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Accident susceptibility index for a passenger ship-a framework and case study

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ABSTRACT

The continuous monitoring and assessment of operational vulnerability and accident susceptibility of passenger ships is crucial from the perspective of ship and passenger safety. Despite the existing solutions for vulnerability monitoring, stemming mainly from watertight door operations, a comprehensive framework for accident susceptibility assessment and monitoring is missing in the literature.

Therefore, this paper offers a straightforward approach, utilizing heuristics rooted in the solid foundations of the first principles related to human performance. The proposed approach allows the evaluation of accident susceptibility of a ship in operation involved in open-sea and coastal navigation. The framework presented is based on observable and relevant factors, known to affect the navigator's performance, and as a consequence accident probability. The layout of the framework as well as the parameters of the developed model are based on literature survey in maritime and aviation domains, knowledge elicited from maritime experts and extensive simulations with the use of an in-house developed ship-ship encounter simulator. Subsequently, the model is applied to selected case studies, involving two distinctive ship types, namely a large cruise ship and a RoPax vessel.

The results obtained for the case study presented in this paper reveal that most of their time the analyzed ships operate with negligible accident susceptibility (87%), while 1% of the cases are labelled as very high accident susceptibility. The remaining share of 12% is distributed among low, moderate and high values of accident susceptibility. The results are in line with earlier studies conducted in the same area but adopting different methods.

The proposed solution can be applied as an onboard decision support tool, evaluating the operational accident susceptibility and vulnerability, thus increasing the crew's situational awareness. Additionally, it can be applied to historical data, allowing ship navigational safety diagnosis and implementation of appropriate countermeasures.

1. Introduction

In the design process of passenger and naval ships the effect of external impact on ship safety is determined by estimating (A) ship susceptibility to an accident or a hit and (B) ship's operational vulnerability to accident/hit. The former represents *the probability of an accident,* while the latter denotes *the probability of sinking or capsizing (for passenger ship) or a kill (for warship) given the accident,* [1,2].

In case of passenger ships, there exist solutions supporting bridge crew in continuous monitoring of the ship's vulnerability to flooding due to open watertight doors, often automatically activating decision support mode if flooding is detected, [3]. Therefore, they aim to increase the crew's awareness of the risks and safety of a ship, see for example [4–6]. A natural extension of such solutions would be a framework for operational assessment of flooding accident susceptibility for a passenger ship resulting from collision or grounding, accounting for relevant

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contributing accident factors. Continuous assessment of both ship vulnerability and susceptibility is an element of a dynamic safety barrier that tends to increase the crew's situational awareness and ship safety through safe operation of watertight doors, [7].

Ship susceptibility to an accident, in the literature often referred to as collision or grounding risk, is conventionally assessed with the use of various types of proximity indicators, which, if properly set-up and monitored, tend to ensure safe operations of ship during her mission, [8].

The most common proximity indicators used in day-to-day navigation are distance to the closest point of approach (CPA) and time to the closest point of approach (TCPA), [9–11]. Alternatively, the concept of ship's domain is applied, [12–19]. The overall goal of those indicators is to delineate a zone (in space, time, or both) a navigator feels comfortable within, and intends to steer clear from other objects to ensure safe passage of their own ship. To this end a navigator performs the necessary maneuvers, according to best practice and company regulations, [19–21]. However, the zone itself does not quantify accident susceptibility.

As an alternative, zone-based methods attempt to quantify the parameters resembling accident susceptibility for a ship in encounters in a probabilistic fashion, e.g. by fuzzy systems based on experts' judgment and big data analytics, [14,22–26]. For a recent review of the methods see for example [27]. However, these types of models are often based on preferences rather than evidence, [28,29]. These shortcomings can heavily mislead potential end-users, when the models are implemented as onboard solution, ultimately leading to underestimation of the accident susceptibility, see [13,30].

Qualitative, probabilistic methods can measure the risk of accident at sea by determining the potential accident-prone locations and associated frequencies of those accidents as well as adopting the above-mentioned proximity indicators. For a review of these methods see for example [31–34]. These methods are generally useful for strategic spatial risk assessment for waterways, [17]. However, they are of limited use for operational assessment of accident susceptibility in day-to-day navigation. This is because they do not sufficiently account for the factors known to govern the performance of a navigator in an encounter situation, such as the complexity and density of nearby traffic, proximity to shallow waters or environmental conditions, [35–37].

From the above it may be concluded that the literature lacks an intuitive, objective, evidence-based method evaluating the level of accident susceptibility for a given ship-ship encounter at sea. The main driving factor behind the accident susceptibility is the performance of a navigator, while professional literature advises that the human factor contribute to accidents at sea, [38] and the lower the navigator's performance, the higher the chances for an error, thus an accident, [35,39].

Navigator's performance is governed by a number of factors, one of those being mental workload, [40–42], which tends to increase with the complexity of the situation, [43–45]. The literature on the complexity of a situation in maritime domain remains scarce and the topic has not been studied in depth yet, see [33,46]. It occasionally appears in research work related to strategic risk assessment for waterways, [41,47,48], tactical conflict detection, [43] or operational risk assessment, [49]. Even then, the complexity is usually defined arbitrarily and taken as an explanatory variable in risk analysis without an in-depth analysis of the variable itself. Therefore, the factors determining the complexity and their effect on the latter remain unexplored.

In contrast, in aviation safety, research on this topic has been carried out more extensively, resulting in detailed evaluation of factors affecting encounter complexity and its effect on human performance, [45,50,51]. For in-depth literature review in this domain the reader is referred to [52]. Therefore, to close the knowledge gap in maritime domain, we combine the existing background knowledge from aviation with maritime experts' knowledge and the existing, however scarce, maritime literature. As a result, we found that the complexity of a navigational situation can be described by the following three factors: waterway complexity, traffic complexity and environment complexity, [37,49,53–57]. By quantifying the factors and combining them into a complexity index describing a given situation around a ship, one can assess how difficult it is for a navigator to cope with the situation, and, as a result, how susceptible the own ship is to an accident given the surrounding conditions. This in turn may help to define traffic situations and so the sea area, where the implementation of mitigation measures would be necessary to ensure safe operation of the ship, such as temporary increase of bridge manning or rerouting the ship.

In this paper we present a generic framework evaluating accident susceptibility index for ships carrying passengers, that is evidence-based, rooted in the first principles, offering indicators that are intuitive and straightforward to interpret by potential end-users (mariners or shore-based safety officers). The models presented are tailored for two types of ship and modes of navigation, namely large passenger and RoPax ships that can navigate in both ocean and coastal environment. The application of the proposed approach is demonstrated by several case studies. The obtained results show that the framework properly reflects the navigational situation. It may be used as an onboard solution for day-to-day navigation i.e. to complement existing onboard vulnerability evaluation tools. Additionally, it could be used to determine and evaluate accident susceptibility levels for a ship in the past, based on historical traffic data. This would allow tempo-spatial assessment of navigational safety leading to better accident risk mitigation and improving safety culture.

The paper is structured as follows: Section 3 introduces the overall concept of the framework, which is followed by the methods applied and data, as presented in Section 4. Section 5 presents case studies while the framework and the results are discussed in Section 6. Finally, Section 6 concludes.

2. Framework and definitions

2.1. Accident susceptibility index

The semi-qualitative framework adopted to assess accident susceptibility index, based on waterway and traffic complexity is presented in Table 1. The proposed framework is rooted in a commonly adopted idea of a risk-matrix, [58]. According to this approach, combining two complexity indices (waterway and traffic) results in the definition of an accident susceptibility index, as follows:

$$\mathrm{AS} = \mathrm{TC} + \mathrm{WwC} \tag{1}$$

Where AS refers to Accident Susceptibility, TC denotes Traffic Complexity and WwC stands for Waterways Complexity. The indices used to describe TC and WwC are expressed on a linear scale as depicted in Table 1. However, the non-uniform distances between the consecutive indices are assumed to account for the anticipated non-linearities in the governing mechanism behind the AS as depicted in Fig. 3. Ultimately, the AS indices are assigned to one of the following classes:

Negligible
Low
Moderate
High
Very high

Whereas for the purpose of AS assignment two sets of mapping functions are defined, based on the prevailing visibility conditions. For conditions of good visibility the following holds:

$$Set1 = \begin{cases} F1: ifASindex = (2,3), thenAS = Negligible \\ F2: ifASindex = (4,5), thenAS = Low \\ F3: ifASindex = (6,7), thenAS = Moderate \\ F4: ifASindex = (8,9,10), thenAS = High \\ F5: ifASindex = (12,14), thenAS = Veryhigh \end{cases}, \tag{2}$$

Table 1
A generic framework evaluating values of accident susceptibility index based on WwC and TC.

		Waterway complexity index - WwC				
		Negligible1	Low2	Moderate3	High5	Very high7
Traffic complexity index - TC	Negligible – **1**	2	3	4	6	8
	Low – **2**	3	4	5	7	9
	Moderate – **3**	4	5	6	8	10
	High – **5**	6	7	8	10	12
	Very high – **7**	8	9	10	12	14

While for restricted visibility the following set is defined:

$$Set2 = \begin{cases} F6: ifASindex = (2,3), thenAS = Negligible \\ F7: ifASindex = (4), thenAS = Low \\ F8: ifASindex = (5), thenAS = Moderate \\ F9: ifASindex = (6,7), thenAS = High \\ F10: ifASindex = (8,9,10,12,14), thenAS = Veryhigh \end{cases}, \quad (3)$$

For conditions of good visibility, as presented in Table 2, the highest value of accident susceptibility index is when a ship navigates through enclosed waters with shallow grounds within short range (waterway complexity is high or very high) and there is moderate to large number of demanding targets around the own ship (traffic complexity is high or very high). At the other end of the scale, a ship faces low accident susceptibility index when she sails through the open sea or remains within some distance from shallow waters while the number of encountering ships requiring attention from the navigator is low. For situations in-between susceptibility is assumed moderate to high.

For conditions of restricted visibility presented in Table 3, accident susceptibility index takes the highest values if a ship navigates through confined waters. This may be critical if the complexity of surrounding traffic is very high, or traffic of moderate complexity is associated with high or very high waterway complexity. Negligible accident susceptibility is associated with the conditions of open sea navigation with lack of surrounding ships or very limited traffic.

In either open seas or coastal navigation high value of accident susceptibility index is considered a situation to be avoided. This is because it leaves very little or no room for improvements in case of erroneous behavior of the own or target ships and therefore considerably increases the likelihood of an accident. In practice, the bridge crew is instructed not to allow such situations to develop. Moderate and high values of the index tend to reflect traffic conditions prevailing in heavily trafficked narrow passages, such as Dover Strait. On the other hand, low index value corresponds to regular open sea navigation with the presence of some target ships.

The logic behind the accident susceptibility framework presented in this paper is based on the results of extensive literature research, maritime experts' knowledge elicitation and simulation model, that are presented in subsequent sections.

2.2. Accident susceptibility framework

The framework presented attempts to evaluate accident susceptibility for a ship in operation in a semi-qualitative manner, based on human performance and underlying to this factors. The literature on

Table 2
Accident susceptibility index for conditions of good visibility (I – negligible, II – low, III – moderate, IV – high, V – very high), based on Table 3 and Eq. (2).

		Waterway complexity				
		Negligible	Low	Moderate	High	Very high
Traffic complexity	Negligible	I	I	II	III	IV
	Low	I	II	II	III	IV
	Moderate	II	II	III	IV	IV
	High	III	III	IV	IV	V
	Very high	IV	IV	IV	V	V

Table 3
Accident susceptibility index for conditions of restricted visibility (I – negligible, II – low, III – moderate, IV – high, V – very high), based on Table 3 and Eq. (3).

		Waterway complexity				
		Negligible	Low	Moderate	High	Very high
Traffic complexity	Negligible	I	I	II	IV	V
	Low	I	II	III	IV	V
	Moderate	IV	III	IV	V	V
	High	IV	IV	V	V	V
	Very high	V	V	V	V	V

Human Reliability Analysis (HRA) presents an inverse relation between human performance and accident probability [35,39]. Human performance is affected by the so called performance shaping factors (PSF). Two PSFs are considered in the accident susceptibility framework: a number of simultaneous tasks and available time [39,59,60]. Thus, safety in operations can be improved by ensuring appropriate level of performance throughout the whole analyzed process, for instance by safeguarding the operator from the factors deteriorating performance, or, alternatively, by exposing the operator to the conditions improving the performance.

The two PSFs - the number of simultaneous tasks and available time - influencing the performance of a navigator steering a ship, are governed by the following three distinctive characteristics of an encounter at sea: available maneuvering space with respect to navigable waters; number and types of encounters with objects on collision courses; hydro-meteorological conditions [43,45–47]. The higher number of control activities that need to be performed simultaneously, or in a short time span, and the smaller maneuvering space available for the ship, the higher is the workload. This in turn increases the probability of navigation errors and an accident happening. These chances are further amplified by the presence of unfavorable hydro-meteorological conditions, which require additional tasks, such as monitoring and adjusting the response of a ship to wind and wave action or anticipating the effect of those in the course of evasive maneuvers. The casual chain representing this link is depicted in Fig. 1.

