $w_{TCPA}=0.2$, $w_{TD}=0.3$  
(b) $w_{DCPA}=1$, $w_{TCPA}=0.8$, $w_{TD}=0.3$  
(c) $w_{DCPA}=1$, $w_{TCPA}=0.2$, $w_{TD}=0.8$

The effect of the uncertainty factor $u$ to the CPI calculation is illustrated in Fig. 16. The increase of uncertainty increases the size of the high risk zones. Although the calculated CPI boundaries remain unchanged, the uncertainty factor affects the distribution of the CPI values, increasing the areas of the higher CPI values. The impact of the uncertainty factor on CPI is more pronounced for higher values.
of the DCPA weighting factor.

Fig. 16. Effect of the uncertainty factor on the CPI calculation for the zig-zag manoeuvre scenario to avoid the crossing situation described in Table 2.

The weighting factors employed in this study are presented in Table 5. The contribution of the DCPA probability to the CPI value is considered more important than the contribution of the TCPA and TD probabilities due to the greater influence of vessel’s distance on the collision risk. By analysing the results of Fig. 15, the TCPA and TD probabilities contributions were considered 20% and 30% of the DCPA probability contribution, respectively.

Table 5. Weighting factors for the CPI calculation.

<table>
<thead>
<tr>
<th>Risk probability category</th>
<th>Weighting factor $w_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCPA</td>
<td>1</td>
</tr>
<tr>
<td>TCPA</td>
<td>0.2</td>
</tr>
<tr>
<td>TD</td>
<td>0.3</td>
</tr>
</tbody>
</table>

In this study, the uncertainty factor is set less than 0.5, considering the accuracy of the collected data and the developed models. The uncertainty and weighting factors were selected after the test of DSS response in various collision scenarios and the evaluation of the CPI distribution considering various combinations of control options.

4.3 Impact of sea depth in CPI estimation

The investigated case studies were performed in deep water conditions, neglecting the influence of the shallow water effects to the hydrodynamic forces during vessel’s manoeuvring. The developed DSS provides the ability to investigate the impact of the sea water depth during navigation and especially
during encounter situations with another vessel. Considering that the sea depth affects the ship’s resistance (Furukawa et al., 2016), the developed tool uses as input the initial engine speed to predict the speed of the vessel, taking into account the effect of the shallow water on the wave resistance and added mass (Mizythras et al., 2017).

The influence of the sea depth for the crossing situation defined in Table 2 was investigated and the calculated CPIs for the cases of sailing in very shallow water and deep water are presented in Fig. 17. When the vessel sails in shallow waters, the turning circle diameter is expected to increase for such ship types (Hooft et al., 1973). Consequently, the reduction of the sea depth results in increasing the areas with higher CPI values. However, it should be considered that during the navigation in shallow waters, the ship main engine may operate closer to its torque limit, which may lead to increased thermal loading and other adverse effects.

![CPI calculation for a zig-zag manoeuvre in a crossing situation.](image)

**4.4 DSS performance against fixed located obstacle**

The performed case studies in the preceding sections focused on the interaction of the own vessel with a single target vessel. The developed DSS applicability can be expanded to the investigation of collision scenarios with a fixed obstacle. Given the main dimensions of the obstacle, and setting the target’s speed to zero, the DSS predicts the CPI for the selected manoeuvring scenarios. The results of a case study that investigates the encounter of the own vessel with a fixed located obstacle are presented.
in Figs. 18 and 19. The obstacle has a maximum length and breadth of 1.2 km and 0.8 km respectively. The obstacle is located in a distance equal to 10 times of the own vessel length ahead and 30 degrees to the starboard side of the own vessel. The safety domain of the selected obstacle is defined half of a nautical mile, assuming that this is the minimum safe distance that should be ensured from the own vessel. The navigation is considered to take place in shallow water conditions ($T_{\text{own}}/d_{\text{SW}}=1.35$) and the initial speed of the own vessel is 13.3 knots. The calculated CPI is performed for both manoeuvring scenarios (zig-zag and heading angle change) not considering the COLREGS rules 13 to 17.

Fig. 18. Calculated CPI for the zig-zag manoeuvre to avoid a fixed obstacle located at a distance of $10L_{\text{own}}$ ahead of the own vessel and at an azimuth of $30^\circ$ to the starboard side.
Fig. 19. Calculated CPI for the heading angle change manoeuvre to avoid a fixed obstacle located at a distance of 10L\textsubscript{own} ahead of the own vessel and at an azimuth of 30° to the starboard side.

