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Research paper

Declarative ship arenas under favourable conditions

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ABSTRACT

According to maritime regulations, a collision-avoidance action shall be taken at an "ample time" while strict interpretation of this term is ambiguous. Evasive manoeuvres, executed by marine navigators on a daily basis, are usually carried out well in advance, while the distance at which they decide to perform such a manoeuvre is mostly subjective and results, e.g., from the navigator's seagoing experience. A proper understanding of the decision-maker's behaviour under favourable conditions, when time pressure does not exist, seems to be essential for the future of maritime safety. This could enable the translation and quantification of seafarers' routine actions, taken many times a day, into collision-avoidance algorithms suitable for Decision Support Systems (DSS) or Maritime Autonomous Surface Ships (MASS). The literature lacks extensive research on this subject, as it focuses mainly on safety-critical actions, which are important but rare events. Therefore, this study aims to fill this gap by surveying practitioners and extracting their expert knowledge. Based on an online survey, the declarative ship arenas, reflecting the distance of evasive manoeuvre initiation, were determined and analysed. The findings revealed that, depending on the participants' profiles, a range of responses among the groups reaches up to 2 NM. The results indicated that navigators become less consistent with growing experience. Determined declarative arenas were consequently incorporated into a simulation-based case study of a passenger ship. The conducted simulations indicated that for several scenarios, the passing distances resulting from the execution of an evasive manoeuvre as per declarative arena were less than 0.5 NM, potentially leading to dangerous situations at close range. This results most likely from an overall problem of translating the distance of manoeuvre initiation into the final passing distance. The findings of this research may be found interesting by shipping companies preparing bridge procedures or for scholars and industry representatives preparing intelligent collision-avoidance solutions for maritime transportation.

1. Introduction

Ship collisions, especially due to the constantly growing number of ships and their large tonnage, can cause considerable economic, social and ecological losses. Nevertheless, the transport of goods by sea is the most widely used method of transport, mainly due to its economic advantages, and it is constantly increasing (Unctad, 2023). Despite numerous efforts taken by the relevant stakeholders and authorities to ensure safety at sea, maritime accidents still occur. Among them, ship collisions and groundings commonly depend on evasive manoeuvres taken by watchkeeping officers, which could be the reason that these are often attributed to human error (Emsa, 2023). However, a recent analysis of the scientific literature on the subject urges caution in making such straightforward judgments and advises a systemic approach to identify the actual causes of the accidents (Wróbel, 2021). Along this line, a user-centred design paradigm has been advocated lately, which aims to improve human performance through positive feedback at the ship design phase (Grech and Lutzhoft, 2016).

1.1. Background

To assist an officer on board in the collision avoidance process,

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several systems and tools have been introduced over the years, to mention a few: RADAR along with Automatic Radar Plotting Aid (ARPA), Automatic Identification System (AIS), and the Electronic Chart Display and Information System (ECDIS). Gradually, various Decision Support Systems (DSS) also were proposed, which aimed to improve the performance of navigators, decrease their workload, and eventually enhance the overall safety at sea (Gil et al., 2020b; Huang et al., 2020; Ożoga and Montewka, 2018). Another prospective application of DSS is the ability to classify a ship encounter as dangerous by involving machine learning and eliminating distance from decision-making factors at the same time (Oruc and Altan, 2023).

There are two popular concepts associated with DSS widely used in maritime risk assessment, namely *ship domain* and *ship arena*. Despite similar name and their depiction as an envelope surrounding an Own Ship (OS), each serves a different purpose. The former indicates the passing distance between the vessels resulting from previously undertaken evasive action. The latter, in turn, delimits the distance of an evasive manoeuvre execution, thus the correct cause of passing distance appearance. Moreover, each of them occurs in different variants depending on the user-needs. Therefore, a proper understanding of both mentioned concepts and recognition of the scientific efforts made to date to their variations seem crucial for properly defining the objectives of this study.

1.2. Ship domain

In the maritime literature, a *ship domain* is defined as "*the sea area around the ship which a navigator would like to keep free, with respect to other ships and fixed objects*" (Goodwin, 1975). There are numerous domains that have been determined by adopting various approaches, such as empirical (Du et al., 2021; Hansen et al., 2013), analytical (Wang, 2010, 2013), probabilistic (Gucma and Marcjan, 2012; Zhang and Meng, 2019), or knowledge-based (Fiskin et al., 2020; Kao et al., 2007). Ship domains are used for a variety of purposes, however, their original aim was to estimate the capacity of a waterway (Fujii and Tanaka, 1971; Goodwin, 1975). Over the years this original application area has inexplicably expanded, and now many authors also apply this concept for risk assessment, effective collision avoidance (Kao et al., 2007; Lopez-Santander and Lawry, 2017; Pietrzykowski and Uriasz, 2009; Xin et al., 2023), or detection of so-called near misses (Szłapczyński and Niksa-Rynkiewicz, 2018; Szlapczynski and Szlapczynska, 2021; Zhang et al., 2016).

Ship domains that are based on the practical knowledge of seafarers are called *"declarative domains"* and are usually determined using questionnaires (Davis et al., 1980; Wielgosz, 2016) or by practical exercises on ship handling simulators (Pietrzykowski, 2008). The use of declarative methods makes it possible to define the envelope of a domain with a focus on its further practical application. Some notable examples of declarative ship domains include the work of Lee et al. (2021), who surveyed various factors that seafarers consider relevant to ship encounter situations. To obtain their results, the authors collected 125 responses with a distinction in respondents' experience at sea. The threshold values determined during the study were then used to propose a novel model of the ship domain. However, the scope of the survey was limited to confined waters only, while the decision-making factors were assessed in terms of their relationship to the Distance at the Closest Point of Approach (DCPA) as an indicator depicting subjective distances. On the contrary, Pietrzykowski and Uriasz (2009) surveyed an open sea area and asked respondents about the minimum safe passing distances resulting from the previously performed evasive manoeuvres initiated at a greater distance between two ships. As a result, the envelopes of ship domains for different navigation situations were obtained. However, the determination of the distance of manoeuvre execution itself was out of the scope of this research. Subsequently, Wielgosz, 2016, used expert research to investigate the effects of ship dimensions and speed ratio on the size and shape of the domain. However, neither the respondents' experience in seafaring nor the type of waters were taken into account. In another study, Fiskin et al. (2020), used expert knowledge only as a framework for evaluating the Mamdani model, which was subsequently used to create the ship domain considering various navigational factors, such as time of day, visibility, weather and traffic conditions, as well as the experience of navigators which were obtained in a course of interviews.

Although some literature on declarative ship domains exists, there is still room for discussion on whether and how ship domains, which are conventionally determined by the minimum distances between encountering ships, should be used to support the process of ship collision avoidance (Montewka et al., 2020).

1.3. Ship arena

As previously mentioned, ship domains are the result of evasive manoeuvres carried out previously and at greater distances. From an operational point of view, it is essential for a navigator to know the distance of evasive manoeuvre execution that will result in a (safe) passing distance, rather than the passing distance itself, or the shape of the ship domain resulting from it (Baldauf et al., 2015b; Hilgert and Baldauf, 1997). The distance at which manoeuvre needs to be initiated is easily interpretable by an Officer of the Watch (OOW) and provides practical, meaningful, and useful results. On the contrary, the ship's domain raises more questions than answers and thus seems unsuitable for practical collision avoidance purposes. Nevertheless, ship domains are too often (mis)used for operational risk assessment at sea (Montewka et al., 2020), for which they are neither designed nor intended (Fujii and Tanaka, 1971; Goodwin, 1975). To perform safe and effective evasive manoeuvres and correctly assess the level of risk associated with a particular encounter situation, an OOW must know the following two boundaries as presented in Fig. 1:

1. An inner boundary at which the critical manoeuvres can still be performed effectively (e.g. the last-chance manoeuvre).
2. An outer boundary at which an effective evasive action must be initiated, including non-critical manoeuvres.

Knowledge of these two envelopes significantly increases the navigators' situational awareness in dangerous ship encounters, thus improving their performance, and having a positive effect on safety at sea.

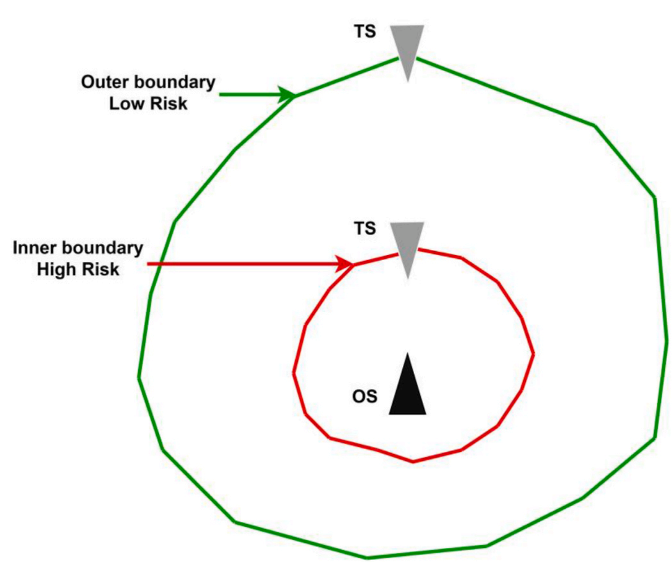

Fig. 1. Two boundaries - inner (red) and outer (green) - considered in an exemplary encounter of own ship (OS) and target ship (TS).