For the purpose of the work presented here, the three distinctive characteristics of encounter situation affecting a navigator's workload and performance are referred to as complexities, related to waterway, traffic and environment. Complexity is defined as "*a measure of difficulty that a particular traffic situation will present to a navigator*", as adopted from [61].

By binding the three types of complexity together an accident susceptibility index is developed, as depicted in Fig. 2. Whereas the indices themselves are based on the input parameters that are to large extent quantitative (e.g. distance and time to navigable waters, proximity indices for collision situation, wave height), with few qualitative exemptions (visibility, availability of navigable waters, level of complexity with respect to the traffic situation). Since the literature supports the presence of compensatory strategies for increasing complexity through individual differences and cognitive strategies or quality of equipment [52], the proposed framework allows for those through adjustments of the parameters of complexity levels.

The developed framework is generic and addresses the conditions of

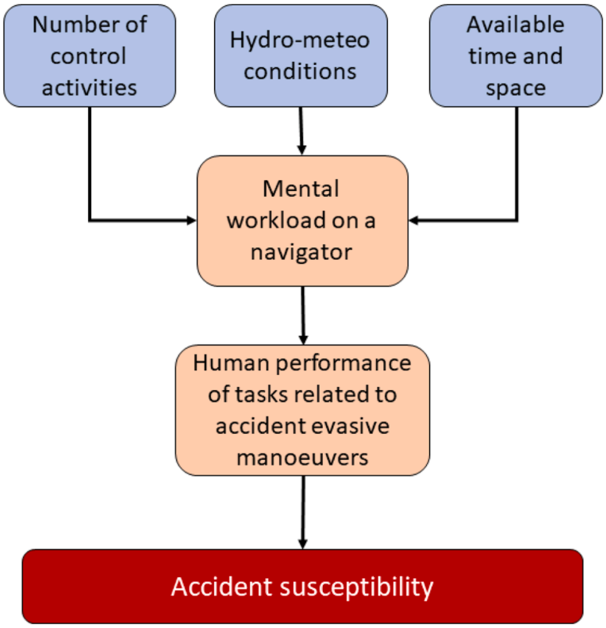

Fig. 1. A causal chain explaining the relation between PSFs, mental workload, human performance and accident susceptibility.

solo watch on the bridge. This means that one watch officer is in charge of navigating the ship. The officer is responsible for detection of the encounters, accident avoidance strategies development and execution, being assisted by a watchman in steering the ship. The framework covers the conditions of open sea and coastal navigation, while the pilotage is out of the scope.

However, the framework can be easily adjusted as well as expanded to account for additional factors and operational conditions that may be found relevant in a specific context, according to particular needs. The framework as presented is deterministic, nevertheless, by adopting other modeling techniques, it can be made probabilistic, thus accounting for the associated uncertainties.

The following sections provide a detailed description of all the elements of the framework, their interrelations and input parameters along with their sources.

2.3. Waterway, traffic and environment complexity indices

Human performance is driven, among other factors, by subjective mental workload, [35,39,50,55,62]. Nonetheless, the literature describes workload-performance relation in a complex manner [35,39]. In aviation, subjective mental workload of an air traffic controller can be modelled by an interesting pattern, as introduced in [44], which assumes that the workload increases as the flight mode develops from 'one-dimensional' i.e. straight flying mode through 'two-dimensional' to 'three-dimensional' flying i.e. climbing, descending and turning-mode. This approach can be used as a basis for the development of complexity index for maritime.

In [44] Lamoureux provides the above mentioned classification from the perspective of external, land-based air traffic controller. However, similar logic can be applied to an officer on bridge, who needs to handle situations of varying level of complexity in his/her daily routine [43]. Trivial situations may lead to boredom and underperformance. Up to a certain point, gradual increment of the complexity of a situation may have positive effects on a human operator, since allocating tasks according to the capacity of the operator may lead to optimal performance. However, when the complexity increases beyond the capacity of the operator, anxiety is likely to lead to a dramatic drop in performance and possibly resulting in an accident [63].

A theoretical presentation illustrating this principle is shown in Fig. 3, where the x-axis depicts increasing resource demands of a task, while the y-axis represents the level of physiological activation (right) and the resultant task performance (left).

The role of a navigator on a ship's bridge is to perform various tasks related to handling the ship safely. There are also other tasks, indirectly related to ship navigation, which can be disregarded in case of demanding navigation-related tasks. Quantifying the complexity of a navigational situation may help in managing the tasks, either by providing additional resources (another operator on the bridge) or decreasing the complexity to a level manageable by one person (choosing an alternative route for a ship).

The complexity of a situation varies with time and is driven by the

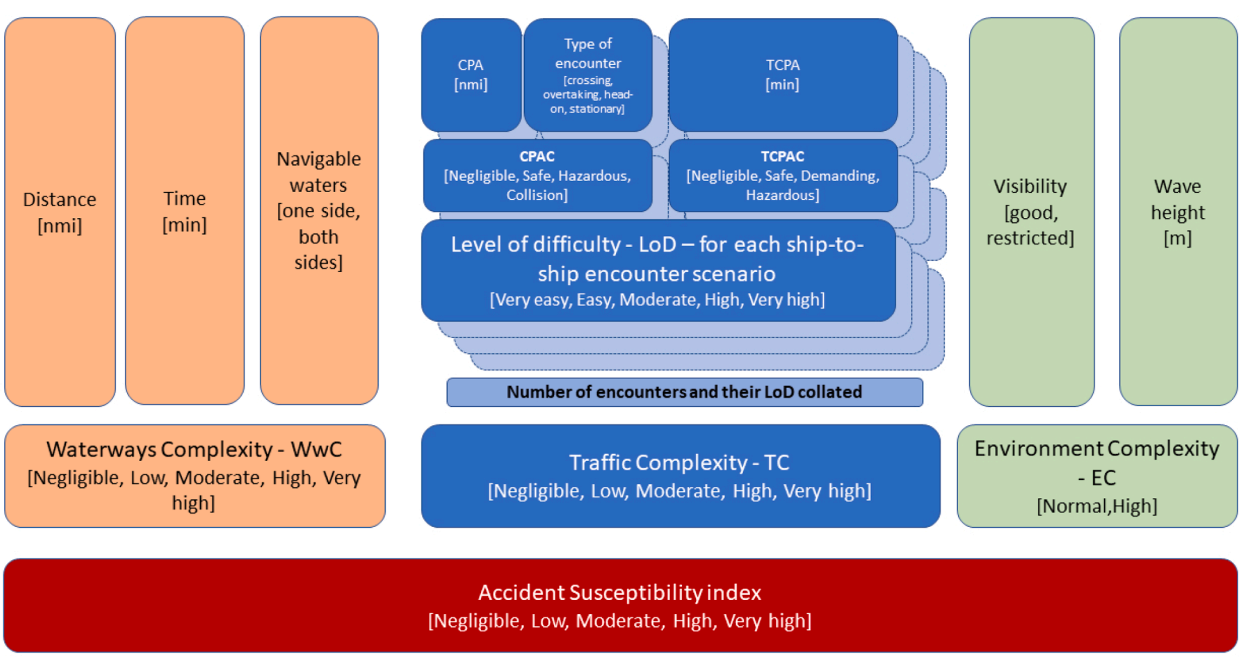

Fig. 2. Framework for accident susceptibility assessment for a ship in operation.

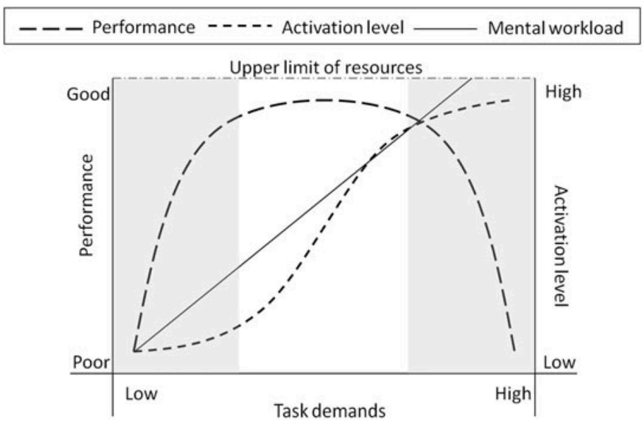

Fig. 3. The relationship between activation level, workload (task demands) and performance [63].

following elements, described in details below [45,47]: (1) waterway complexity, (2) traffic complexity, (3) environment complexity.

Waterway complexity (WwC) describes the mental workload exerted on a navigator by the need for monitoring a ship's track against bathymetry and adjusting her course and speed in proximity of shallow waters if needed. The time required to reach the shallow water is the main governing factor for WwC. Moreover, a distinction is made whether the water is restricted on one or both sides, since this limits the number and types of available evasive manoeuvers [49]. WwC reaches high values in a situation where a ship navigates through waters enclosed on both sides, with limited time for manoeuvers. It achieves moderate values when one side of the ship remains open, while it arrives at negligible value if the time to reach shallow water is long, giving large manoeuvering space for the ship.

Traffic complexity (TC) reflects the navigator's workload induced by the surrounding traffic, namely the type and number of encounters the operator needs to handle and the time available for the task. Four types of encounters are accounted for in this framework: crossing, head-on, overtaking and encounter with stationary object. For each type the classes of proximity indicators are defined. Type TC is defined by the following parameters:

1 the closest distance between two encountering ships (CPA),
2 the time to reach the closest distance from the present time instant (TCPA),
3 the number of target ships and combination of their proximity indicators (CPA,TCPA).

Traffic complexity determination is based on the number of target ships (that needs navigator's attention and action), and types of encounters contributing to the navigator's workload. To assess the TC of a surrounding traffic situation a proxy is defined and referred to as level of difficulty (LoD), which is assigned to each target ship. The LoD is determined based on target's CPA/TCPA combination in the following fashion: the easier the target to handle, namely the higher – CPA/TCPA – the longer the time available and/or the larger maneuvering space, thus the lower the level of difficulty (LoD). Additionally LoD may be dependent on the type of encounter, as presented in tables 4-5. For the purpose of this framework the LoD takes 5 stages, which are as follows: very easy, easy, moderate, high, very high. The classification is based on good seamanship, domain literature and expert's knowledge, as explained in Section 5. For example, very easy LoD is assigned to target ships that do not pose any collision threat or if there is risk of collision but the available time is long (>18′). Very high LoD is assigned to target ships which are less than 6′ away and significant course alteration is required. Cases in which large course alteration is needed but the time is sufficient or minor course alteration in short time is required are labelled with high LoD. Cases in between are labelled as easy or moderate. The number of targets to monitor and respond to along with their associated LoD will determine the difficulty for a navigator to handle a given navigational situation, thus allowing to quantify **the traffic complexity (TC)** of a given navigational situation. To this end the following generic heuristics are adopted, while the detailed parameterization of TC is given in Section 5.4.2:

1 **TC is negligible** if there is lack of or very few targets in vicinity, not posing collision threat (LoD – I);
2 **TC is low** if the targets in vicinity have LoD not higher than II.
3 **TC is moderate** if among all the targets there is a moderate number of targets at LoD III.
4 **TC is high** if a large number of targets is labelled with LoD III, and/or moderate number of targets is at LoD IV.
5 **TC is very high** in all the remaining situations (e.g. large number of targets to follow at LoD III or IV or 1+ target(s) at LoD V).

The presented logic is supported by the available literature from the aviation domain and the results of conducted knowledge elicitation among maritime experts (nautical officers and captains), as presented in Sections4.1 and 5.1.

Environment complexity (EC) attempts to describe the effect of relevant hydro-meteorological features on the mental workload of a navigator. The framework presented here accounts in a semi-qualitative manner for the anticipated effect of restricted visibility on the accident susceptibility index. This is mainly based on the recommendations of Cruise Ship Safety Forum [49], and the results of expert knowledge elicitation conducted in this work. The framework makes distinction between good and restricted visibility, by assigning accident susceptibility index accordingly. Another factor that may affect human performance, and, consequently, accident susceptibility, such as wave height is taken here as a constant thus not increasing the workload. This is acceptable as the ships taken as case studies here (passenger ship and RoPax) usually operate in favorable weather conditions [64]. For the case study presented here, conditions of good visibility are assumed. This is due to a lack of reliable tempo-spatial data on visibility. However, if the framework is to be employed on board ship, the actual visibility conditions can be used for instant and continuous evaluation of accident susceptibility. Aggregating all those factors into a framework and attributing them with parameters would allow for assigning numerical values to a given navigational situation, thus describing how susceptible to an accident a ship is. A flowchart presenting the process of accident susceptibility index assignment is shown in Fig. 4.

Table 4
Matrix evaluating levels of difficulty (I–V) for ship-ship encounters.