The derived results demonstrate that the CPI reduces when the vessel turns to the portside direction in both manoeuvring scenarios. In case that the vessel continues her course without changing her heading angle, the CPI increases to a level that can be proven dangerous for her safe navigation. The high CPI values are observed for the heading angle change manoeuvring scenario (Fig. 19) in the case where the vessel’s turning to the starboard side. Although the change of the heading angle to the port side is the safest option/alternative, the results provides the additional insights to the OOW for reducing the collision probability up to 60% by selecting the maximum heading angle to the starboard side,
combined with the selection of the maximum rudder angle and ordered engine speed.

5 Conclusions

This study presented the development of decision support methodology for collision avoidance of ocean-going vessels. An integrated model that represents with sufficient accuracy the ship manoeuvrability and propulsion system response is employed to generate the input parameters required by the DSS. The integrated model couples a 3-DOF manoeuvring model with an MVEM approach for the estimation of the engine's response, providing an accurate estimation of the own vessel’s trajectories in different manoeuvring scenarios. The derived ship trajectories were approximated by employing B-spines functions considering seven control points. The non-dimensional coordinates for these seven points for each manoeuvre and combination of the control options populated a database that is used to investigate various scenarios depending on the sea conditions and the relative location of the target vessel/obstacle. This derived CPI were used to classify the control options, which are available to the OOW to avoid the collision with any possible obstacle.

The main contribution of the present study is the DSS development that is able to assess the impact of the alternative control options to avoid a possible collision, this providing useful insight to the OOW for making decisions. The tool predicts the collision probability in terms of the CPI for each manoeuvring scenario that may be selected from the OOW, as well as the timing that the manoeuvring control actions should be performed. Moreover, the followed approach takes into account the propulsion system performance, increasing the accuracy on the prediction of the vessel’s speed and the number of the available control options. The derived results demonstrated the influence of the ordered engine speed to the collision avoidance manoeuvres, a control parameter that is not considered in the majority of research studies. Finally, an alternative definition of the CPI is proposed taking into account the direction of the vessels and the time that the target vessel remains within the risk zone of the own vessel.

This methodology can be applied both in the design phase and has potential for a real-time implementation on-board ships as a decision support tool, either assisting in case of collision avoidance by calculating the CPI or providing on-time with the available options to the ship navigator. The OOW will be benefited for timely and effective decision making by using a system with the proposed decision
support, which estimates the collision probability for all the possible combinations of manoeuvring scenarios and control options.

The selection of specific manoeuvring scenarios and the prediction of the collision probability in each case of the proposed procedures introduces a new era of semi-automation in ship’s navigation. The DSS advises the OOW for the actual steps that should be followed to avoid the collision, as well as the relevant probability accompanying each decision. Thus, the tool results act complementary to the existing equipment and regulations, keeping the human element in charge of the actions that should be performed to avoid the collision.

The existing approach has promising potential for further development and improvements on its final implementation. Particularly, the CPI calculation was based on a database that was generated with predefined manoeuvring scenarios. Simulation of additional predefined manoeuvring scenarios will improve the efficiency of the DSS and the accuracy of the CPI calculation. Moreover, additional parameters may be used for the estimation of the CPI, such as the connection of the domain size with the weather conditions and human factors. Considering that the collision with a single target vessel is more possible to occur in the open sea, the existing DSS can be further improved in order to predict the CPI in case that multiple target vessels are involved.

**Acknowledgements**

This work was partially supported by the “HOLISHIP – Holistic Optimisation of Ship Design and Operation for Life Cycle” project that was funded from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 689074. The authors greatly acknowledge the funding from DNV GL AS and RCCL for the MSRC establishment and operation. The opinions expressed herein are those of the authors and should not be construed to reflect the views of DNV GL AS and RCCL.
Appendix A

The definition of the risk zone uncertainty problem includes the normal distribution of the risk zone size between two points, using the uncertainty factor as an independent variable. The first point (A) represents the lowest risk zone with the maximum size and the second point (B) the highest risk zone with the minimum size. The distribution should be shifted close to the highest probability level (point C) when the uncertainty of the location is high (e.g. 100%) and to the lowest probability level when the certainty is high. For the calibration of the uncertainty factor influence, the assumption that a linear distribution of risk zone size is used when the uncertainty is 50%. Moreover, the edges of the risk zones distributions should remain fixed when the uncertainty factor changes. In favour of simplicity and considering the verticality of the asymptotes AC and BC, a new coordinate system is selected using the line AB that connects the curve’s edges as x’ axis (Fig. A.1).