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The inner boundary describes an area required to perform the critical actions (last-chance manoeuvres) in a given close-quarters situation, which is why it is also called a *critical area* (Gil, 2021). Such an envelope can be determined in various ways, e.g., as a result of a series of ship encounter simulations using an advanced ship motion model (Gil, 2021; Gil et al., 2020a; Krata and Montewka, 2015; Szlapczynski et al., 2018), dynamic predictions based on fast-time simulations (Baldauf et al., 2015a), or simply by ship handling simulator trials (Montewka and Krata, 2014).

In (Zhang et al., 2012), a formula was proposed that allows for determining the distance of the inner boundary by setting the "*restricted area*" of ships. This area was calculated by measuring the lengths of the encountering ships (Yim and Park, 2022). proposed a similar approach, in which the minimum distance to perform the manoeuvre execution was determined taking into account the relative bearings and headings of the vessels. This was also assessed in relation to the violation of the pre-defined restricted area. They are therefore determined with a greater margin, but still within a critical range from the authors' point of view. Due to their safety-critical aspect, the concepts of the last-chance manoeuvres presented in the mentioned works are also sometimes implemented in the onboard DSS facilitating collision avoidance process (Dugan et al., 2023; Koszelew and Wołejsza, 2018; Marley et al., 2023; Pietrzykowski et al., 2017). However, it should be noted that these examples refer to critical situations that can usually be avoided with routine and appropriate navigation or, if they are unavoidable, occur only rarely.

As far as the second (outer) limit is concerned, it remains largely subjective. It reflects, among other things, human behaviour, knowledge, good seamanship, or the company's procedures. In addition, the International Regulations for Preventing Collisions at Sea (COLREGs) (Colregs, 2003), do not specify the exact distance or time at which the action should be taken, but instead provide the following recommendation in Rule 8: "*Any action to avoid a collision shall be taken […] in ample time*". It should be noted that the term "*ample time*" is not precisely defined. However, the time of manoeuvre execution is directly related to the preferred (i.e. subjective) distance at which an evasive action is executed with sufficient lead time, according to the perception of the OOW. To define this limit, navigators' preferences, experience and perception of sufficient time/distance must therefore be taken into account.

Surprisingly, there is not much scientific literature on the second, outer boundary that should be considered by the OOW during collision avoidance. It is called the "*arena*" in the available literature and was introduced by (Colley et al., 1983; Davis et al., 1980). It is defined as "*the area around one's vessel which, if breached, causes the mariner to consider whether to perform a collision avoidance manoeuvre*". However, most studies that estimate arenas using data from navigation devices lack a thorough investigation of the factors influencing the dimensions of arenas (Su et al., 2012; Tsou, 2016; Zhang et al., 2015). Only a few studies have analysed the relationship between the time of an evasive manoeuvre initiation and the ship arena size (Zhu et al., 2001). Some of them emphasised the need to use experts' knowledge in defining an effective distance of evasive manoeuvre execution, but without distinguishing ship operational conditions or the level of expertise of navigators (Dinh and Im, 2016). Given this, there is relatively little work on methods and models to determine the outer boundary at which the navigator feels comfortable and confident to perform an evasive manoeuvre. This is particularly important, as an OOW still has enough time to make some corrections if necessary, so the collision avoidance action can still be performed efficiently without violating the critical limit (inner boundary).

It should be noted that the above information is not only indispensable for today's navigators but also for the maritime transport systems of the future, in which both manned and unmanned ships will be present and should coexist safely (Kim et al., 2022; Mehak et al., 2023; Perera and Murray, 2019). Therefore, the translation of experts' knowledge into the language of machines is of utmost importance for future maritime safety (He et al., 2017; Huang et al., 2020; Li et al., 2021). Furthermore, the correct interpretation of COLREGs, including the aforementioned Rule 8, poses a challenge for intelligent collision-avoidance systems in meeting operational safety requirements (Bakdi and Vanem, 2022; Lyu and Yin, 2019; Wang et al., 2024a; Wróbel et al., 2022; Xu et al., 2022; Zhu et al., 2024). Consequently, the awareness of the navigational situation around a ship and the timing execution of evasive manoeuvres are also directly related to the effectiveness of collision-avoidance algorithms developed for autonomous ships, especially, when considering the initiatives taken so far by the International Maritime Organisation (IMO) concerning the introduction of Maritime Autonomous Surface Ships (MASS) (IMO MSC, 2021; Pietrzykowski et al., 2022; Wang et al., 2024b, 2023).

1.4. Contribution

Therefore, the main objective of this paper is to analyse the relationship between the navigators' profile and their collision-avoidance decision-making habits. This was made to allow further quantification and translation of the practitioners' preferences during routine operations into the time/distance of evasive action initiation. In order to systematise the study, the following research questions (RQs) were posed:

1. How does the experience of a navigator affect the preferred distance of a manoeuvre execution under favourable conditions?
2. How does the type of navigational area change the shapes of declarative ship arenas?
3. What is the size and shape of the generalised declarative arenas of a ship?
4. How do declarative arenas affect the passing distances between two vessels and are those sufficient for ensuring safety?

In order to answer these questions, an online survey was prepared to determine various declarative ship arenas, reflecting navigators' preferences on the distance of an evasive manoeuvre execution. To this end, a large Ro-Pax (Ro-Ro passenger) vessel was selected to serve as a safety-critical case-study vessel. As the study focuses on an outer boundary during the decision-making process, the conditions for the arena determination were favourable in terms of weather, traffic, and the ship's surroundings. These obtained arenas were further analysed separately for confined and open waters, as well as with respect to the participants' experience at sea and their professional licence. Afterwards, the declarative arenas were applied to the simulation-based case study, which verified the results of the evasive manoeuvres taken during various ship encounters. This, in turn, enabled a comparative analysis of the decisions made by the navigators at different stages of their sea-going careers, along with their safety-related implications. A graphical representation of the research procedure employed in the study and highlighting its main stages is provided in Fig. 2.

The rest of the paper is structured as follows: Section 2 presents the methods and materials used in the study, focusing on a detailed description of the conducted expert survey and simulation-based case study. Section 3 describes and analyses the obtained declarative arenas with respect to the respondents' profile and especially their sea-going experience. In this section, results of computer simulations determining a passing distance between two vessels are also investigated. Section 4 presents and elaborates key findings of the study along with the identified limitations and directions of future work. Section 5 concludes the paper.

2. Methods and data

In order to determine the shape of the ship arenas, expert knowledge was utilised. To achieve this, an online survey among active navigators

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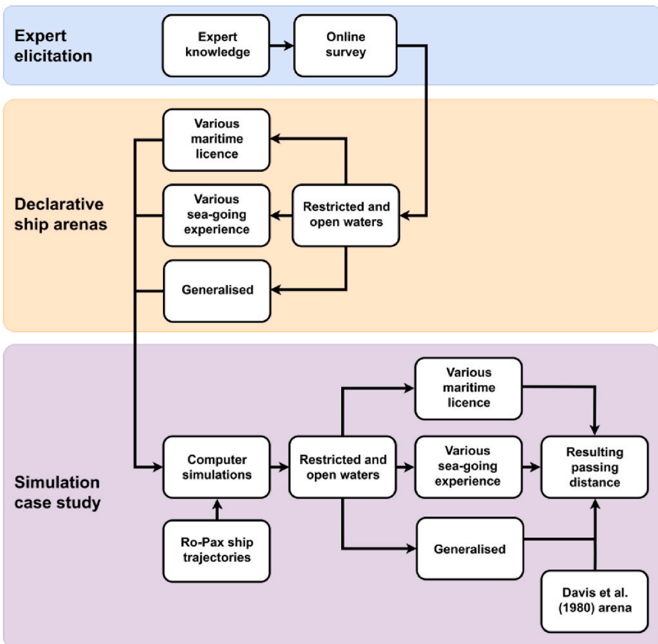

Fig. 2. Overarching framework of the study.

was carried out to obtain their preferred distances for performing evasive manoeuvres for each target displayed on the radar screen. These distances were used to create the declarative ship arenas, which were afterwards used in a case study to simulate selected ship encounter scenarios, and finally to determine passing distances between the vessels. The following section introduces the design of the questionnaire used to determine the experts' knowledge, respondents' profile, data preparation procedure, as well as an overview and the scope of the case study.

2.1. Survey design

The expert study was conducted to obtain information about the envelopes of the declarative arenas reflecting navigators' preferences under favourable conditions. Therefore, an interactive online survey was conducted on a group of practitioners, who were asked about their preferences regarding the distance to a target ship (TS) when initiating evasive manoeuvres.

Before starting the survey, each participant was familiarised with the objectives of the study, the research assumptions, and the instruction for completing the questionnaire. To this end, the respondents were introduced to the description of the radar screen used in the survey, as well as to the guidelines on how to utilise the range sliders to give answers, thus indicating a distance of manoeuvre execution. Additionally, the manoeuvring information of the selected Ro-Pax vessel, i.e., the pilot card and its wheelhouse poster were shared with respondents to gain their awareness about the ship's manoeuvrability and thereby enhance the credibility of their assessments.