TCPA CPA	1-Negligible	2-Safe	3-Demanding	4- Hazardous
1-Negligible	LoD I	LoD I	LoD I	LoD I
2-Safe	LoD I	LoD II	LoD II	LoD II
3-Hazardous	LoD I	LoD II	LoD III	LoD IV
4-Collision	LoD I	LoD III	LoD IV	LoD V

Table 5
Levels of difficulty (I–V) for encountering stationary objects.

TCPAC CPAC	1-Negligible	2-Safe	3-Demanding	4- Hazardous
1-Negligible	LoD I	LoD I	LoD I	LoD I
2-Safe	LoD I	LoD II	LoD II	LoD II
3-Hazardous	LoD I	LoD II	LoD III	LoD III
4-Collision	LoD I	LoD III	LoD IV	LoD V

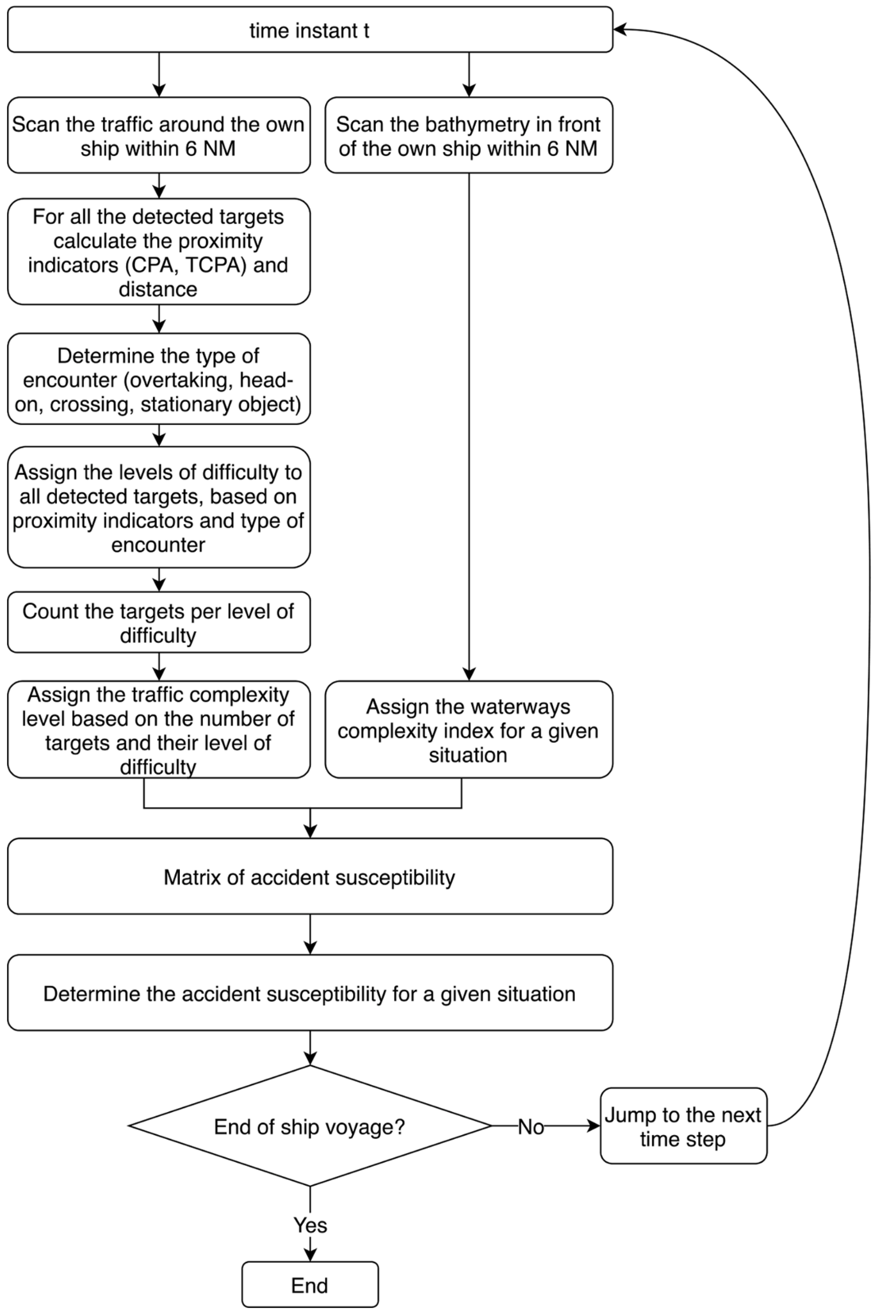

Fig. 4. Flowchart demonstrating process of accident susceptibility assessment.

3. Methods and data

3.1. Experts' knowledge elicitation

Experts' knowledge was elicited to: (1) obtain information on current practices related to avoiding collision and grounding accidents onboard large ships carrying passengers; (2) improve the understanding of the factors influencing the workload of a navigator; (3) estimate the parameters governing the accident susceptibility framework. For this purpose, an online questionnaire survey was performed, and 17 cruise ship operators and 16 RoPax operators were invited to contribute.

The survey was carried out anonymously in the spring of 2020. The link to the survey was first sent to the crew department of several companies running cruise ships and RoPax, and was subsequently forwarded to the relevant personnel working on board. Basic information about the ship type involved in the survey as well as the distribution of ranks of respondents is depicted in Fig. 5. The majority of the respondents for RoPax ships are officers and captains. For cruise ships these are staff captain and superintendents. The questionnaire covered the following questions:

1 What are the different navigational statuses used on your ship?
2 What are the conditions affecting the complexity of navigation in a given operation?
3 Does the complexity of navigation influence the bridge manning If so, how?
4 Is there a sea state (for example significant wave height) that raises navigation status to the highest?
5 In the cases of CPA&TCPA what are the adopted safe limits?
6 What is the minimum accepted CPA/TCPA for your vessel depending on the factors?

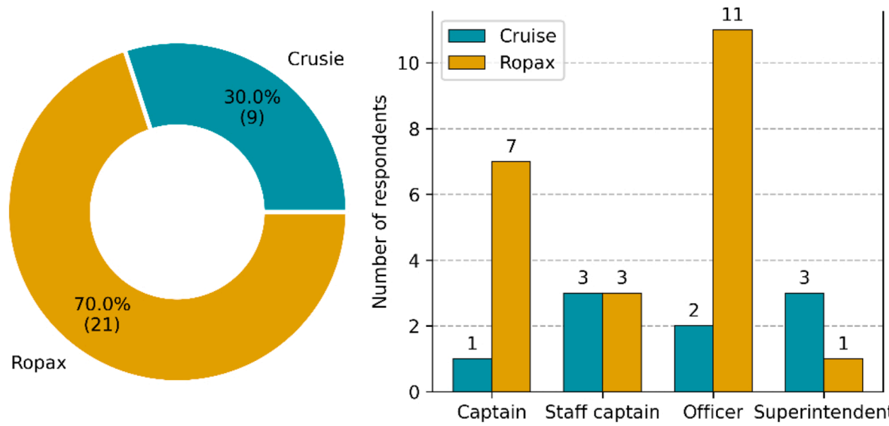

Fig. 5. Type of ship and position of the respondents.

7 How many target-ships a navigator typically handles simultaneously in heavy traffic areas?
8 Are there any limits for shallow water or distance to the shore?

Among eight only one was a multiple choice question (Q1), while the remaining were open questions (Q2-Q8). The obtained written responses were analysed, appropriate classes were developed and the answers were classified accordingly. For example, in case of Q2 whenever a respondent mentioned traffic (i.e. *traffic, volume of traffic, traffic density, heavy traffic, very intense maritime traffic, close quarters situations*) such answer was classified as "Traffic". A class named "Weather" was developed based on answers containing the following words: *rough weather, bad weather, windy conditions, heavy weather, wind, sea state*. A class named "Visibility" encompasses the following answers: *visibility, bad visibility, reduced visibility*. The "Distance to shore" class was developed based on the following answers: *narrow channels, proximity to hazards, ship's draft, close to land and hazards*.

Answers to all the questions were handled in a similar manner.

3.2. Encounter simulation model

An encounter simulation model has been used to derive the limiting values for input parameters for traffic complexity, such as TCPA. To this end, we utilized the concept of *Collision Avoidance Dynamic Critical Area* (CADCA), evaluated for a given type of the own ship. CADCA is a required maneuvering zone which surrounds the own ship in a close-encounter situation and delimits positions of the last-minute maneuver. Thus, the CADCA is based on a critical navigational scenario, which indicates the last moment when the execution of an evasive maneuver is still possible [65–67]. Based on CADCA and the speed of encountering ships, the time available to perform a safe evasive manoeuver can be derived.

To obtain CADCA, an in-house encounter simulator has been developed and used in a wide range of scenarios for given operational parameters of the ship model selected [68]. The CADCA concept is based on the geometrical approach and ship motion physics, as an advanced 6DoF motion model called LaiDyn is used as the simulator input data [69,70],. Therefore, the CADCA changes its shape accordingly to the operational (and environmental) conditions, as ship trajectories vary for different simulation scenarios [71].

To provide a high accuracy indicator for collision resolution, an extensive number of simulations was conducted for each mutual position of the objects (see Fig. 6). The simulation begins when a single projection of the ship's hull (enlarged by the safety margin) virtually moves backward from each initial position. Afterward, the trajectory for a given scenario is overlaid, while the own ship proceeds accordingly. The sequence is repeated for as long as the first position where the effective execution of the evasive maneuver is determined. The distance

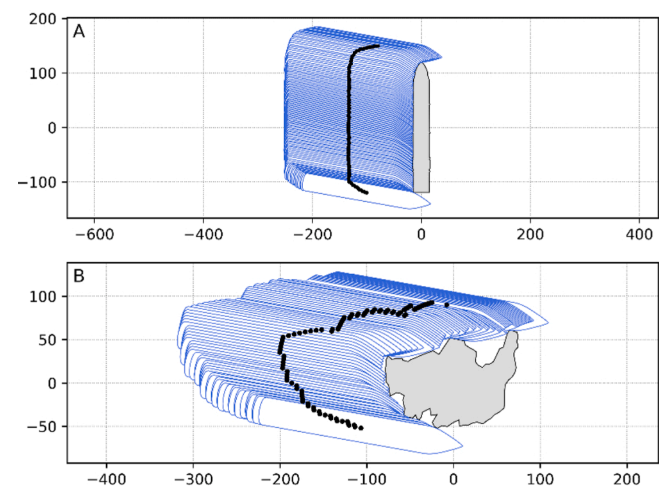

Fig. 6. The initial positioning of ship hull projections at the beginning of the simulation for a single heading, the obstacles are coloured in gray.

(MDTC – *Minimum Distance to Collision*) between the own ship and target ship is calculated along with the bearing. The simulation process is realized for all possible initial ship headings. This method of maneuvering area determination allows for conducting simulations covering all possible angular combinations and it ultimately depicts even irregular shapes of the target.

Assuming the worst navigational case, the final envelope of the CADCA is presented as a geometrical superposition created from the critical areas delivered for each ship heading. Finally, the critical area is enlarged using a convex envelope in order to approximate its irregular shape into the polygonal one, include uncertainties, and adopt a proactive approach to safety. For further information regarding the CADCA determination please refer to [68].

3.3. Traffic and ships data

It is indispensable to test the proposed framework data on maritime traffic and navigable waters. To this end, historical data obtained from Automated Identification System (AIS) was used, covering the year 2019 for the case of representative large passenger ships – m/s Mein Schiff 6, and 8 months of 2019 for large RoPax – m/s Finnstar. The cruise ship represents an average size cruise ship which operates in various different sea areas during the studied period. The RoPax is a typical ship of this type for the Baltic Sea, operating on a fixed route across the Baltic Sea, connecting two harbours Helsinki-Vuosaari in Finland and Lübeck-Travemünde in Germany. These ships are depicted in Figs. 7 and 8, along

Gross tonnage:	98 811
Length over all	295.26 m
Beam:	36.2 m
Design draft:	8.25 m
Passengers:	2 534
Crew:	1 030

Fig. 7. Studied cruise ship Mein Schiff 6 and her main parameters **https://vesselregister.dnvgl.com/VesselRegister/vesseldetails.html?vesselid=34,556

Gross tonnage:	45 923
Length over all:	218.77 m
Beam:	30.50 m
Design draft:	7.10 m
Passengers:	554

Fig. 8. Studied RoPax ship Finnstar* and her main parameters ***https://www.vesselfinder.com/pl/vessels/FINNSTAR-IMO-9,319,442-MMSI-230,981,000 **https://www.finnlines.com/freight/ms-finnstar.

with the main particulars of the ships.

The AIS data comes from NAPA Fleet Intelligence, which incorporates AIS data from several vendors. Data for year 2019 originated from Vesseltracker[1] and contains global ship positions, headings and speeds, among other information. Time resolution of the AIS datapoints is approximately 3 min.

Altogether, there were 64,446 AIS datapoints for the Mein Schiff 6, while the ship has operated world-wide and has wide global coverage. However, there are gaps in the AIS data over some sea areas, which can be seen as straight black lines connecting the AIS points, (see Fig. 9).