![Fig. A.1. Risk zone size distribution and coordinate system rotation.](image)

The length of the line that connects the two edges and the angle used for the coordinate system rotation is calculated from the following formulae:

\[
d_{AB} = \sqrt{(P_{\text{max}} - P_{\text{min}})^2 + (s_{\text{max}} - s_{\text{min}})^2}
\]

Eq. (A.1)
\[
\theta = \text{atan} \left( \frac{s_{\text{max}} - s_{\text{min}}}{P_{\text{max}} - P_{\text{min}}} \right) \quad \text{Eq. (A.2)}
\]

The domain of the function that will describe the size distribution in the new coordinate system $X'Y'$ is $[0, d_{AB}]$ and its connection with the probability level index in the $XOY$ system is estimated by using the proportionality theorem:

\[
X' = \frac{X - P_{\text{min}}}{P_{\text{max}} - P_{\text{min}}}d_{AB} \quad \text{Eq. (A.3)}
\]

The definition of the asymptotes curves in the $X'Y'$ system is provided by the following equations:

AC: $Y'X_C' - X'Y_C' = 0 \quad \text{Eq. (A.4)}$

BC: $Y'(X_C' - d_{AB}) - X'Y_C' + d_{AB}Y_C' = 0 \quad \text{Eq. (A.5)}$

where the coordinates of the point $C$ in the $X'Y'$ system can be found from the formulae:

\[
X_C' = (P_{\text{max}} - P_{\text{min}})\cos\theta, \quad Y_C' = (P_{\text{max}} - P_{\text{min}})\sin\theta \quad \text{Eq. (A.6)}
\]

The geometric place of the points that belong to the curves ‘AC’ and ‘BC’ can be identified by the multiplication of the Eq. (A.4) and (A.5):

\[
c_2 Y'^2 + c_1 Y' + c_0 = 0 \quad \text{Eq. (A.7)}
\]

where:

\[
c_2 = X_C'(X_C' - d_{AB}), \quad c_1 = Y_C'[d_{AB}(X_C' + X') - 2X'X_C']u' \quad \text{and} \quad c_0 = Y_C'^2(X' - d_{AB}) \quad \text{Eq. (A.8)}
\]

In order to control the curvature of the size distribution between the two edges, the factor $u'$ is included in coefficient $c_1$ of Eq. (A.7):

\[
u' = \sqrt{\frac{0.5}{u - 0.5}} \quad \text{Eq. (A.9)}
\]

where $u$ is the factor for the uncertainty estimation, with a domain of $[0, 0.5)$ and $(0.5, 1]$. Thus, the solution of the quadratic equation (A.7) can be used for the estimation of the risk zone size distribution.

When the uncertainty factor is 0.5, the solution of Eq. (A.7) is $\lim_{u \to 0.5} Y' = 0$.

In case that the uncertainty is between $[0, 0.5)$, Eq. (A.9) is still valid, whilst the Eq. (A.8) is replaced with the following expressions for the calculation of quadratic equation coefficients:

\[
c_2 = X_C'(d_{AB} - X_C'), \quad c_1 = Y_C'[d_{AB}(X_C' + d_{AB} - X') - 2(L - X)X_C']u' \quad \text{and} \quad c_0 = Y_C'^2(X' - d_{AB}) \quad \text{Eq. (A.10)}
\]
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>vessel's breadth (-)</td>
</tr>
<tr>
<td>c</td>
<td>coefficient (-)</td>
</tr>
<tr>
<td>d</td>
<td>distance/sea depth (m)</td>
</tr>
<tr>
<td>D</td>
<td>Vessel's depth (m)</td>
</tr>
<tr>
<td>L</td>
<td>vessel's length (m)</td>
</tr>
<tr>
<td>n</td>
<td>engine's speed (-)</td>
</tr>
<tr>
<td>P</td>
<td>probability (-)</td>
</tr>
<tr>
<td>s</td>
<td>size (-)</td>
</tr>
<tr>
<td>T</td>
<td>vessel's draught (m)</td>
</tr>
<tr>
<td>t</td>
<td>time (s)</td>
</tr>
<tr>
<td>u</td>
<td>uncertainty factor (-)</td>
</tr>
<tr>
<td>V</td>
<td>vessel's speed (m/s) or (knots)</td>
</tr>
<tr>
<td>w</td>
<td>weighting factor (-)</td>
</tr>
<tr>
<td>X</td>
<td>x-coordinate (m)</td>
</tr>
<tr>
<td>Y</td>
<td>y-coordinate (m)</td>
</tr>
</tbody>
</table>

#### Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>β</td>
<td>rudder angle (degrees)</td>
</tr>
<tr>
<td>θ</td>
<td>angle (degrees)</td>
</tr>
<tr>
<td>φ</td>
<td>yaw angle (degrees)</td>
</tr>
<tr>
<td>ϕ</td>
<td>yaw rate (degrees/s)</td>
</tr>
</tbody>
</table>