The above-mentioned research assumptions of the study were as follows:

- Twelve distances of evasive manoeuvre execution considering a target located on bearings equally spaced every 30° should be evaluated
- The distances should be assessed for two navigational scenarios – separately for open sea and confined waters
- Only one, clearly dangerous target is always present on the radar screen (DCPA ~0 NM)
- All non-stationary radar echoes are already acquired;
- The radar screen is always in North-up display mode, relative motion, and with 30-min relative vectors
- The preferred distance of an evasive action taken by OS or TS should be assessed, depending on the COLREG-related scenarios
- Given COLREG Rule 18, both the OS and the TS are considered herein as two power-driven vessels
- All traffic, operational, and environmental conditions are favourable:
  - The own ship and the navigation equipment are in good condition and without defects
  - There is always time for an effective evasive manoeuvre (TCPA 30 min)
  - Weather conditions such as visibility, sea state, or precipitations are favourable
- A modern Ro-Pax ship is considered a reference model for OS
- The study is anonymous – only general information about a respondent is collected (country, age, experience, professional licence, etc.)

The online survey was designed in a way that allows for an easy indication of the desired distance to a target ship (TS) located at a particular bearing. To make both, the assessment of the navigation situation and the estimation of the distance intuitive and user-friendly, a screen of a typical ship's radar was displayed as a separate question for each TS located at a different bearing. This was supplemented with a slider used to select the distance of manoeuvre execution, and a reminder regarding the purpose of the question. Such a sample question – one of 24 that differ in TS location and navigation scenario (12 for open and 12 for restricted waters) – is presented in Fig. 3.

As depicted, for each question in the survey the same task was posed:

"*Please assess the preferred distance of an evasive manoeuvre execution between own ship and the target. Select an appropriate position on the slider accordingly to the scale presented*".

In addition, to make all questions clear enough in terms of practical interpretation of the COLREG rules, each radar screen was captioned as follows:

"*The navigational situation depicted on the radar screen is only an exemplary one. As per COLREGs, you should assess the preferred distance of your own evasive manoeuvre execution or an expected distance, at which the target should turn*".

The situation displayed on the radar screen represented in each question the current surroundings of the OS depending on the considered navigational area and presented the TS at different bearings. The radar settings (orientation, presentation, length and type of vectors, etc.) did not change between the subsequent questions. The acceptable range for the distance selection on the slider was from 0.1 to 10 NM in steps of 0.1 NM. While answering the questions, each participant was familiar with the scale of the slider, as well as with the current (or final) position of the slider's tip, as the corresponding numerical value in nautical miles was additionally displayed in a tooltip.

Before sending out the survey invitations and beginning to collect responses, the questionnaire was verified by both the authors and a small testing group of practitioners (three OOWs and one Cpt.). This allowed initial comments on the questionnaire to be gathered and taken into account before the actual survey began, confirming the validity of its design and selection of the method of obtaining information.

2.2. Respondents' profile

A total of 76 responses were received, 64 of which met the eligibility criteria. A total of 12 responses were excluded because of unreliable or missing values, which was due to poor completion of the survey. For instance, some questions were only answered with one of the extreme values, either 0.1 NM or 10 NM; in some cases, most of the answers were

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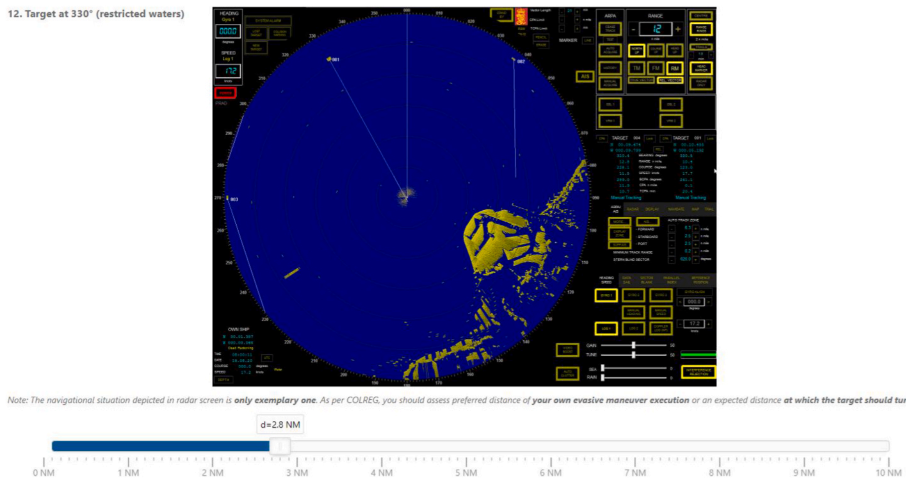

Fig. 3. Exemplary survey question in the restricted waters part of the study. It presents an interactive slider for distance selection, as well as the radar screen depicting the navigational area around OS and the threatening target at 330°.

null values indicating that a respondent did not move the slider tip at all, some others were simply testing responses made to verify the survey by the authors. In addition, single and clear outliers or single missing values were sometimes observed within the answers of the same expert. In such cases, to not lose the entire answer, individual errors were corrected during data processing by calculating the mean value based on two neighbouring (and reasonable) distances.

Among the 64 final answers, the holders of four maritime diplomas could be identified: Officers of the Watch, Chief Officers (CO), Master Mariners (Cpt) and Sea Pilots. The largest group, consisting of 28 navigators, were the holders of the operational level licence, i.e. OOW, followed by CO (16), masters (12) and pilots (8). The vast majority of the study participants were male (56) and 6% were female (4). Furthermore, a total of 4 respondents chose not to declare their gender. A more detailed breakdown of the respondents concerning their declared gender and licence is shown in Fig. 4.

Regarding the nationality of the participants, the large majority (almost 75%) stated Polish (47). This is fully understandable considering the country of origin of the study authors, which directly facilitates the search for relevant respondents. However, as the survey was part of an international research project, and the invitation to participate was published on specialised portals (both maritime and scientific), foreign experts also took part in the survey. As can be seen in Fig. 5, Germany, Portugal, and Ukraine were represented by three participants, Croatia

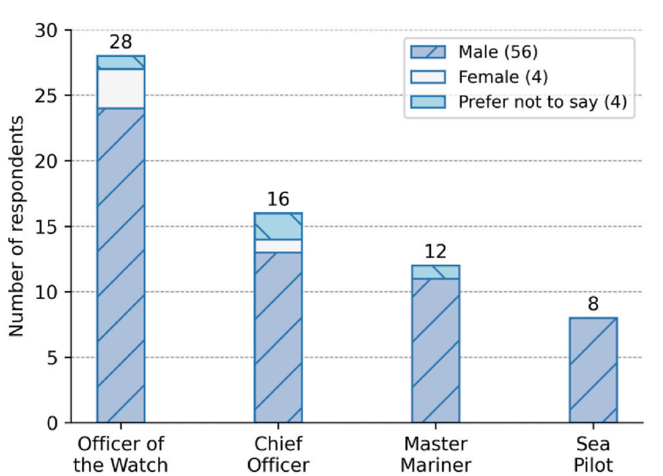

Fig. 4. Breakdown of the interviewees regarding their declared gender and professional licence.

by two, and the remaining countries (USA, UK, China, Ireland, Finland, and Romania) by one navigator.

In addition to the above information, the survey participants also provided information regarding their seagoing experience (Fig. 6). It should be noted that a correlation between professional experience at sea and the license held is not always obvious, but the general trend was as expected. Namely, the greater the professional experience of a respondent the smaller the share of OOWs and the larger of the management licences, such as captains or pilots. In some cases, seafarers with extensive experience prefer to continue their work at the operational level of their career instead of taking management positions (such as three OOWs with more than 10 years of experience on board). Some officers are also simply reluctant to take the responsibility that comes with being a ship's master and his duties. For this reason, it seems useful to consider both the experience and licence in further analysis of the results, as a particular diploma does not always directly reflect the experience of a navigator, especially in the collision avoidance field.

2.3. *Aggregation of responses*

Because of various experiences and professional licences among the respondents, it was necessary to handle their answers in a slightly different way if aggregation of the results was needed, e.g., when creating generalised ship arenas. Since the answers of the more experienced participants can be generally considered more reliable (and therefore closer to reality), the weightage of the responses concerning the maritime diploma declared by the respondent was adopted. This method also allows for capturing another important aspect of the respondent's experience, namely, the unusual specificity of the work of sea pilots, who work daily exclusively on port approaches. Thus, despite their vast experience and high qualifications, their responses, especially in relation to the open sea, were strongly underestimated. Therefore, when the results of all respondents had to be aggregated (e.g., to generalise ship arenas), the following weights were arbitrarily adopted in both open and confined waters: 0.7 for OOW, 0.85 for CO, and 1.0 for Cpt. For sea pilots, a distinction between open sea (0.5) and restricted waters (0.9) was additionally applied.

When results needed to be aggregated, the responses were averaged using a weighted geometric mean (WGM), considering the above-mentioned weights. This approach to results aggregation was chosen because of its greater robustness to extreme values than the arithmetic mean, and better reflection of the group's intentions, which is used in group decision-making (Butler et al., 1997; Dong et al., 2010; Forman and Peniwati, 1998).

For the sake of further results analysis, the geometric standard de-

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Fig. 5. Breakdown of the respondents in relation to their declared country of origin.