For Finnstar the geographical coverage area is smaller, since the ship navigates within Baltic Sea only, between Helsinki-Vuosaari (Finland) and Lübeck-Travemünde (Germany). Thus, the gaps in the data are much narrower. In practice, whole journeys of the ships are recorded without significant loss of information. Altogether, there were 375 373 datapoints for Finnstar and sourrounding target ships for the analysis.

The continuous flow of AIS datapoints was split into separate voyages by applying NAPA Port and Terminal database. The database makes use of public port and terminal data, the “United Nations Code for Trade and Transport Locations” (UN/LOCODE) data plus information on past ship movements from AIS data and other sources of information, containing roughly 80,000 locations globally. Ship position and AIS data were split into voyages by identifying ship departure and arrival times. These events are triggered when the ship is within 10 NM of a port location and has been stationary for one hour, i.e. the average speed has been less than 1 m/s.

To delineate navigable waters, and thus estimate the waterway complexity, bathymetry data was obtained from the **Ge**neral **B**athymetric **C**hart of the **O**ceans (GEBCO) database,[2] which is a global terrain model for ocean and land, providing information on a grid with spatial resolution of 30 as. i.e. 0.5 Nautical Miles (926 m) at the equator.

3.4. Traffic data processing for traffic complexity

In the presented analyses two ships, m/s Mein Schiff 6 and m/s Finnstar are labelled as “own ship” and the other ships within the same area are called “target ships”. In case of m/s Mein Schiff 6 there are over 100,000 datapoints describing the trajectories of the own ship and target ships. To enable the processing of such large dataset, in the first step, a spatial and temporal bounding box was set with respect to the own ship. Therein all ships within 0.5° of latitude and longitude from the own ship location were included. Since AIS datapoints of target ships were recorded at different time instances than the own ship AIS datapoint, the temporal limits to the bounding box needed to be applied. Therefore, the target datapoints that are obtained within 1 min (+/- 1 min) from the own ship datapoint time-label were included.

In the second step, the haversine method was used to calculate the distance from own ship to each potential target ship, and only ships within 10 nautical miles from the own ship are included as targets. For these targets TCPA (Time to the Closest Point of Approach) is calculated. Negative value of TCPA represents an encounter situation, where the Closest Point of Approach has already been reached and the target is moving away from the own ship. Thus, all targets with negative TCPA are excluded. For ships with positive TCPA, DCPA (Distance at the Closest Point of Approach) was also calculated.

Traffic data processing is essential when the proposed framework is used to analyze the past trajectories, since the proximity indicators need to be calculated for the same time instances. However, when the framework is applied in an on-line mode, when the accident susceptibility is calculated instantly, the indices can be easily calculated on the same time-scale. Thus, there is no need for the traffic data processing as described above.

Each encounter with a target ship was firstly labelled into one of the following encounter types:

[1] https://www.vesseltracker.com
[2] https://www.gebco.net

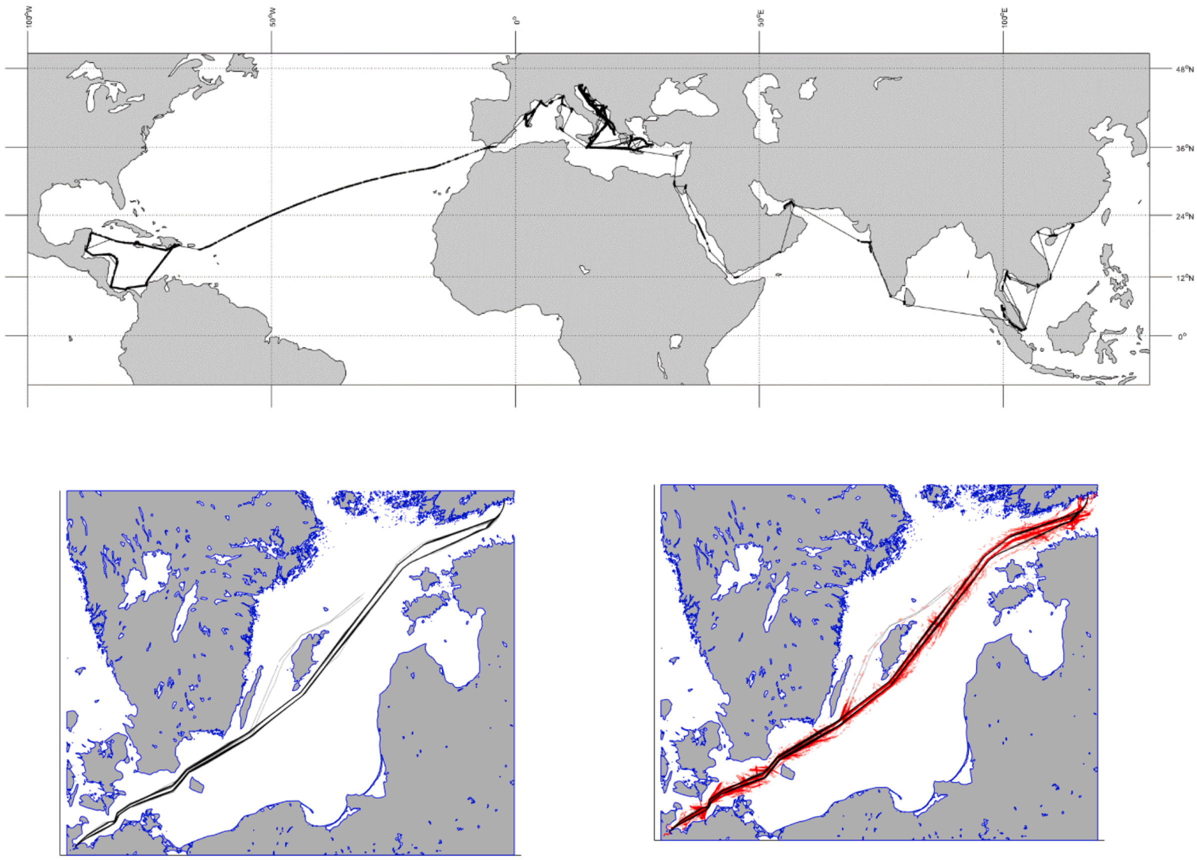

Fig. 9. Visualization of the datapoints used for the analysis. In upper pane – m/s Mein Schiff 6 AIS datapoints (black dots) during year 2019, connected by lines. In lower pane m/s Finnstar datapoints in black and target ships datapoints in red (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

- passing stationary objects is when the speed of the target ship is less than 0.5kn,
- crossing is when the difference between own ship and target ship heading is between |10| and |170| degrees,
- overtaking and head-on encounter is when the difference in headings is between 0 and |10| degrees or |170| and |180| degrees.

3.5. Bathymetry data processing for waterway complexity

The waterway complexity (WwC) was calculated based on ship location, speed, heading and bottom bathymetry. Bottom bathymetry, as obtained from GEBCO database, is represented as grid points having resolution of 30 arc-seconds. i.e. 0.5 Nautical Miles (926 m) at the equator. Shallow ground indicates that a point in the grid has smaller depth than the ship draft including required under keel clearance, i.e. 20% of ship draft or at least 2 m, [72]. The studied ship, m/s Mein Schiff 6, has 8.25 m as the design draft, thus 2.0 m under keel clearance is considered, and all points with depth smaller than 10.25 m are defined as shallow water. For m/s Finnstar the shallow water was defined as areas of depth less than 9.1 m.

Possible shallow water is searched at 10 NM radius around the ship. However, as the bathymetry grid has fixed latitude and longitude intervals, first the bathymetry grid inside *a* +/−20 min (∼0.67°) bounding box around ship's position is extracted. This bounding box contains 6 400 depth points. Thus, data was extracted at each ship position, leading to over 60 000 ship position datapoints for year 2019. The distance from the ship position to each depth datapoint with depth less than 10.25 m was calculated by applying the haversine formula.[3] Also, the bearing to each point was calculated. Shallow ground points with distance greater than 10 nautical miles from the ship and points on stern sector (115 to 180 deg from bow on both sides) were filtered out. Then the closest shallow water point on each side of the ship, starboard (SB) sector 0 to 115 deg from bow, and portside (PS) sector 0 to −115 degs from bow, were sought. Distances to closest shallow water point on starboard and portside sectors were used to define the waterway complexity, as presented in the following section. The time of fly to the closest point was obtained by dividing distance to the closest point by ship speed, regardless of her heading.

In the following section the framework for accident susceptibility will be applied over a wide dataset describing maritime traffic, evaluating the accident susceptibility index for selected case studies.

4. Parameters of accident susceptibility model and case study

This section introduces the parameters and the resulting model for accident susceptibility assessment suitable for ships carrying passengers, namely cruise ship and a RoPax ship. Additionally, the section presents the case-studies and obtained results in the form of time series of accident susceptibility index for a given voyage, as well as locations over sea areas that feature the highest accident susceptibility index (aka *hot spots*).

[3] https://en.wikipedia.org/wiki/Haversine_formula

4.1. Experts' knowledge-based parameters

A summary of the responses received for the 8 questions introduced in Section 4.1 is presented graphically in the Figs. 10–14. The information received allows a better understanding of the conditions under which the two analyzed ships operate. Additionally, the experts' knowledge elicitation allowed naming and quantifying the factors contributing to the traffic, waterways and environmental complexity.

From Fig. 10 it becomes evident that the dominating navigational status of the analyzed ships is "at sea", followed by "limited visibility", while encountering heavy traffic is also noteworthy. For the cruise ship the situation is a bit different, with the distribution of different navigational statuses close to uniform, without any predominating status.

As per Q2 "*What are the conditions affecting the complexity of navigation in a given operation?*", the majority of respondents indicated traffic, followed by the environmental conditions and distance to the shore, as depicted in Fig. 11.

As per Q3 "*Does the complexity of navigation influence the bridge manning?",* all the responses were positive, stating that the bridge manning is increased in complex situations. While the majority of respondents indicated the complexity of traffic and visibility as the main driving factors for the increased bridge manning, few respondents mentioned narrow waters.

When answering Q4 "*Is there a sea state (for example significant wave height) that raises navigation status to the highest?*", slightly over one-third of respondents claimed that such limiting value does not exists, while almost half of the respondents were of the opposite opinion, with a majority of those pointing to wave height of 4 and 5 m – Fig. 12.

As per Q5 "*In the cases of CPA&TCPA what are the adopted safe limits?*" – CPA of 1 nautical mile prevails in the responses, assuming the target passing ahead of own ship. However, higher values are also noted, while a few responses claimed safe CPA of 0.5 nautical mile, see Fig. 13.

With reference to Q6 about the minimum accepted CPA/TCPA, the respondents made distinction between open sea and restricted waters as well as crossing and overtaking types of encounters. In case of the open sea and crossing, the minimum CPA was claimed to fall between 0.5 and 1 nautical mile, while in case of overtaking the limit was indicated at 0.2–0.5 nautical mile. In case of restricted waters, this parameter was believed to be within the range of 0.1–0.25 nautical mile. Additionally, the respondents claimed, that in case of reduced visibility CPA/TCPA will be increased, depending on type of vessel and area.

Responses collected with regard to Q7 "*How many target-ships a navigator typically handles simultaneously in heavy traffic areas?*" indicated two peak values, one around 5–6 targets and another at 9–10, while two respondents allow for 11 and 12 targets, as depicted in Fig. 14. Following the commentary provided by the respondents, it became evident that the first peak corresponds to an average number of targets a navigator can follow, while the other peak denotes the maximum number of targets that can be followed simultaneously by an operator.

Answers given to Q8 on the navigable sea depth revealed that the prevailing minimal under keel clearance is around 2 m for the ship types considered, which roughly corresponds to 20% of ship's draft.

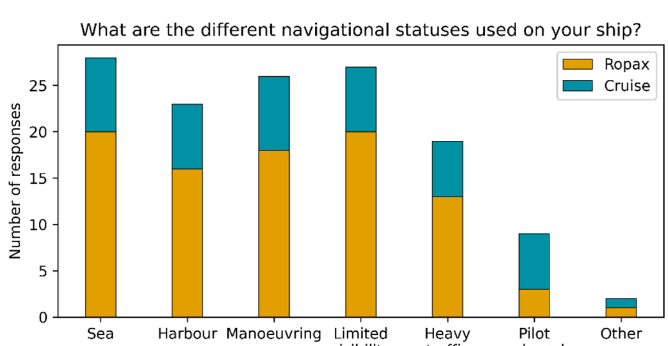

Fig. 10. Answers to Q1- breakdown of various navigational statuses used onboard the analyzed ships.

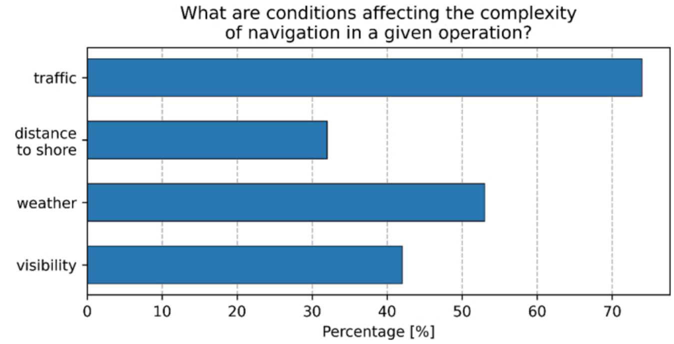

Fig. 11. Summary of answers to Q2-conditions affecting the complexity of navigation in a given operation.