#### Subscript

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>initial condition</td>
</tr>
<tr>
<td>abs</td>
<td>absolute value</td>
</tr>
<tr>
<td>azi</td>
<td>azimuth</td>
</tr>
<tr>
<td>cal</td>
<td>calibration</td>
</tr>
<tr>
<td>coll</td>
<td>collision</td>
</tr>
<tr>
<td>head</td>
<td>heading angle</td>
</tr>
<tr>
<td>i</td>
<td>time step</td>
</tr>
<tr>
<td>j</td>
<td>stage</td>
</tr>
<tr>
<td>k</td>
<td>category</td>
</tr>
<tr>
<td>man</td>
<td>manoeuvre</td>
</tr>
<tr>
<td>max</td>
<td>maximum</td>
</tr>
<tr>
<td>min</td>
<td>minimum</td>
</tr>
<tr>
<td>ord</td>
<td>ordered</td>
</tr>
<tr>
<td>own</td>
<td>own</td>
</tr>
<tr>
<td>pos</td>
<td>position</td>
</tr>
<tr>
<td>rel</td>
<td>relative</td>
</tr>
</tbody>
</table>

### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACAS</td>
<td>air-borne collision avoidance systems</td>
</tr>
<tr>
<td>AIS</td>
<td>automatic identification system</td>
</tr>
<tr>
<td>ANN</td>
<td>artificial neural network</td>
</tr>
<tr>
<td>ASV</td>
<td>autonomous surface vehicle</td>
</tr>
<tr>
<td>BNWAS</td>
<td>bridge navigational watch alarm</td>
</tr>
<tr>
<td>COLREGS</td>
<td>preventing collisions at sea</td>
</tr>
<tr>
<td>CPI</td>
<td>collision probability indicator</td>
</tr>
<tr>
<td>DCPA</td>
<td>distance at close point of approaching</td>
</tr>
<tr>
<td>DOF</td>
<td>degrees of freedom</td>
</tr>
<tr>
<td>DSS</td>
<td>decision support system</td>
</tr>
<tr>
<td>ECDIS</td>
<td>electronic chart display and information</td>
</tr>
<tr>
<td>FTCS</td>
<td>first time-in-point of closer-quarters</td>
</tr>
<tr>
<td>FTID</td>
<td>first time-in-point of immediate danger</td>
</tr>
<tr>
<td>MCR</td>
<td>maximum continuous rating</td>
</tr>
<tr>
<td>MPC</td>
<td>model predictive control</td>
</tr>
<tr>
<td>MVEM</td>
<td>mean value engine model</td>
</tr>
<tr>
<td>OOW</td>
<td>officer on the watch</td>
</tr>
<tr>
<td>PAD</td>
<td>predicted areas of danger</td>
</tr>
<tr>
<td>PID</td>
<td>proportional-integral-derivative</td>
</tr>
<tr>
<td>SOLAS</td>
<td>Safety of Life at Sea (International Convention)</td>
</tr>
<tr>
<td>TCPA</td>
<td>time to close point of approaching</td>
</tr>
<tr>
<td>TD</td>
<td>time duration</td>
</tr>
<tr>
<td>VO</td>
<td>velocity obstacle</td>
</tr>
</tbody>
</table>

### References


Lee, H.J., Rhee, K.P., 2001. Development of collision avoidance system by using expert system and
search algorithm. International Shipbuilding Progress. 48(3), 197-212.

products and COLREGS. Proceedings of the Intelligent Data Engineering and Automated

in wind, wave, current and shallow water. Proceedings of MARSIM and ICSM’90, June 4-7,
Tokyo. 403-411.

products and COLREGS. Proceedings of the Intelligent Data Engineering and Automated

in wind, wave, current and shallow water. Proceedings of MARSIM and ICSM’90, June 4-7,
Tokyo. 403-411.

Liang, Y., Cai, C., 2016. Intelligent collision avoidance based on two-dimensional risk model.
8301816640251.

doi.org/10.1007/11739685_84.


Minorsky, M.L., 1930. Automatic steering tests. Journal American Society of Naval Engineers. 42, 285-

behaviours extracted from AIS data. Proceedings of the International Conference on Marine
01/9781315099132-26.

System Performance during Manoeuvring in Shallow Waters. Proceedings of the International
Ocean and Polar Engineering Conference (ISOPE). 1091-1098, June 25-30, San Francisco, CA,


Moe, S., Pettersen, K.Y., 2016. Set-Based Line-of-Sight (LOS) path following with collision avoidance
for underactuated unmanned surface vessel. Proceedings of the 24th Mediterranean
Conference on Control and Automation (MED). June 21-24, Athens, Greece. https://doi.org/10.1
09/MED.2016.7535964.

Reliability Engineering and System Safety. 95, 573-589. https://doi.org/10.1016/j.ress.2010.01.0
09.

Montewka J., Krata, P., Przemyslaw, K., (2014) Rowards the assessment of a critical distance between