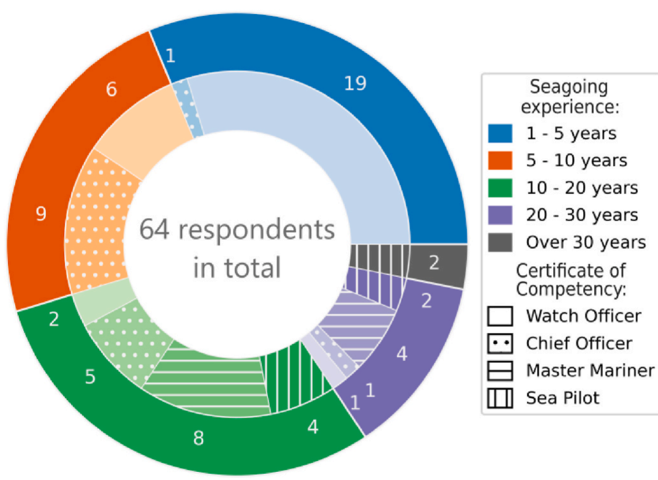

Fig. 6. Breakdown of the respondents concerning seafaring experience in relation to professional licence held.

viation (GSD) factor was also employed. As the GSD is dimensionless and thus not easy for practical interpretations, it should be considered together with the calculated WGM. However, as it is a geometric type of standard deviation, it cannot simply be added to or subtracted from the WGM. Therefore, two additional factors were calculated to depict the range of the distances obtained. The first describes the range *to* the geometric mean (WGM/GSD), while the second describes the range *from* the mean (WGM · GSD). Finally, the geometric standard error of the mean (GSEM) was also calculated, which allows us to measure the accuracy of the estimated WGM. This indicator corresponds to the standard error, similar as for the arithmetic mean, and includes both the variability of the data and the sample size.

2.4. Simulation-based case study

The simulation study was designed to finally verify the declarative ship arenas obtained from the questionnaire and to see what passing distances would result from their application in selected encounter situations.

2.4.1. Scope of the study

To conduct computer simulations of evasive manoeuvres according to determined declarative arenas, a set of ship motion trajectories was required. This was delivered using a 6DOF ship motion model called *LaiDyn* (Matusiak, 2021). To make the simulation study comparable with the aforementioned survey, a very similar Ro-Pax ship was used, serving here as both OS and TS. The main particulars of the selected sample ship are length overall (LOA) 221.5 m and beam 32 m. The ship turning trajectories were prepared for various rudder and speed combinations, as different evasive manoeuvres were investigated. To increase the reality of the simulation outcome, the trajectories were prepared in the presence of slight environmental disruptions described by the impact of irregular sea waves. However, to be in line with the assumptions of the expert survey, compared to the previous study (Szlapczynski et al., 2024), only a limited range of the wave parameters depicting favourable conditions was used to reduce wave impact on the ship's response.

Each simulation commences at a larger, predefined distance between the own and the target ship, but their initial combination of course and speed yields a dangerous encounter indicated by near-zero DCPA. When TS, as it approaches, reaches the envelope of the OS's declarative arena, the own ship starts initiating an evasive manoeuvre. This applies to any scenario, regardless of the TS bearing and relevant COLREGs. The distance at which two vessels eventually pass each other as a result of a previously performed manoeuvre will be designated DCPA as presented in Fig. 7. For the sake of easy interpretation of the results, this distance was expressed as a multiple of the selected Ro-Pax ship's LOA (221.5 m).

2.4.2. Simulation scenarios

To establish the DCPA values between two encountering vessels, seven encounter scenarios were defined and consequently applied in computer simulations Fig. 8. These scenarios vary in terms of the initial position and course of the TS (Table 1), in order to create a dangerous

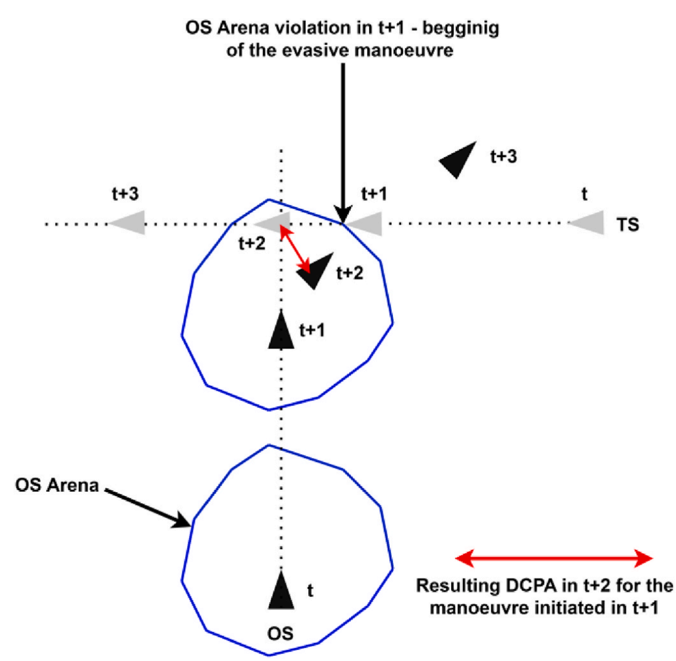

Fig. 7. The general idea of carrying simulation study.

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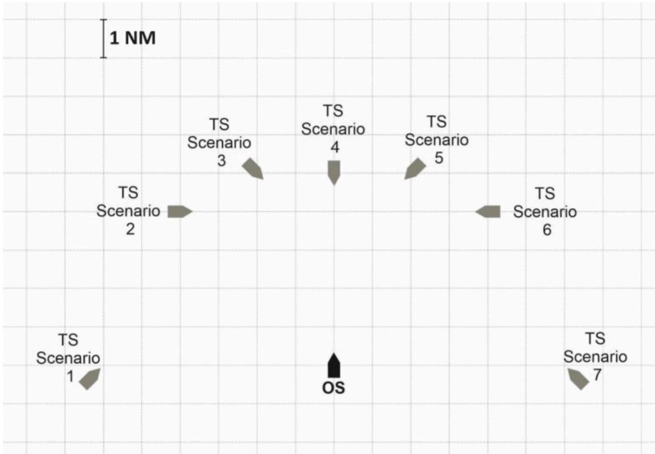

Fig. 8. An overview of the TS positions and courses at the beginning of each simulation scenario.

Table 1
Details of the TS positions and courses at the beginning of each scenario.

Scenarios	Target Ships		
	Relative position X [NM]	Relative position Y [NM]	Course [°]
Scenario #1	−6.36	−0.36	045
Scenario #2	−4.00	4.00	090
Scenario #3	−2.12	5.12	135
Scenario #4	0.00	5.00	180
Scenario #5	2.12	5.12	225
Scenario #6	4.00	4.00	270
Scenario #7	6.36	−0.36	315

encounter if a ship will not take any evasive action. The initial positions of TS are related to the OS's position, which is situated in the origin of the adopted coordinate system (OX = 0.0, OY = 0.0). In scenarios #1 and #7, the TS is initially located abaft the OS's beam.

The parameters of evasive manoeuvres taken during the simulation study, as well as conditions which were common for all scenarios (like OS details or environmental conditions), are provided in Table 2. The OS speed in each scenario was set to 16 knots, while the TS speed was 16 knots in scenarios #2 - #6 and 24 knots in scenarios #1 and #7.

All angles, courses, and course alterations are given in navigational notation and are therefore measured clockwise from the OY axis indicating North (000°), while distances are presented in nautical miles. For each simulation scenario, two evasive manoeuvrers were considered,

Table 2
Parameters of the conducted simulation scenarios.

Parameter name	Parameter value
OS course [°]	0.0
OS position X [NM]	0.0
OS position Y [NM]	0.0
OS speed [kn]	16
TS speed for scenarios #2 - #6 [kn]	16
TS speed for scenarios #1 and #7 [kn]	24
Significant wave height [m]	0.9
Wave peak period [s]	4.5
Wave angle [°]	0.0 (following seas)
Manoeuvre #1	
Rudder deflection [°]	5
Course alteration [°]	20
Delay of rudder deflection [s]	5
Manoeuvre #2	
Rudder deflection [°]	15
Course alteration [°]	40
Delay of rudder deflection [s]	9

differing in the magnitude of rudder deflection and intended course alteration:

- Manoeuvre #1 (slight): rudder deflection 5°, course alteration 20°
- Manoeuvre #2 (firm): rudder deflection 15°, course alteration 40°

Both manoeuvres are considered safe from a practical point of view, as declarative ship arenas were established for favourable operational and navigational conditions. During the simulation process, a delay for the rudder deflection was also taken into account, being 5 and 9 s, respectively. It was also assumed that OS initiates evasive manoeuvre resulting in its course alteration as soon as TS violates its arena.

3. Results and analysis

As the case study model of the own ship was presented in the survey together with its features and manoeuvring data, this aspect was unified and known to all participants to the same extent. Therefore, there are two remaining factors that affect the perceived (sufficient) distance when executing an evasive manoeuvre under favourable conditions: the professional licence, which in most cases is related to the navigators' seagoing experience, and the space required to execute the manoeuvre, which results from the type of navigation area (available water depth). With this in mind, the following parts of this section present the declarative ship arenas determined in the course of the expert survey and analyse them considering the navigators' experience for both confined and open waters.

Given the limited scope of the sample, which may not be wholly representative of the population of seagoing practitioners, the authors intended to prioritise the identification of trends instead of the investigation of exact numerical results. Nevertheless, the statistical indicators employed in the study have enabled the greatest possible objectivity to be maintained.