4.2. CADCA-driven parameters

In the proposed framework, the CADCA was employed to determine the lowest TCPA threshold allowing for accident evasive action in all types of waterway/traffic complexity scenarios. Assuming that vessels proceed with a constant velocity at the beginning of an encounter, the minimum distance between the ships at which they can still perform a successful collision avoiding action can be translated into the time necessary for the execution of a last-minute maneuver.

The CADCA may be obtained for a specific type of ship, while for the purpose of this study, the models of two concept passenger vessels were selected, namely D-Ropax of Napa Ltd and Floodstand-B cruise ship (see Table 6 for particulars). These two aim to represent the m/s Finnstar and m/s Mein Schiff 6 respectively.

The CADCAs presented in Fig. 15 depict the time required for effective execution of a last-minute maneuver for D-Ropax (blue) and Floodstand-B (red). Two encounter types were considered i.e. with stationary (Fig. 15a), as well as moving obstacles (Fig. 15b). In the simulations each model of the vessels was utilized both as the own ship and as the target.

In each case, the last-minute maneuver was executed by setting the rudder hard to starboard side (+35°) at 20 kts. As the critical navigational scenario is considered, it has been assumed that the target ship stays passive, thus maintaining her course and speed (20 kts). The planned alteration of the own ship's course is 30° or 360°, depending on the angular arrangement resulting from ship headings and positions. This distinction was made to keep the parameter of simulated maneuvers as close to professional practice as possible and to avoid unusual solutions.

As presented, the required area (and, as a result, also time) in the encounters with stationary obstacles is significantly smaller than for moving targets. Eventually, in the accident susceptibility framework, the encounters are labeled as the most dangerous both for waterway complexity and traffic complexity when the TCPA is less or equal to 6 min.

4.3. Waterway complexity parameters

The main parameter for waterway complexity is the presence of shallow water, whether on both sides of the ship or on one side. The criteria for waterway complexity levels are listed below and visualized with color codes as depicted in Table 7.

1 **Negligible** when ship operates in deep water and there is no need to consider under keel clearance when planning collision evasive maneuver (the closest obstacle is more than 6NM or 40 min) [74].

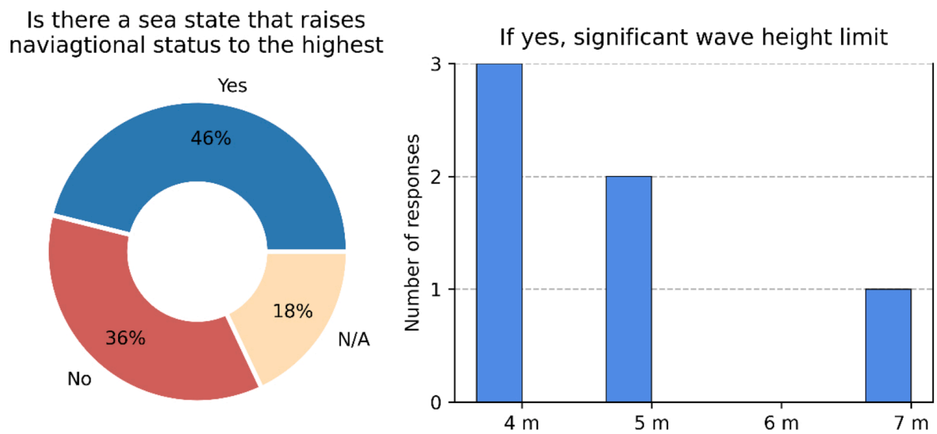

Fig. 12. Summary of answers to Q4-sea states rising the navigational status to the highest.

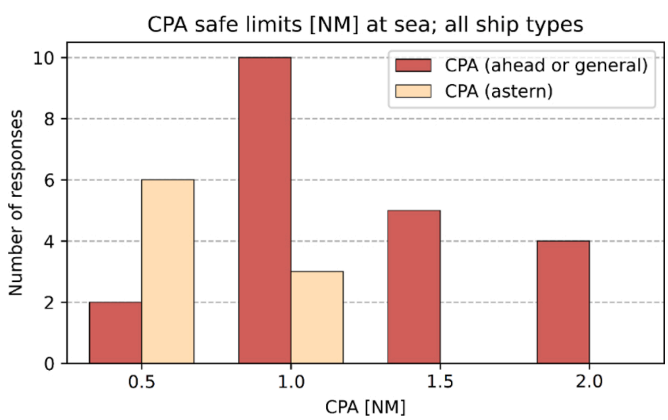

Fig. 13. Summary of answers to Q5-adopted safe CPA limits.

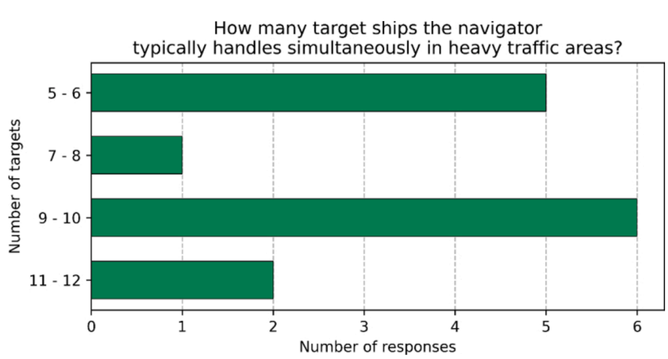

Fig. 14. Summary of answers to Q7-number of targets that navigator typically handles in heavy traffic areas.

Table 6
The particulars of the ship models selected, as given in [73],.

Name	Type	L_{OA} [m]	B [m]	T [m]
Floodstand-B	Cruise ship	238.0	32.2	8.8
NAPA D-Ropax	Ro-ro passenger / ferry	219.2	30.0	7.2

2 **Low** when any obstacle is between 3 and 6NM or 20 and 40 min forward of both beams, [49].
3 **Moderate** when grounding line of fixed obstructions are between 2 and 3NM or 10–20 min of one beam and open sea forward of the other beam, [49].
4 **High** when grounding line or fixed obstructions are between 1 and 3NM or 6–20 min forward of both beams, [49], or between 1 and 3 NM or 6–10 mins of one beam.
5 **Very high** – when grounding line or fixed obstructions are less than 1NM or 6 min, which is set with the use of simulator-based experiments and the concept of the CADCA [67,68],.

4.4. *Traffic complexity parameters*

Traffic complexity index is determined based on the proximity indicators, number of targets and their level of difficulty, as presented in Section 3.2. Whereas, this chapter serves the following:

- parametrization of the proximity indicators adopted for the case study presented in the subsequent sections;
- provision of the detailed guidance on target aggregation procedure as per their level of difficulty.

4.4.1. *Estimation of proximity indicators*

The proximity indicators are defined for the following four types of encounters:

- crossing,
- head-on,
- overtaking,
- encounter with stationary objects.

Crossing type of encounter is defined as a situation where the difference in headings of encountering ships falls within the range of ⟨10–170deg⟩. The following classes for TCPA (TCPAC) and CPA (CPAC) are defined, (Ożoga and Montewka 2018):

TCPAC

1 **Negligible** - TCPA>18 min. In this state there is enough time to evaluate, plan and execute necessary collision avoidance maneuver.

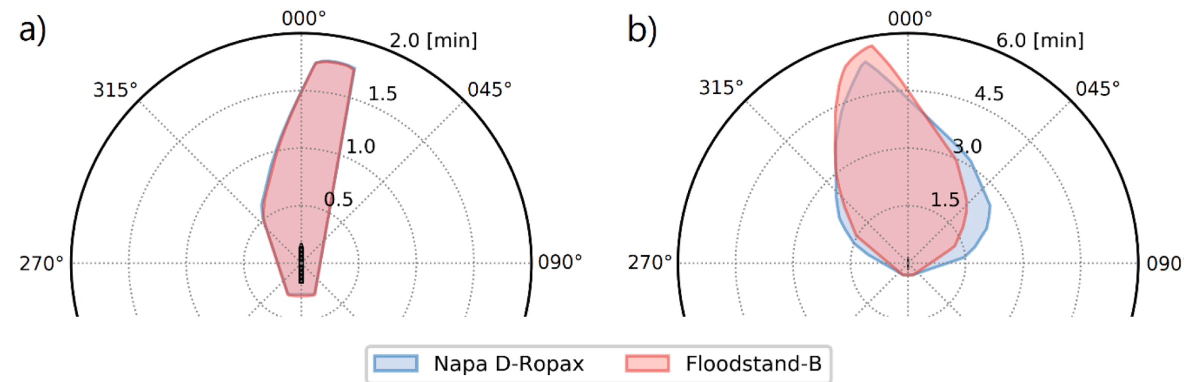

Fig. 15. The CADCAs calculated for two ship models and two types of encounters presented as time to the last-minute maneuver (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

Table 7
Waterway Complexity criteria based on distance and time to shallow waters.

Distance / Time	Shallow waters on one side	Shallow waters on both sides
over 6 NM / over 40 min	Negligible	Negligible
(3–6] NM / (20–40] min	Low	Low
(2–3] NM / (10–20] min	Moderate	High
(1–2] NM / (6–10] min	High	High
[0–1] NM / [0–6] min	Very High	Very High

2 **Safe** (action initiation) - 18 min ≥ TCPA > 12 min. In this state either of the ships (i.e. own or target) should execute a safe maneuver, if necessary. Such a maneuver is known as Comfortable Limit Manoeuvre – CLM. It is a maneuver known to a navigator and does not compromise the safety of the ship or her cargo. The lower limit of TCPA for this state is the less time required to perform CLM, [75].
3 **Demanding** - 12 min ≥ TCPA > 6 min. During this state, in case of collision risk, the navigator must make a decision and execute a maneuver appropriate for a given situation. However, due to time limitations, and ship maneuverability demands, in certain encounters, especially those requiring large course alteration, it is not feasible to perform CLM. Thus, more aggressive action needs to be taken.
4 **Hazardous** – TCPA ≤ 6 min. It represents an interval in which an own ship is not able to avoid the risk of a collision with a target by executing the last-chance maneuver (LCM). However, it does not exclude the possibility of avoiding such a collision following cooperation of the ships involved in the encounter. This value is based on CADCA, as explained in Section 5.2.

CPAC

1 **Negligible** - CPA>1.5NM, CSSF [49].
2 **Safe** - 1.5NM≥CPA>1 NM. This state assumes no direct hazards of collision. The margin for unexpected maneuver of a target, leading to collision encounter, is assumed large [76].
3 **Hazardous** - 1 NM≥CPA>0.5 NM. This state assumes a potentially hazardous encounter, due to small margin for unexpected maneuver of a target and significant influence of errors stemming from CPA calculations [76,77].
4 **Collision** - 0.5 NM≥CPA. Such situation must be avoided due to short distances between encountering ships. Small CPA and TCPA indicate very limited maneuvering space which is tantamount to collision for large ships, like the ones analyzed here [78–80].

The classes of proximity indicators (CPAC and TCPAC) for crossing type of encounters can be summarized as follows:

$$CPAC=\begin{cases} 1 if CPA > 1.5NM \\ 2 if 1.5NM \geq CPA > 1NM \\ 3 if 1NM \geq CPA > 0.5NM \\ 4 if 0.5NM \geq CPA \end{cases} \quad TCPAC=\begin{cases} 1 if TCPA > 18min \\ 2 if 18min \geq TCPA > 12min \\ 3 if 12min \geq TCPA > 6min \\ 4 if 6min \geq TCPA \end{cases} \tag{4}$$

Overtaking and head-on types of encounters describe situations, where two ships are on parallel courses or close to it. **Overtaking** is a situation where the difference in headings of the two meeting ships falls within the ⟨0–10deg⟩ range, while the range for **head-on** yields (170–180 deg). For overtaking and head-on encounters, the TCPAC is defined as for a crossing encounter. However, CPAC is determined as follows, mostly based on expert's judgment as presented in Section 5.1 and our earlier works (Ożoga and Montewka 2018):

1 **Negligible**, CPA>1 NM.
2 **Safe**, 0.5NM≥CPA>1 NM.
3 **Hazardous**, 0.5NM≥CPA>0.1 NM.
4 **Collision**, 0.1 NM≥CPA.