3.1. *Ship arenas concerning navigators' profiles*

To find an answer for both RQ1 and RQ2, the obtained declarative ship arenas were presented according to various professional licences, as declared by the survey participants separately for the open sea and restricted waters. As shown in Fig. 9, each of the presented ship arenas consists of two *envelopes* created using the geometric mean of the respondents' answers. To ensure a legible and intuitive representation, the arenas for open waters were shown in blue, while the arenas for restricted waters were marked red. The scaling between the subplots is the same to allow easier comparison and give a better insight into the licence-related discrepancies between respondents' results. Please note that the ship symbol in the center of each graph does not correspond to the actual dimensions of its hull, but only indicates the ship's heading (000°).

As for the responses of the OOWs Fig. 9 (a), it can be observed that their arenas have the most circular shape among all obtained. In both open and confined waters, the smallest value of the envelope, reflecting the OOWs' greatest conviction about safety of the vessel, is reached when the target is directly behind the OS's stern. The OOWs in open waters allocated more space and thus greater manoeuvring room for TSs located on their starboard side. This is most likely due to Rule 15 of the COLREGs, which required OS to give way to the other vessel on its starboard side because of the crossing situation. Interestingly, this general tendency to increase the size of the arena in favour of the sectors on the starboard side diminishes slightly in confined waters, and the distances determined by the OOWs are quite similar regardless of the side.

Analysis of the responses obtained from CO-licenced seafarers shows a less consistent pattern than for OOWs, as shown in part (b) of Fig. 9. The impression of irregularity is caused by a sudden drop of the assessed distance in the port bow sector as well as on bearings located astern,

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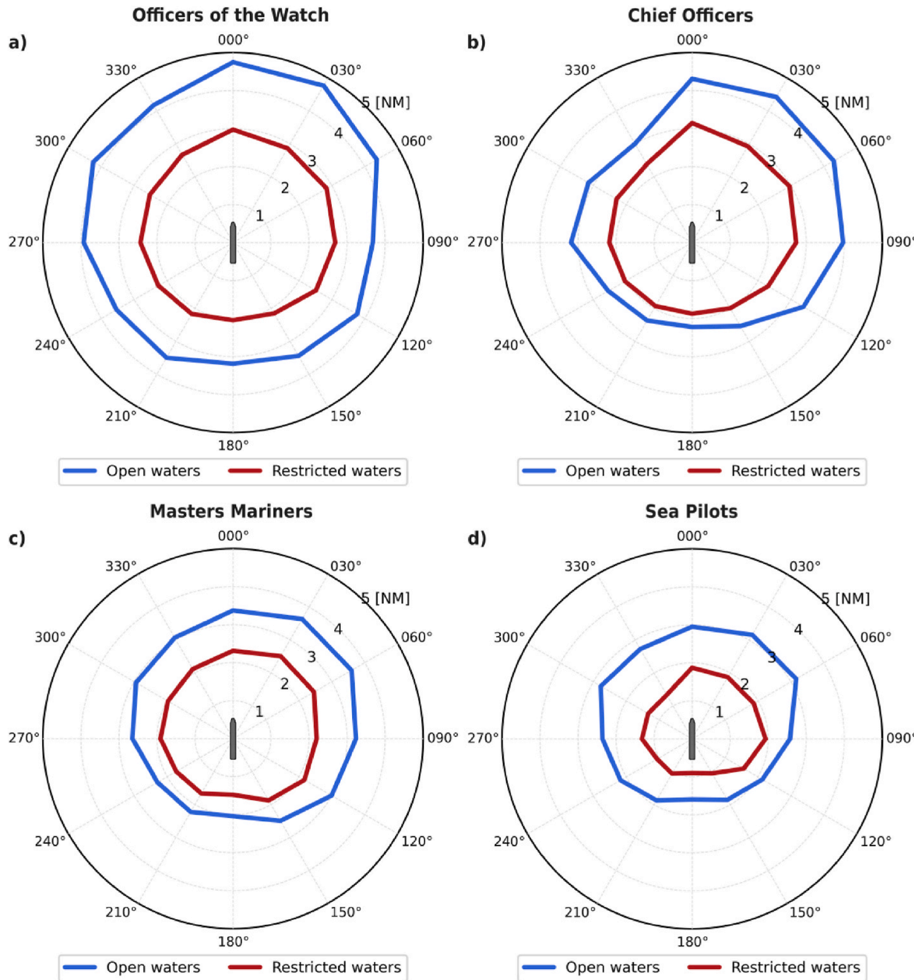

Fig. 9. Declarative ship arenas defined by Officers of the Watch (a), Chief Officers (b), Masters Mariners (c), and Sea Pilots (d) for open sea (blue) and restricted waters (red).

with a discrepancy reaching only 3 cables between open and confined waters. The differences are more distinct in the forward sectors, whereas they are considerably larger on the starboard side. In this latter case, the envelope for open waters is 1.5 times larger than that for restricted waters.

The envelope curves determined for master mariners are even smaller compared to the previous ones Fig. 9 (c). This becomes particularly clear when analysing confined waters, where the captains set the lower limit at 1.5 NM. The envelope determined by captains for open waters is characterised by greater volatility than for confined waters. As a result, the preferred manoeuvring distance in open waters is highly variable, with a difference of 1.6 NM between the minimum and the maximum, while in confined waters, the difference is relatively small, at 0.9 NM. Therefore, it seems crucial for captains to maintain a certain minimum safety buffer in confined waters, which should not be exceeded, as the manoeuvring range is limited by the environment regardless of the bearing in which TS is located. In contrast, open waters are more forgiving of potential errors, and this simple truth was also confirmed by the captains.

When analysing the envelopes given by the sea pilots in Fig. 9 (d), it is immediately apparent that this group of experts has the greatest tolerance for close-quarters situations, especially in confined waters. This is due to the type of routine work they perform on a daily basis. For example, the minimum values for TS located abaft of the OSare sometimes even less than 1 NM. In confined waters, the pilots generally set a distance threshold for executing manoeuvres between 0.9 NM and 1.9 NM, depending on the TS's location. In open waters, however, the ship arena's envelope is more circular and its limits vary more widely, ranging from 1.6 NM to 3.2 NM.

3.1.1. A comparison of ship arenas concerning navigators' licenses

All respondents analysed in the open sea scenario share a common characteristic, namely that the highest distance for the TS was identified on the starboard bow. In this sector, there is also a difference in the subjective distance at which an evasive manoeuvre should be initiated between captains and pilots, who set this at around 3–3.5 NM, while OOWs and COs indicated a distance around 1.5 times greater.

There also seems to be unanimity among the seniors (captains and pilots) for each of the 12 bearings in open waters. Notably, captains exercise a slightly higher degree of caution compared to sea pilots. This could be because, despite having a pilot on board who is familiar with a particular area, the master always bears responsibility for the vessel.

As for the responses of the watchkeeping officers, it is noteworthy that they remain consistent regardless of the TS bearing. This tendency is similar to the responses of the pilots or captains, albeit with a slightly lower sense of caution. Accordingly, it is expected that OOWs on open waters anticipate that the manoeuvre will occur at a distance of approximately 1.5–2.0 times that of captains and pilots. It should be noted that the minimum distance at which OOWs believe a manoeuvre should be executed falls within the declarative arena of the latter group.

When it comes to COs, it appears that the limits of the arena's envelope for TS located on the forward or starboard side sectors are

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generally quite similar to those identified by OOWs. Interestingly, the perception of the COs in the aft sectors of the ship is closer to that of the captains or pilots. In one case (330°), the value even falls slightly below the envelope determined by the masters. Although COs are more experienced than the OOWs, they also appear to be less consistent in their judgements. This can be concluded from analysing the GSD values, which are significantly larger for this group of respondents. The largest deviation is found for the 300° bearing (GSD = 2.0), while for OOWs the value is 0.5 less.

Interestingly, in restricted waters, the caution of seafarers, expressed as the limit of the envelopes, seems to be similar and comparable, regardless of the diploma obtained, unlike in open waters. Based on the collected answers, it seems that the shape resembles a regular figure. However, there is a clear distinction between seafarers serving as regular crew on ocean-going vessels and sea pilots. The arenas designated by the former are characterised by greater preferred distances when performing evasive manoeuvres.

3.2. A comparison of ship arenas concerning navigators' seagoing experience

In Fig. 10, a comparison of the determined ship arenas according to respondents' experience is presented. It is of note that licence held does not always reflect the experience in collision avoidance. On the left-hand side of Fig. 10, which pertains to open waters, it could be argued that individuals may become more at ease as they gain more seagoing experience.

When analysing responses of seafarers who have more than 15 years of experience (the two most experienced groups), we can see that the values tend to stabilise in a range of around 2 NM–3 NM of preferred distance. Considering their great experience, it can be concluded that the bearing on which the TS is located finally loses its relevance on the perception of the distance at which the manoeuvre should be performed. This group may prefer to maintain a certain distance within their comfort zone, regardless of the circumstances. Although there may be differences, they are not as noticeable as with other groups.

The next group of the less experienced, i.e. those with 10–15 years of sea service, corresponds to the trend that the provision margin gradually increases with decreasing experience. In this particular group, it is evident that a greater degree of caution is exercised when navigating in open water, particularly concerning starboard-bow bearings.

When it comes to the less experienced navigators, there are two main findings. Firstly, some of the respondent groups (6–10 years) allocated in some cases slightly more space than the less experienced group (3–6 years). Secondly, navigators with up to 3 years of experience allocated a similar distance for almost all bearings. What distinguishes this group from the others is the fact that they maintain a significant distance of 4 NM for TS located astern while others established that it was at least 1.5 times smaller. From this, one could conclude that inexperience can lead to a greater safety margin around the OS, regardless of the COLREG rules.