The summary of classes of proximity indicators suitable for parallel types of encounters takes the following form:

$$CPAC=\begin{cases} 1 if CPA > 1NM \\ 2 if 1NM \geq CPA > 0.5NM \\ 3 if 0.5NM \geq CPA > 0.1NM \\ 4 if 0.1NM \geq CPA \end{cases} \quad TCPAC=\begin{cases} 1 if TCPA > 18min \\ 2 if 18min \geq TCPA > 12min \\ 3 if 12min \geq TCPA > 6min \\ 4 if 6min \geq TCPA \end{cases} \tag{5}$$

Stationary object encounter scenario assumes any floating or fixed offshore structure or a ship operating with a speed lower than 0.5 kn The TCPAC, as a measure of time available for performing a collision evasive maneuver is defined similarly to that for a crossing encounter. However, the CPAC informs about the shortest anticipated distance between the own ship and the target in the course of encounter, and is defined based on expert's judgment and literature review, as follows [81,82]:

1 **Negligible**, CPA>1 NM.
2 **Safe**, 0.5NM≥CPA>1 NM.
3 **Hazardous**, 0.5NM≥CPA>0.3 NM.
4 **Collision**, 0.3NM≥CPA**.** This state corresponds to the safe zone of offshore installations, which equals 500 m.

The classes of proximity indicators for encounter with stationary object can be summarized as follows:

4.4.2. *Traffic complexity evaluation based on target aggregation*

Traffic complexity levels are defined based on the numbers of targets to follow and their corresponding levels of difficulty, as introduced in Section 3.1. The number of targets to follow by a navigator, without increasing the workload significantly is found to be five, as elicited from the experts – see Section 5.1. The number of target ships between 5 and 10 is expected to generate an additional workload, whereas if the number of simultaneous targets to follow is more than 10, it is assumed difficult to manage by a single officer on watch, as indicated by the

$$CPAC = \left\{ \begin{array}{c} 1 if CPA > 1NM \\ 2 if 1NM \geq CPA > 0.5NM \\ 3 if 0.5NM \geq CPA > 0.3NM \\ 4 if 0.3NM \geq CPA \end{array} \right. \quad TCPAC = \left\{ \begin{array}{c} 1 if TCPA > 18min \\ 2 if 18min \geq TCPA > 12min \\ 3 if 12min \geq TCPA > 6min \\ 4 if 6min \geq TCPA \end{array} \right. \tag{6}$$

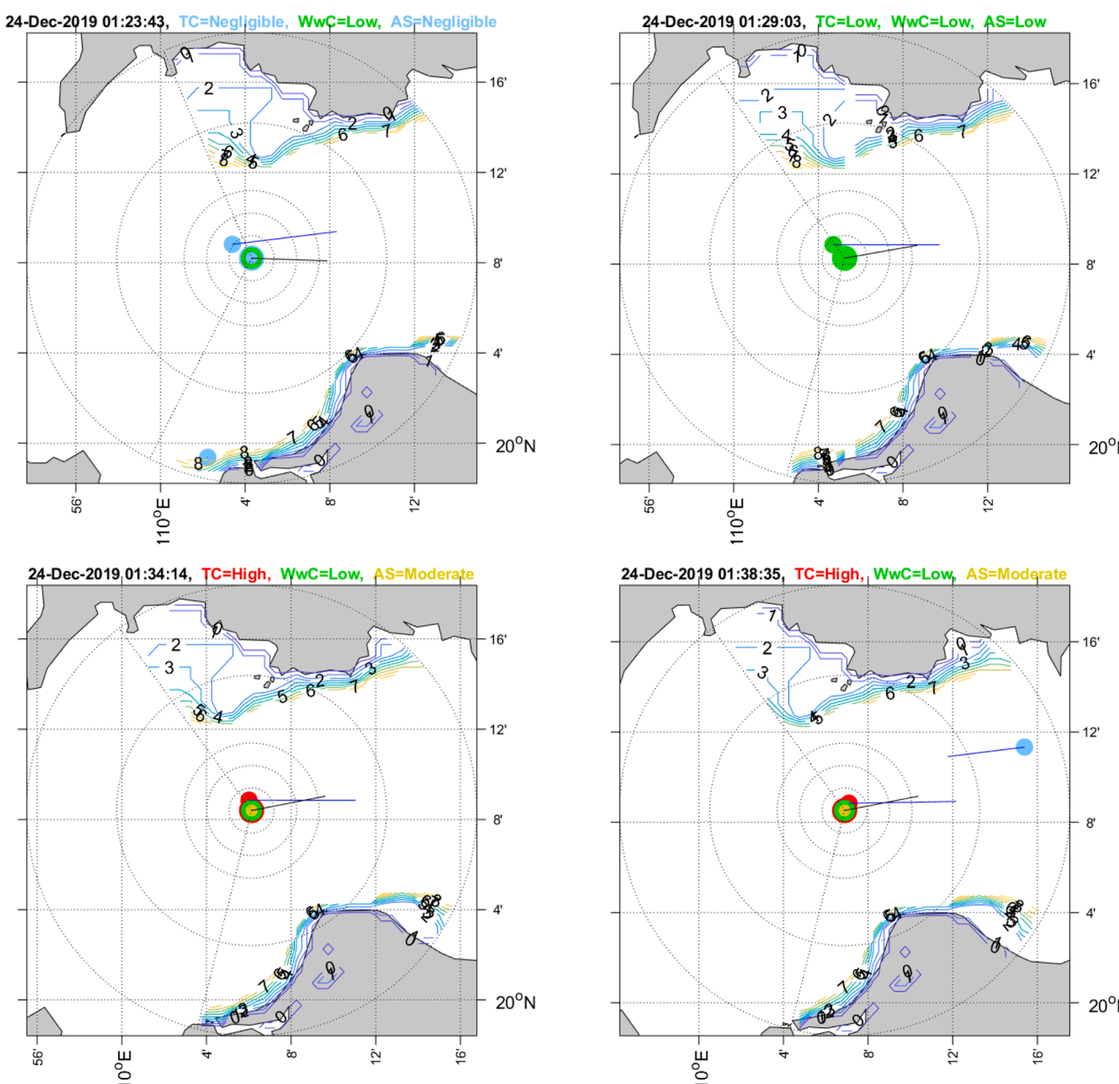

Fig. 16. Target ship overtakes own ship. Traffic Complexity develops from Negligible to High. The following color code is applied: blue – negligible; green – low; yellow – moderate; red – high; black – very high. Target ships are marked according to the level of difficulty of the encounter. The own ship is marked with concentric circles, where the inner one denotes accident susceptibility, the middle one labels waterway complexity and the outer circle stands for traffic complexity (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

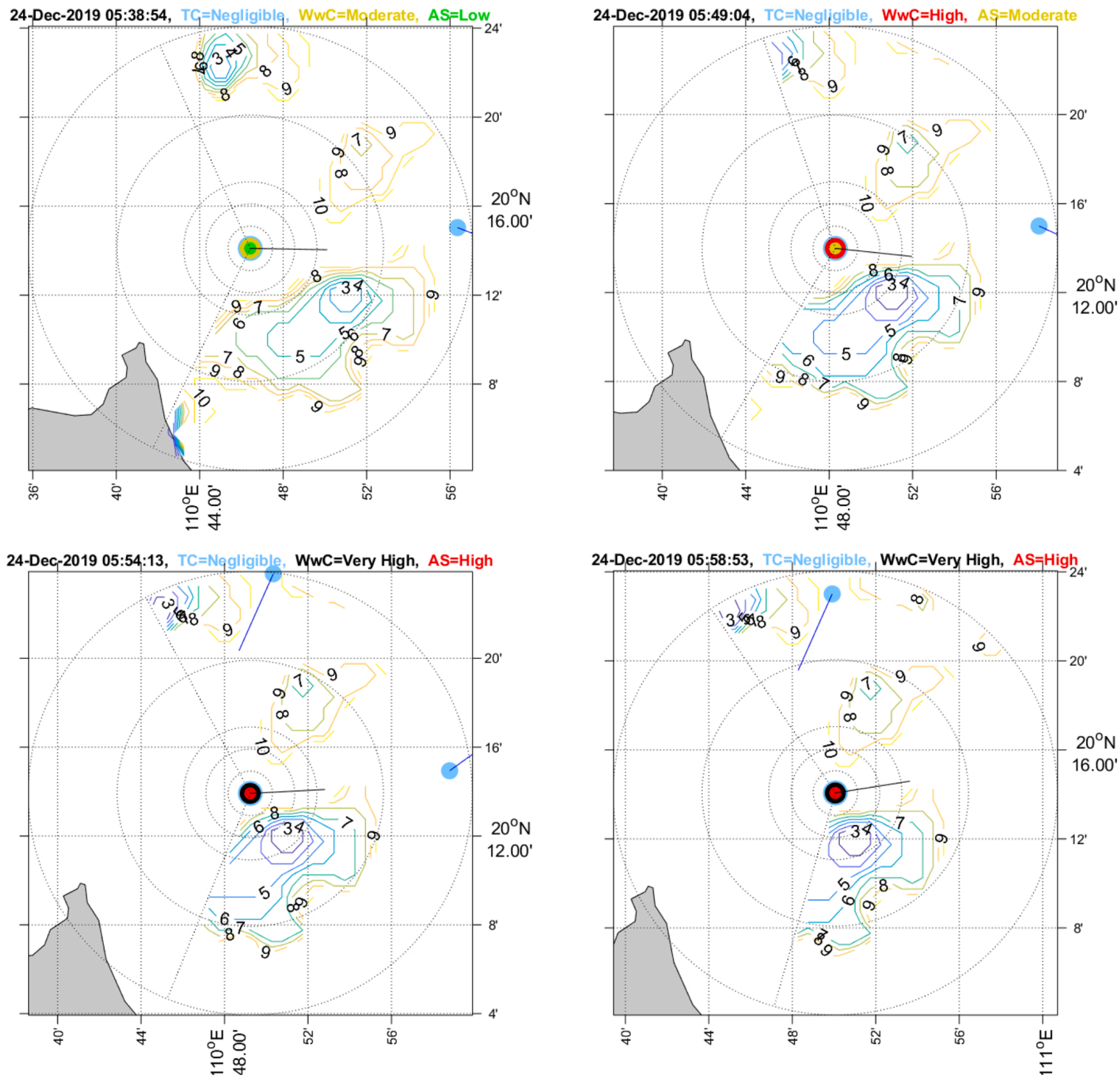

Fig. 17. Own ship navigates close to shallow water. Waterway Complexity develops from Moderate (shallow ground on starboard between 2 and 3 NM and on portside over 3NM) to Very High (shallow ground closer than 1NM away) (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

results of research in aviation [45], and supported by the findings from the online survey, as depicted in Fig. 14. This is tantamount to a situation where the likelihood of operator underperformance becomes unacceptable.

Thus, **traffic complexity (TC)**, which tends to reflect the navigator's workload induced by the surrounding traffic, is obtained by adopting the following logic, accounting for the number of the encountering targets and their corresponding **levels of difficulty** (**LoD**):

1 **TC is Negligible** if there is a lack of targets or the targets are not posing collision threat (LoD - I).
2 **TC is Low** if the targets in the vicinity are labelled with LoD II.
3 **TC is Moderate** if among all the targets there are 1–5 targets at LoD III.
4 **TC is High** if there are 5–10 targets at LoD III, and/or 1–5 targets at LoD IV.
5 **TC is Very high** in all the remaining situations, e.g. there is a large number of targets to follow (>10) at LoD III or IV or 1+ target(s) at LoD V.

4.5. *Case study*

This section demonstrates the implementation of the accident susceptibility framework over the selected case studies, involving a large cruise ship or a RoPax vessel, as introduced in Section 4.

The recorded and analyzed AIS data describe the normal and safe operations of ships and the intention of these case studies is to investigate what accident susceptibility levels occur in normal operation of passenger ships. In case of a cruise ship, which is involved in world-wide navigation, the selected voyages of 2019 cover heavy traffic waters, such as approaches to Singapore, Hong Kong or Rijeka (Croatia).

Whereas in case of a RoPax, operating on a fixed route on the Baltic Sea between Finnish and German harbours, selected days of 2019 are presented, where the whole voyage between two ports of Lübeck-Travemünde and Helsinki-Vuosaari is recorded and analysed with respect to accident susceptibility index.

4.5.1. *Large cruise ship*

Voyage from Vietnam to Hong Kong. Situations depicted in Figs. 16 and 17 reflect snap shots from a voyage from Vietnam to Hong Kong when the ship passes through heavily trafficked Qiongzhou Straight, with

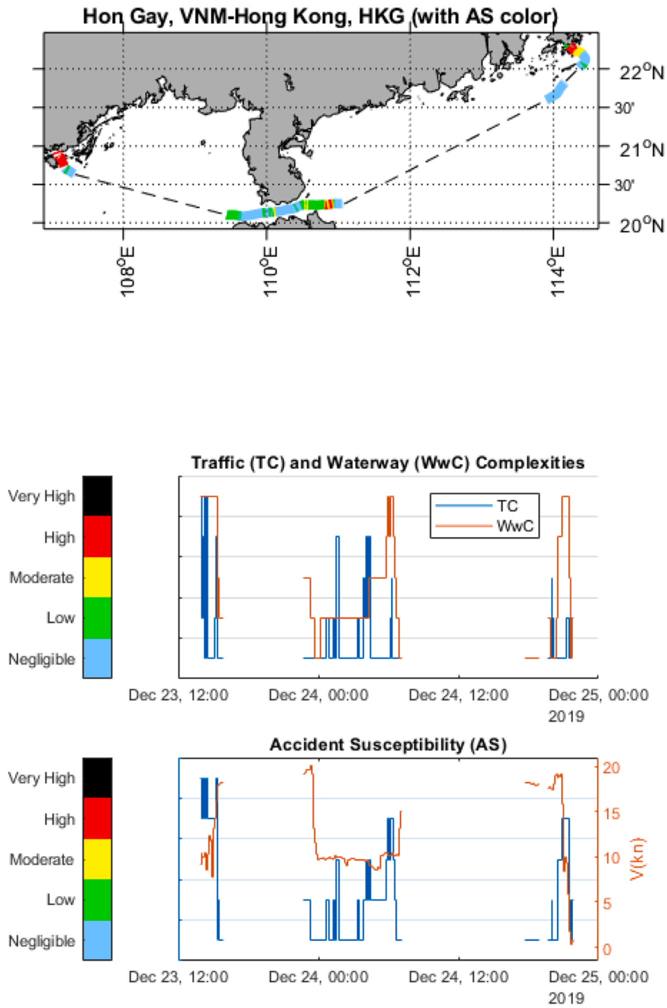

Fig. 18. Voyage from Vietnam to Hong Kong: the upper image shows the track of the voyage with colors indicating the Accident Susceptibility, the dashed line shows a gap in the AIS data longer that 40 min. Below, two time histories show Traffic and Waterway Complexities and Accident Susceptibility Index. In the time history of AIS also the ship speed is shown. No values are shown for gaps in AIS data.

various types of encounters and ship types.

Fig. 16 presents a situation, where the own ship is overtaken by another ship, traffic complexity developing from negligible to high and shallow ground within 3 to 6 NM from the ship, waterway complexity thus being low. The own ship is in the middle of the images with surrounding 1,2,3,6, and 10 NM radii drawn on dashed lines. All other ships are marked as circles with velocity vector indicating position after 20 min if the ship continued at the same speed and heading.

Target ship color shows the *Level of difficulty* of the encounter with the given ship. Own ship is marked with concentric circles, where the outer circle indicates TC; the middle one denoting WwC, while the inner circle represents accident susceptibility index. The development of WwC index from moderate to very high is shown in Fig. 17. The following color code is applied:

- Blue – Negligible,
- Green – Low,
- Yellow – Moderate,
- Red – High,
- Black – Very High.

Fig. 18 illustrates the entire voyage of the ship from Vietnam to Hong Kong. There are two long gaps in the data during the voyage. However, both the departure and the arrival, as well as the part of the voyage through Qiongzhou Straight have good AIS data coverage.

The accident susceptibility index becomes high and very high at the departure, upon arrival harbor and in the strait. It is mostly due to land proximity and crossing traffic.

Voyage from Rijeka to Trieste. The second example is a short voyage from Rijeka (Croatia) to Trieste (Italy) with very good AIS data coverage. After the departure from Rijeka waterway complexity is high, but since traffic complexity is mainly low or negligible, the accident susceptibility index remains moderate. During the voyage in the Adriatic, the accident susceptibility index is negligible. However, on arrival at Trieste it increases to very high for a short period of time. This increase is caused both by traffic and the presence of shallow waters. At the same time, the velocity is decreased, and a pilot embarks the ship. Example images from the voyage are shown in Fig. 19 and the route and time histories are presented in Fig. 20.

Arrival to Singapore. The third example is voyage from Malaysia to Singapore, with focus on the arrival to a very busy port of Singapore, as

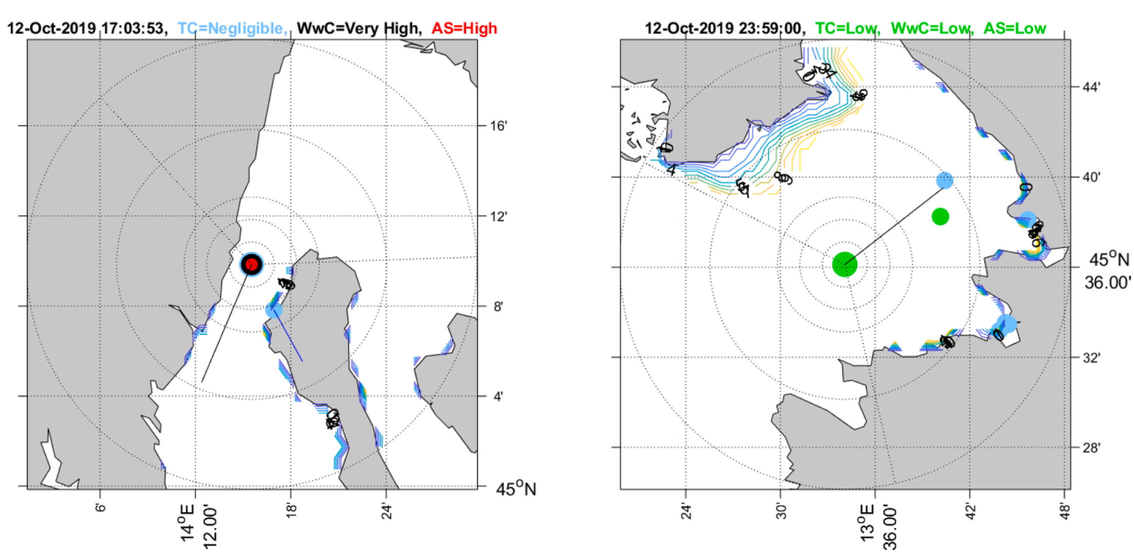

Fig. 19. Images on departure from Rijeka (left) and arrival to Trieste (right).

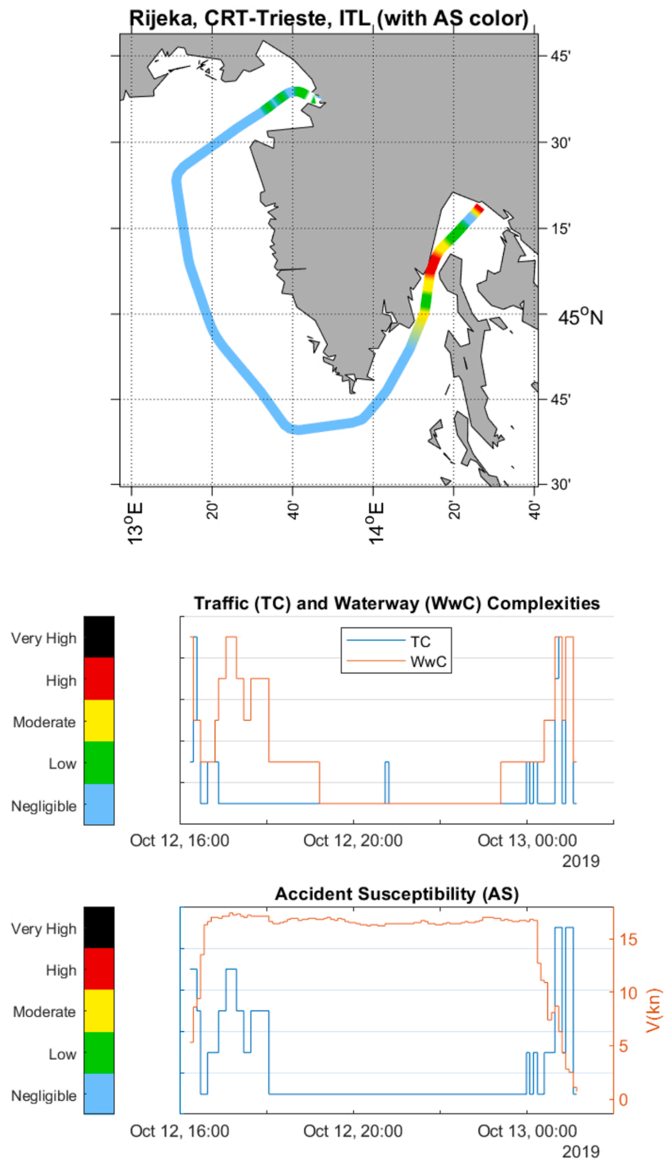

Fig. 20. Voyage from Rijeka to Trieste: the upper image shows the track of the voyage with colors indicating Accident Potential, the dashed line shows a gap in the AIS data longer that 40 min. Below, two time histories show Traffic and Waterway Complexities and Accident Susceptibility Index. In the time history of ASI also the ship speed is shown. No values are shown for gaps in AIS data.

depicted in Fig. 21. Therein a great number of anchored ships and parallel, oncoming, and crossing traffic is shown. The whole voyage is presented in Fig. 22, along with time histories for traffic and waterway complexity and accident potential. Due to dense traffic and the presence of shallow water upon approach to Singapore, the accident susceptibility index remains very high for long periods of time.

4.5.2. RoPax ship

The analyzed RoPax ship steams through the Baltic Sea between two ports: Helsinki-Vuosaari in Finland and Lubeck-Travemunde in Germany. The single voyage takes about 28 h. In this section, two distinctive voyages are depicted and accident susceptibility index is analyzed. One voyage represents winter season and the other is for summer season. Moreover, the results of aggregation of the 145 voyages carried out by the RoPax in 2019 are depicted and heat maps showing the accident susceptibility index for the ship in the Baltic Sea are presented.

Voyage 1-winter season. Fig. 23, upper pane, bottom-left corner, depicts the trip that took place on 6 and 7th of January 2019, where the ship departed from Lubeck-Travemunde in Germany and sailed towards Helsinki-Vuosaari in Finland (Fig. 23, upper pane, top-right corner). The departure and arrival locations feature high to very high waterway and traffic complexity. Additionally, there are several locations along the route facing high traffic complexity, especially in the areas of crossing or merging traffic lanes. Beside those points, the accident susceptibility index remains negligible for most of the sailing times.

On the other hand, in Fig. 24 the highest accident susceptibility is shown for the departure of the ship from Helsinki-Vuosaari including navigation along the coastal fairway through shallow waters and cutting through dense inbound traffic to Helsinki. In contrast, the further stage of voyage, taking place within the traffic separation scheme, features negligible accident susceptibility due to organized parallel traffic, not posing significant threat to the RoPax ship.

Voyage 2-summer season. The voyage lasted from 13th and 14th of June 2019, in the middle of the summer season in the Baltic Sea, as depicted in Fig. 25. Therein, the areas featuring high and very high accident susceptibility indices correspond to those defined for the winter-time voyage as depicted in Fig. 23. However, it becomes evident that the summer voyage creates additional challenges to the ship, since the number of locations where she faces high accident susceptibility index is higher, compared to wintertime voyage. This can be explained by intense summer traffic of passenger ships between southern Sweden and Bornholm Island, as well as some other destinations in the area, however detailed explanation would need in-depth case-by-case investigation, which remains out of the scope of this study.

Aggregation of multiple voyages. Finally, all the voyages of RoPax in 2019 are aggregated, and heat maps for accident susceptibility levels are presented in Fig. 26, while the distribution of the calculated levels is depicted in Fig. 27. Data presented in Fig. 26 clearly shows that very high accident susceptibility is associated mainly with the departure and arrival areas, due to proximity of shallow waters and the presence of merging, as well as crossing traffic, accounting for less than 1% of total cases recorded, as depicted in Fig. 27. Such high level of accident susceptibility index has not been recorded for the ship in the high seas, for which, however, there exist certain sea areas where accident potential is high, and those are due to complex merging or crossing as well as dense traffic. This level of index takes 4% of the total number of recorded cases. The moderate level takes a 3% share in the total and is distributed along the route. It is mainly driven by to passing distance to other targets navigating on parallel course along the traffic separation systems existing in the analyzed area. At the same time, cases labelled with low level of accident susceptibility index take 5% of the total. The remaining 87% is taken by negligible accident susceptibility level. It is worth emphasizing that the distribution of the accident susceptibility indices is similar to the results obtained for the same area, adopting a different, less intuitive but more sophisticated and costly method, as presented in [83–85].

However, the aggregated information on the accident susceptibility indices does not account for plausible seasonal variation. This would require further analysis, which is beyond the scope of this work.