The arenas for confined waters are shown on the right side (b) of Fig. 10. As in the previous case analysed in Fig. 9, the envelopes generally show no significant differences and resemble circles in shape. It appears that navigators, regardless of their experience, can attempt or anticipate evasive manoeuvres within a range of about 1–3 NM. Nevertheless, there are some slight differences. For example, there is a difference in the size of the envelope for all bearings reported by respondents with the least experience, i.e. up to 3 years. Furthermore, the respondents with up to 10 years of experience required a larger distance to execute evasive manoeuvres but mainly in forward sectors. Navigators with over 10 years of experience share a similar approach in restricted and open waters. The bearing of the TS is no longer a significant factor as long as the manoeuvre is carried out at a distance of at least 2 NM.

3.3. Generalised declarative ship arenas

By combining and averaging all collected responses, the obtained preferred distances for evasive manoeuvres were used to create the generalised declarative ship arenas shown in Fig. 11. To this end, the results were processed using the weighted geometric mean (WGM) according to the research procedure described in Section 2.3, with the weighting aiming to take into account to some extent both the experience of navigators and the specificities of the daily work of sea pilots. This makes it possible to find an answer to the question RQ3 and to determine the distance/time perceived by the navigators as sufficient to perform evasive manoeuvres under favourable conditions. The above can be achieved by analysing the aggregated results of all navigators surveyed, regardless of their additional grouping. In addition, as before, the differences between the values collected for confined and open waters can be observed. Additionally, Table 3 shows the resulting distances together with the basic statistical indicators for each of the analysed bearings, separately for the confined and open waters. The corresponding statistical indicators can be used to additionally evaluate the consistency between the answers of all respondents or to assess statistical errors.

The analysis of the results indicates that the largest envelope is

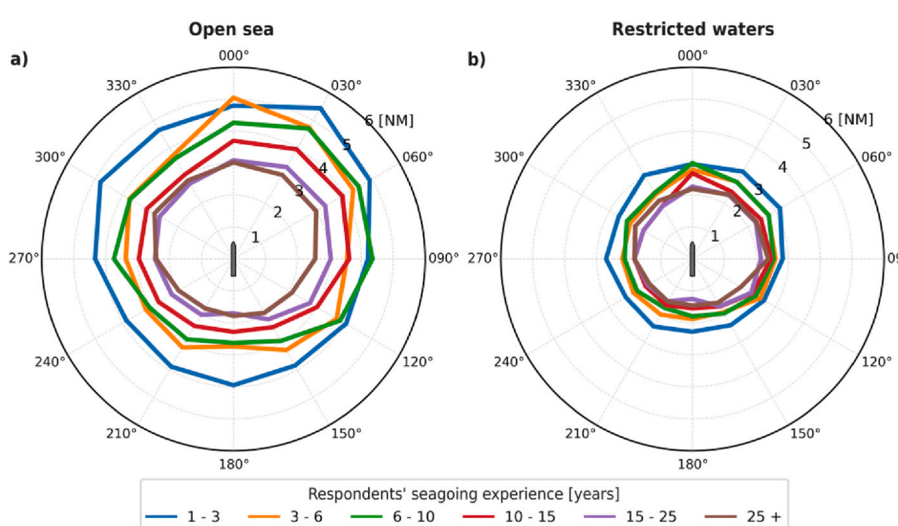

Fig. 10. Declarative ship arenas established for the open sea (a) and confined waters (b) concerning navigators' experience.

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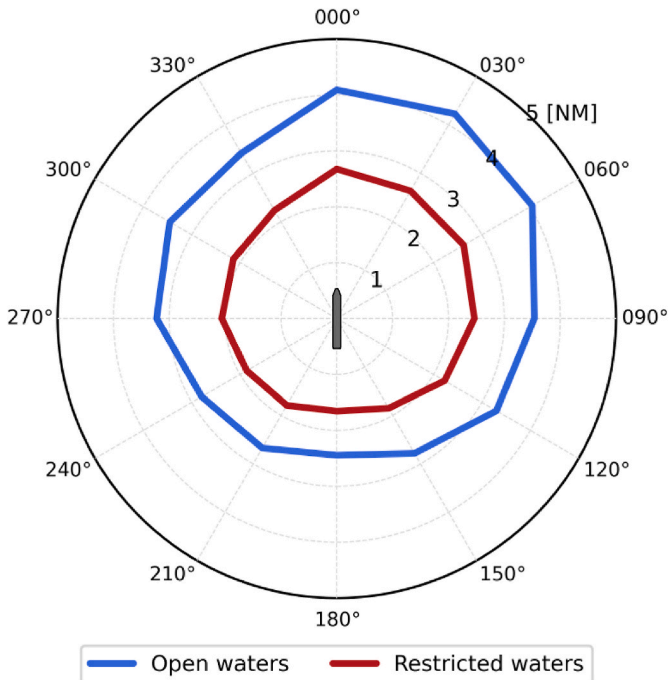

Fig. 11. Generalised declarative ship arenas determined from the aggregated results for the open sea (blue) and confined waters (red).

perceived in head-on and crossing situations, as recognised in COLREGs rules 14 and 15. The surveyed navigators typically maintain a limit of about 4 NM for the TS within the sector from 000° to 060° (the most critical one) in the open sea. In restricted waters, the maximum distance is limited to about 2.7 NM in the forward sector of the OS and decreases by 0.3 NM for the starboard side beam (090°).

It is worth noting that TS located behind the OS do not receive much attention, which is reflected in the shortest distances required to execute an evasive manoeuvre as given by the navigators. In open waters, the manoeuvring zone reaches in the aft sectors a minimum of 2.5 NM, while in confined waters, the change is less noticeable compared to the other sectors, and the envelope reaches a minimum of 1.7 NM.

Given the numerical results presented in Table 3, the geometric standard deviation (GSD) factor (second column) calculated for aggregated responses ranged for the open sea from 1.55 to 1.80. The data indicate that bearings 000° and 030° had the lowest dispersion of the values, while bearings abaft of the OS showed slightly lower degree of data consistency and thus lower agreement among the experts. In the confined waters, the greatest agreement was found behind the starboard beam (1.72), while the greatest inconsistency, similar to the open waters, was found in the aft sectors of the OS (2.05).

For the generalised declarative arenas using aggregated results, the geometric standard error of the mean (GSEM) is between 1.06 and 1.08 in the open sea and between 1.07 and 1.09 in confined waters. The aforementioned values indicate that the WGM may fluctuate by up to ± 9%, which can be interpreted as a moderate but sufficient degree of precision.

3.4. Simulation-based case study

To find an answer for the RQ4, this section will present the simulation results, which are the translation of the manoeuvre execution distance into the actual distances at which ships will pass each other.

3.4.1. A comparison of declarative arenas' impact on manoeuvre results concerning navigators' profiles

Table 4 presents the results of the DCPA values when the manoeuvres were carried out at the distance corresponding to the ship arena, according to the preferences of the respondents. The data is differentiated by licence held and the type of navigation area, as described in Section 3. The values are expressed in terms of the length overall (LOA) of a selected model vessel (221.5 m).

The resulting DCPA depends greatly on the size of an arena and the size of course alteration related to the executed manoeuvre. As for the former, of key importance is the radius of the sector from which TS approaches. As for the latter, as expected, a more substantial manoeuvre usually resulted in a larger DCPA than in the case of the moderate one (with one exception noted).

Except for Scenario #2, where TS maintains the 090° course and is approaching from the port bow, all arenas' sizes are sufficient for ensuring DCPA of at least 200 m (≈ 0.1 NM). However, a passing distance of 1 cable or even less is very dangerous and should not take place, especially when bearing in mind uncertainties associated with the simulation study and ship motion modelling as well as favourable conditions. The relevant regulations pertaining to the safe navigation of seagoing vessels are set by the shipowner or the vessel's master. These are commonly referred to as "Company Standing Orders" or "Master Standing Orders", and define the minimum distances that must be maintained between vessels when passing nearby. This value is changeable, but typically it is established within the range of 0.5–1.0 NM (Director of Marine Operations, 2023; Marine Accident Investigation Branch, 2014; Marine Accident Investigation Branch, 2011, 2003). In the case of ships designed to carry passengers, such as the Ro-Pax, these values are sometimes even higher, reaching 1.5 NM when passing ahead of another vessel (Marine Accident Investigation Branch, 2009). In order to maintain the aforementioned passing distance of at least 0.5 NM, which is the worst-case threshold value, a minimum of approximately 4.2 model lengths of Ro-Pax are required. As presented in

Table 3
Numerical description of the aggregated declarative arenas with basic statistical parameters.

Bearing [°]	Type of navigational area									
	Restricted waters					Open sea				
	WGM [NM]	GSD [-]	*WGM/GSD* [NM]	*WGM • GSD* [NM]	GSEM [-]	WGM [NM]	GSD [-]	*WGM/GSD* [NM]	*WGM • GSD* [NM]	GSEM [-]
000	2.67	1.76	1.52	4.72	1.07	4.09	1.55	2.64	6.34	1.06
030	2.64	1.78	1.49	4.68	1.07	4.23	1.55	2.73	6.54	1.06
060	2.62	1.77	1.49	4.63	1.07	4.04	1.57	2.57	6.36	1.06
090	2.46	1.73	1.43	4.25	1.07	3.54	1.66	2.13	5.86	1.07
120	2.23	1.72	1.30	3.83	1.07	3.30	1.58	2.09	5.21	1.06
150	1.85	1.92	0.96	3.57	1.09	2.78	1.64	1.70	4.55	1.06
180	1.66	2.05	0.81	3.39	1.09	2.44	1.80	1.36	4.41	1.08
210	1.79	1.92	0.93	3.44	1.08	2.67	1.65	1.63	4.40	1.06
240	1.87	1.83	1.11	3.42	1.08	2.79	1.66	1.69	4.63	1.07
270	2.06	1.86	1.07	3.44	1.08	3.23	1.62	1.99	5.25	1.06
300	2.13	1.99	1.11	3.42	1.09	3.45	1.67	2.06	5.78	1.07
330	2.23	2.01	1.06	4.82	1.09	3.42	1.66	2.06	5.68	1.07

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Table 4
Resulting DCPA values of ship-ship encounters simulated for the ship's evasive action, initiated at a distance defined by the declarative arenas. DCPA is expressed in the LOA of the model vessel (221.5 m).

Scenarios and manoeuvres		Arenas							
		Restricted waters				Open waters			
		OOW	Chief officer	Captain	Pilot	OOW	Chief officer	Captain	Pilot
Scenario #1	Manoeuvre #1	3.69	3.22	2.72	1.62	6.37	4.93	4.03	3.54
	Manoeuvre #2	9.95	8.68	7.33	4.37	17.14	13.29	10.84	9.53
Scenario #2	Manoeuvre #1	2.01	1.77	1.49	0.82	3.55	2.47	2.41	2.16
	Manoeuvre #2	0.72	0.64	0.54	0.32	1.23	0.87	0.85	0.77
Scenario #3	Manoeuvre #1	2.64	2.38	1.91	1.00	4.61	3.29	3.14	2.69
	Manoeuvre #2	3.55	3.21	2.56	1.33	6.24	4.43	4.23	3.63
Scenario #4	Manoeuvre #1	3.35	3.60	2.37	1.73	5.95	5.31	3.93	3.31
	Manoeuvre #2	5.44	5.86	3.84	2.78	9.72	8.67	6.40	5.39
Scenario #5	Manoeuvre #1	3.51	3.64	2.81	1.90	6.46	5.87	4.56	3.84
	Manoeuvre #2	6.20	6.45	4.96	3.32	11.48	10.44	8.09	6.79
Scenario #6	Manoeuvre #1	4.04	4.19	3.40	2.33	7.00	6.65	5.36	4.56
	Manoeuvre #2	7.55	7.83	6.33	4.33	13.11	12.47	10.04	8.54
Scenario #7	Manoeuvre #1	1.72	1.72	1.31	1.11	2.50	2.65	2.16	1.59
	Manoeuvre #2	4.63	4.65	3.66	3.01	6.73	7.16	5.74	4.31

Table 5
Resulting DCPA values of ship-ship encounters simulated for the ship's evasive action initiated at a distance defined by the declarative generalised arenas and the Davis arena. DCPA is expressed in the LOA of the model vessel (221.5 m).

Scenarios and manoeuvres		Ship arenas		
		Generalised: restricted waters	Generalised: open waters	Davis et al. (1980)
Scenario #1	Manoeuvre #1	2.99	5.07	2.14
	Manoeuvre #2	8.06	13.66	5.78
Scenario #2	Manoeuvre #1	1.63	2.81	2.47
	Manoeuvre #2	0.59	0.99	0.87
Scenario #3	Manoeuvre #1	2.12	3.67	4.00
	Manoeuvre #2	2.85	4.97	5.41
Scenario #4	Manoeuvre #1	2.91	4.98	5.22
	Manoeuvre #2	4.72	8.14	8.52
Scenario #5	Manoeuvre #1	3.12	5.55	6.05
	Manoeuvre #2	5.50	9.86	10.76
Scenario #6	Manoeuvre #1	3.65	6.26	6.49
	Manoeuvre #2	6.81	11.72	12.16
Scenario #7	Manoeuvre #1	1.53	2.36	1.69
	Manoeuvre #2	4.15	6.36	4.58

Tables 4 and it is frequently the case that this assumed critical distance is violated.

In the context of restricted waters and minor rudder deflection, this condition is only met by the chiefs in the case where the TS is approaching from the starboard side (Scenario #6). In the area of open waters, there is a tendency among pilots and captains to allocate an insufficient arena for such a manoeuvre. Pilots maintained the assumed safe distance only in Scenario #6. However, OOWs and chiefs also do not keep this safety margin in all cases. In the case of OOWs, the required safety limit is not maintained when the TS is in the port side bow (Scenario #2) or starboard quarter sector (Scenario #7).

A greater course alteration (Manoeuvre #2) yields better results, nevertheless, in some scenarios, the required safety DCPA was also not maintained. This is once more the prerogative of pilots and captains, especially in restricted waters. In the case of open waters, OOWs, chiefs, and masters generally maintain a safe passing distance, except for Scenario #2, where TS approaches from the port bow. Surprisingly, in this scenario, less rudder deflection, like per Manoeuvre #1, results in a greater passing distance. This can be attributed to two reasons. Firstly, this particular scenario is very demanding, as evidenced by (Szlapczynski et al., 2018). Secondly, in the early phase of the turn, the OS moves counter to the desired direction. This affects the action's early phase more in case of larger rudder deflection.

In the case of maritime pilots, the safety distance was additionally not maintained when the TS is located in front of the bow and slightly to the port side (Scenario #3).

3.4.2. A comparison of generalised declarative arenas and Davis arena's impact on manoeuvre results

This section compares the generalised declarative arenas for restricted and open waters determined by a weighted geometric mean of all respondents, with the arena defined by (Davis et al., 1980), who introduced the term *arena*. Since Davis did not distinguish between different levels of maritime experience or between open and restricted waters when determining their arena; therefore, both generalised ship arenas presented in Section 3.4 were used to allow comparative analysis.

Table 5 presents the results of the determined DCPA values. The size of the Davis arena is roughly between the generalised arenas for restricted and open waters (see Fig. 12), despite Davis et al. originally specifying their arena for open waters. The reason for this may be the fact that over the last decades, there have been significant developments in the field of maritime transport and a notable shift in attitudes towards increasing maritime safety. However, the main difference is that for the Davis arena, the sector ahead of the beam is much larger than the one located abaft. This results in the DCPA values being larger for the Davis arena than for both generalised arenas where the TS is ahead of the OS (Scenarios #3 to #6).

Considering the pre-established DCPA threshold of 0.5 NM, certain conclusions can be drawn. With a generalised arena for restricted waters and a minor course alteration, the assumed safe passing distance is not maintained in any of the analysed scenarios. A more significant alteration in course, as exemplified by Manoeuvre #2, is also not sufficient in each case. This is evident when the TS is located on the port side bow

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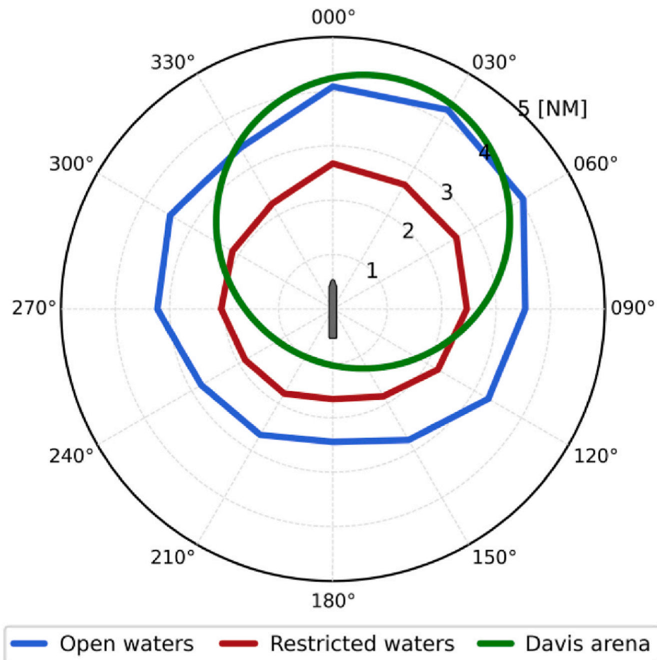

Fig. 12. Comparison of the Davis arena with the generalised arenas as identified by respondents.

sector, or behind the starboard beam of the OS.

Application of the generalised declarative arena for open waters leads to a larger DCPA (compared to Davis arena) in scenarios where the TS position is abaft or is approaching from port bow (Scenarios #1, #2, and #7). In the case of Scenarios #1 and #7, this can be explained by OS significantly moving back within the Davis arena, which leads to a smaller aft sector. In this case, a minor course change is not satisfactory when it comes to the Davis arena.

Moreover, the initial position of the TS on the port side bow (Scenario #2 and #3) results in a violation of the safe DCPA. This is the case for a slight course alteration for declarative arenas and the arena defined by Davis et al. In Scenario #2, even a more significant course alteration is insufficient.

4. Discussion

The present study determines the preferred distances for evasive manoeuvres under favourable conditions, considering navigational area type and seafarers' experience. It visualises and discusses preferences for all participants, differentiating by experience level and maritime license. In addition, a discussion can be made on the case study results to gain insight into the process of understanding and translating the preferred distance of the manoeuvre initiation into the corresponding distance at which the vessels eventually passed each other.

4.1. Findings

This study confirmed that, depending on sea experience, the envelopes of the determined declarative arenas vary between open and restricted waters to different extents. In general, a larger available room is expected in open than restricted waters due to the specificity of the navigational area. However, the study revealed that in confined waters, OOWs execute manoeuvres much closer than in open waters achieving quite similar results as senior officers. Some changes in the distances obtained from the COs' values can also be noted, especially in the starboard side bow sector, however, to a smaller extent than in OOWs. Seniors, understood herein as pilots and captains alter these distances least. It may be therefore concluded that open water arenas vary noticeably depending on the seafarer's experience, while arenas for restricted water are much more uniform and constricted.

Another observation is that pilots focus less on the TS location than the ship's regular crew when considering open waters. Their regular work may serve here as an explanation. Holders of other licences use more prudence with the TS located on the starboard side relative bearings, especially those ahead of the bow. Pilots assign more uncertainty to these bearings in confined waters than OOWs and masters, who assign similar levels regardless of TS bearing.

With increasing navigational experience, the distinction between the preferred distances for performing manoeuvres becomes less clear. Certain seagoing experience is sufficient for the confidence level to reach a stable state. The same observation applies to maritime licences. This is particularly apparent in open water.

When analysing the concordance between respondents with different levels of experience and licences, it is interesting to note that the most experienced pilots are the least concordant. The value of the geometric standard deviation is the highest in all the cases analysed, which indicates a large discrepancy and lack of consensus in their judgements. It should be noted that OOWs or COs, who are significantly less experienced than the sea pilots, seem to be more consistent in their judgements.

As evidenced by the case study, in numerous scenarios, the DCPA value arising from the specified preferred manoeuvre distance is considerably lower, with a value of less than 0.5 NM. This shows that it is challenging to determine the appropriate distance to commence a manoeuvre to ensure a safe passing distance. Thus, the timing of manoeuvring is often misinterpreted concerning the resulting passing distance between two ships. Surprisingly, the more experienced navigators tend to face greater difficulties in this regard. This may result from the change of their position and thus daily activities from operational to management level. Therefore, after all, despite the fact that they are seniors, they perform routine collision-avoidance actions less frequently because they perform typical navigational watches less often. Another reason may be attributed to the over-reliance on one's skills in the case of more experienced navigators and greater caution, or even anxiety, in encounter situations, in the case of less experienced OOWs.

In order to improve maritime safety, it is recommended that the following measures should be considered:

- DSS introduced on board should be more focused on the right moment of an evasive manoeuvre execution, so as a result of this indication, vessels will pass each other at a greater (safer) distance.
- The *trial manoeuvre* option, which is one of the basic Automatic Radar Plotting Aid (ARPA) features for collision avoidance, should be employed more frequently, as it is a simple but existing solution to gain the navigator's awareness about the translation of evasive manoeuvre distance into resulting passing distance. Therefore, it is recommended that greater emphasis be placed on radar training in the proper use of this option.
- Pilot cards and wheelhouse posters may be insufficient for a proper understanding of ship manoeuvre characteristics; thus, additional steps such as ship handling simulators with advanced ship motion models should be more extensively incorporated in the ship officers' training process.

4.2. Limitations

The main identified limitations of the study are related to both the research design and the experts' perceptions, together with typical cognitive biases. First and foremost, the survey was designed in such a way that the experts were forced to respond to a model ship, which was a Ro-Pax vessel. Although this information was clearly available together with the manoeuvring characteristics of the vessel and associated data (such as the pilot card), it is not known which types of vessels the navigators invited to the survey had served at sea. As a result, it could be

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difficult for the experts to discard their working habits on other types of vessels (and thus of different sizes or in companies with different safety bridge procedures). These work experiences, probably on other types of vessels, could have directly influenced the experts' answers. Therefore, survey findings may be biased to some extent by the differing understandings and behaviours of various navigators.

Although countermeasures such as the anonymisation of the survey were taken, the existence of other limitations must also be acknowledged. These include cognitive biases of the navigators involved in the study, which may have had a direct impact on the results and which are mainly related to so-called self-assessment and egocentric bias. Furthermore, as the survey focused on safety aspects, the respondents might portray themselves in a better light than they actually are by giving answers that represent their decisions or actions as safer than in their daily routine.

In order to develop a generalised arena, arbitrary weights were assigned with respect to the individual licences of the respondents. Nevertheless, the weights adopted, have only a relatively small impact on the numerical values without any significant effect on the shape of the arenas obtained, as well as the tendencies in the results indicated in the previous sections of the paper.

It is also necessary to emphasise the survey sample size of $n = 64$ responses. Considering the number of active seafarers with at least an OOW diploma, the number of responses collected in the survey cannot be considered statistically reliable. Nevertheless, it should be recognised that this is not such a small value that conclusions cannot be drawn from it, especially those regarding trends rather than exact numerical values. The statistical indicators showing the deviations of respondents' assessments, as well as the introduced weighting of the responses, were intended to partially reduce the impact of the small sample size, or at least shed more light on the disparities and uncertainties that exist due to this reason.

4.3. Future work

Future work on the topic of declarative ship arenas should focus on two main aspects, namely i) overcoming existing limitations, and ii) expanding the scope of the survey.

Regarding the first issue, it would be beneficial to redesign the survey, so that in the future information is collected on the type and size of ship on which a respondent has the most seafaring experience. In addition, the sample would need to be expanded, which would further increase the statistical reliability of the results obtained. Furthermore, this would facilitate a more comprehensive analysis of the distinctions in preferred distance preferences among navigators with varying degrees of experience in diverse contexts. Both measures should lead to a more consistent result by compiling a larger (and thus statistically more robust) number of responses. Furthermore, these responses would come from navigators working on the same type and size of the vessel, which should indicate similar behaviour in practice.

An extension of the survey, on the other hand, could aim to obtain responses not only to ship declarations in favourable conditions but also in more demanding situations, like in restricted visibility when according to the COLREGs there are no "*stand-on*" or "*give-way*". These scenarios could reflect situations in which the navigator's reaction time, the existing pressure, and the ship's environment are much more demanding thus yielding different results.

In future studies, it may be beneficial to compare the determined declarative arenas with others existing in the literature as an extension of the case study. The use of other literature arenas would also allow for expanding the simulation campaign and include additional scenarios from which more accurate data could be obtained. It is suggested that future research on declarative arenas determined under demanding conditions could benefit from an expansion of the set of evasive manoeuvres to better depict more challenging rudder deflections or different ranges of course alterations.

5. Conclusions

Firstly, the investigated the influence of the navigators' seafaring experience on the preferred distance of an evasive manoeuvre execution, thus manoeuvring space to be allocated for efficient collision avoidance (RQ1). The analysis showed that less experienced navigators were more cautious in both open and confined waters, extending ship's arena up to 5.5 NM. With increasing experience, individuals tended to feel more confident and, as a result, the envelope of the ship's arena became smaller and was characterised by a distance of more than 2 times less. Navigators generally reach a stable level of professional confidence after 10 years of seafaring experience, which remains constant thereafter.

Secondly, the perception of preferred distances with respect to different navigational areas was also compared (RQ2). The analysis indicated that envelopes of ship declarative arenas are smaller for restricted waters in each analysed case which met the authors' expectations. However, for captains and pilots, the change in the size of arenas between open and restricted waters was less noticeable compared to the more variable perspective of less experienced OOWs and COs. The available manoeuvring area affects all relative bearings equally, reducing or increasing the envelope by a fixed value which depends on the licence held.

The objective of the (RQ3) was to determine and analyse the generalised declarative ship arenas from the joint perspective of all navigators involved. It was observed that, in general, more attention was given to the target ship located on the starboard bow sector, where the arena extends to a distance of 4.3 NM, which may be related to COLREGs. The least caution was paid by the respondents to the target ship located astern, where declarative arena reached more than 1.5 times lower distances. This is understandable, as in practice this case is the least threatening, due to favourable regulations and the relative velocities of the ships.

Lastly, the simulation-based case study identified the actual distances at which ships will pass each other, depending on the preferred distances of manoeuvre initiations (RQ4). The results revealed that in certain encounter situations, especially within restricted waters, the distances assessed by the respondents may be insufficient to maintain relevant passing distance. The resulting DCPA in many cases are less than 0.5 NM, which can pose a real threat to the safety of navigation. This demonstrates the challenge of identifying the optimal timing for initiating an evasive action and translating the distance of manoeuvre execution into the resulting passing distance, even for those with extensive navigational experience. The simulation results for generalised arenas were additionally compared with the well-known ship arena defined by (Davis et al., 1980). This made it possible to conclude that the size of the Davis arena is roughly between the generalised arenas for restricted and open waters. Thus, in certain scenarios, the distance of the manoeuvre execution as defined by Davis arena is also not enough to maintain a safety buffer between encountering vessels.

The results of this study may be useful for researchers interested in maritime transportation safety and those investigating the impact of human operators on collision-avoidance decision-making. Maritime industry representatives and shipping companies may also take interest in the study's findings, particularly those working on the implementation of autonomous vessels, navigational Decision Support Systems, or seeking training inspirations for the crew members aimed at increasing the level of their awareness and safety.

CRediT authorship contribution statement

Filip Zarzycki: Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization. **Mateusz Gil:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation. **Jakub Montewka:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition,

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Conceptualization. **Rafał Szłapczyński:** Writing – original draft, Software, Methodology, Formal analysis. **Joanna Szłapczyńska:** Writing – original draft, Software, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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