5. Discussion

The presented framework for accident susceptibility assessment for a ship in operation attempts to integrate relevant factors affecting mental workload of a navigator onboard a ship that may negatively influence the navigator's performance, increasing the probability of a vessel being involved in an accident – collision or grounding. To perform such integration, domain knowledge from human reliability analysis, aviation and maritime safety is utilized. To this end, we performed extensive

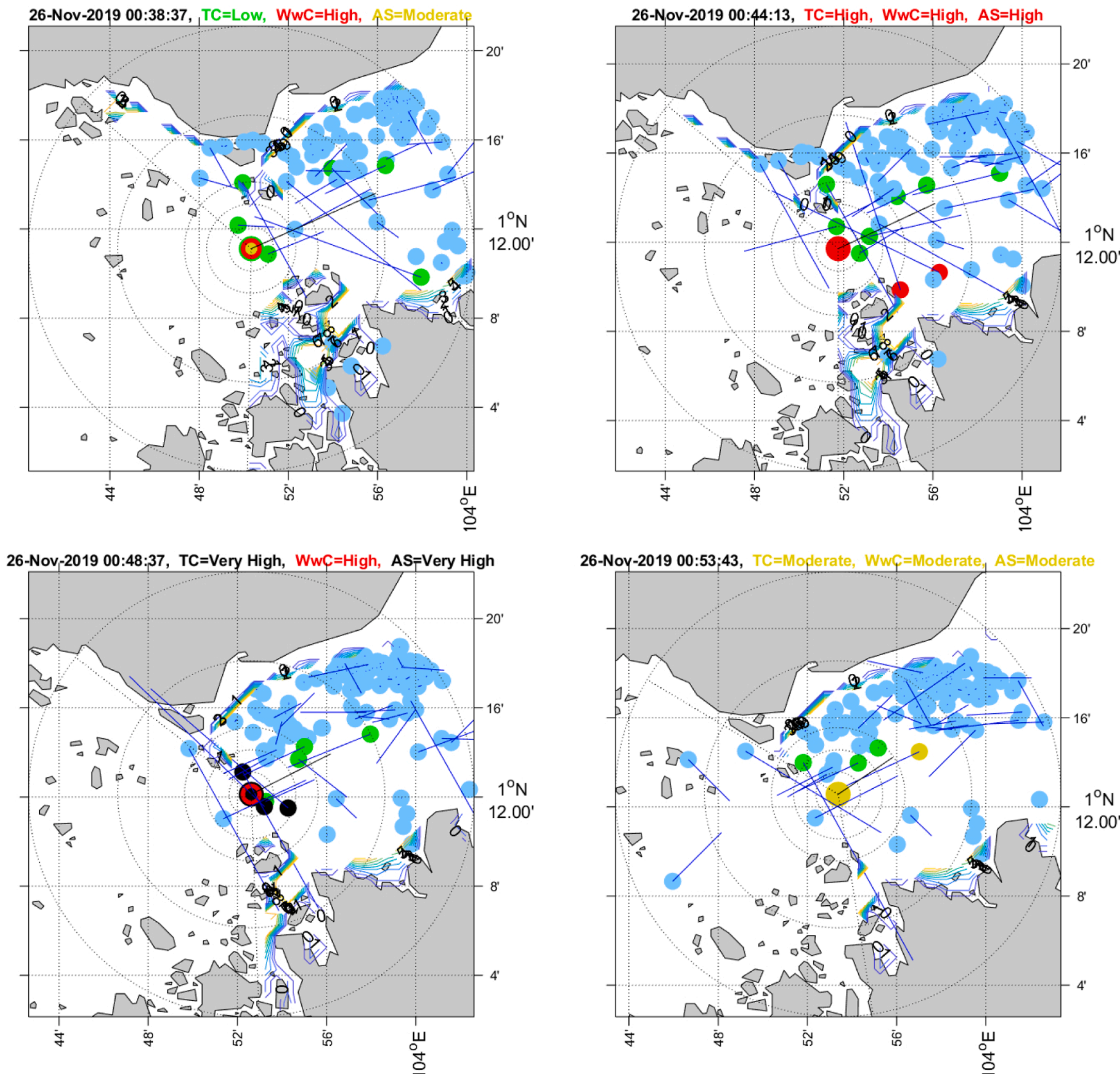

Fig. 21. Images from left above (at 00:38 UTC) through right below (00:53 UTC) show arrival to Singapore with a great number of anchored ships and parallel, oncoming, and crossing traffic, plus shallow ground on both sides.

literature research, conducted numerical simulations, elicited experts' knowledge and consulted good seamanship practice. As a result, we define three main elements governing accident susceptibility. They are as follows: traffic complexity, waterways complexity and environmental complexity. The framework developed is generic, however its parameters as presented here tend to reflect the operational conditions of two types of ships carrying passengers: a large cruise ship and a RoPax vessel. Application of the framework on selected case studies proves the suitability of the developed solution for the given purpose, which can be two-fold: (1) as an onboard decision support tool; (2) as a tool for the analysis of historical traffic.

When the framework is applied as onboard solution, the values of parameters determining traffic complexity and waterways complexity may be adjusted, depending on the company regulations or prevailing conditions. However, the default parameters have been carefully evaluated utilizing the best available knowledge and evidence. In case of the use of the framework for the analysis of past trajectories, the parameters need to be checked and the user shall make sure these correspond well with the vessel type analyzed.

The framework is based on heuristics, which can be burdened with some degree of subjectivity. Nevertheless, to a large extent it remains generic, since it is based on first principles, thus making the framework transferable among various ship types and scenarios. The first principles adopted here are related to the factors and conditions affecting human performance. First, the amount of navigable waters - and so, manoeuvering time available - will determine the types of manoeuvers that a given ship can perform to avoid an accident. The narrower the water, the less freedom navigators have, and as a consequence, are more constrained in their collision avoidance strategies. Second, the restricted navigable waters together with the number of target ships to handle and their corresponding level of difficulty, as well as environmental conditions, such as visibility or wave height, build up workload and stress that affect human performance, ultimately leading to errors [86].

This mechanism is claimed to be generic, supported by the relevant literature, however the way the surrounding situation is perceived by navigators is subjective and will depend on various factors and compensatory mechanisms, such as experience or personal traits [52]. Despite those personal differences, it is still feasible to parametrize the framework according to the available data obtained from the literature and elicited from experts, bearing in mind that those parameters are subject to change if the framework is to be applied to different ship types and sizes from the ones presented in this paper. This holds for all the indices in the framework, namely waterway complexity index, traffic complexity index and environment complexity index.

When it comes to heuristics adopted for the estimation of traffic complexity, it is based on the number of targets to follow and their levels

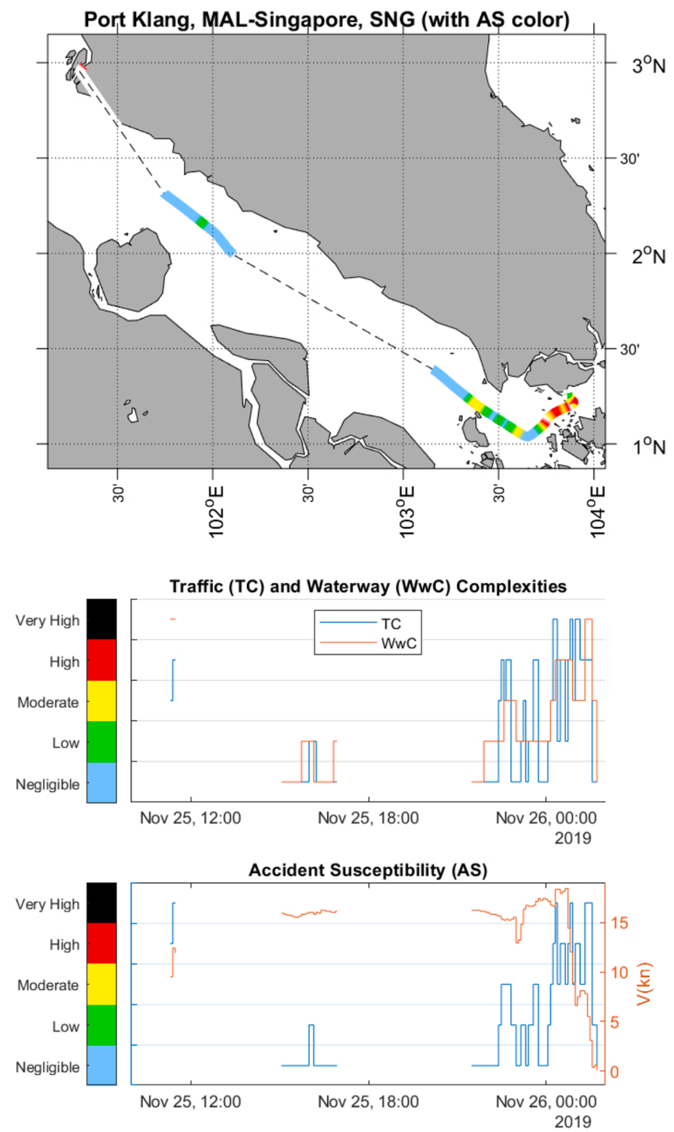

Fig. 22. Voyage from Malaysia to Singapore, with high traffic and waterway complexity on arrival: the upper image shows the track of the voyage with colors indicating Accident Potential, the dashed line shows a gap in the AIS data longer that 40 min. Below, two-time histories show Traffic and Waterway Complexities and Accident Susceptibility Index. In the time history of ASI also the ship speed is shown. No values are shown for gaps in AIS data.

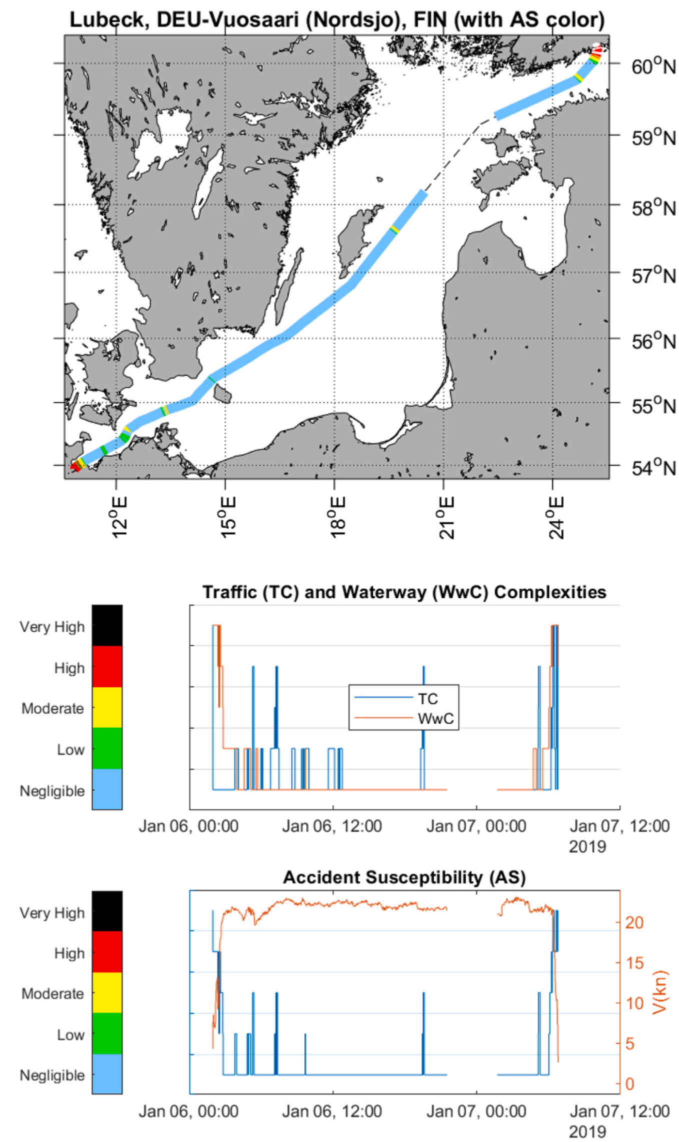

Fig. 23. Winter time voyage from Lubeck (Germany) to Vuosaari (Finland), with high traffic and waterway complexity at departure and arrival. The upper image shows the track of the voyage with colors indicating Accident Susceptibility, the dashed line shows a gap in the AIS data longer that 40 min. In the lower image, two time histories show Traffic and Waterway Complexities and Accident Susceptibility Index. In the time history of ASI also ship speed is shown. No values are shown for gaps in AIS data.

of difficulty, which is driven by the proximity indicators such as CPA and TCPA. The higher the number of targets surrounding the own ship requiring navigator's attention and action, the more difficult the situation is. As a result, the higher the workload for the navigator, the higher the accident susceptibility index. As a result of a survey carried out among watch officers exclusively for the purpose of this research, the average number of targets handled by navigators without additional burden, is found to be five. At the same time, the maximum number of target ships a navigator can safely handle is set as 10, which is supported by aviation literature and a survey among maritime expert. Similarly, the number of targets higher than 10 is found to be very challenging for one person to handle at a time, as presented in Section 5. Those numbers are obtained for the contemporary technological solutions in collision avoidance systems as installed on board vessels and present the level of training received by the bridge crews. Even so, with the prospective technological advancements in this area, those numbers may change in the future.

The proximity indicators, such as TCPA and CPA, adopted here as limiting, are based on prevailing practices on board ships as well as ship dynamics. However, these parameters can be adjusted, according to ship types or company regulations if required.

Environment complexity is understood as the anticipated effect of hydro-meteorological conditions and visibility or workload of a navigator. Although the framework makes a distinction between good and restricted visibility, since Convention on the International Regulations for Preventing Collisions at Sea (COLREGS) governing collision avoidance strategies clearly describes the conduct of vessels depending on visibility conditions [87], the case study presented is carried out with the assumption of good visibility. This is done mainly due to the lack of reliable historical data on visibility for the analyzed areas. If the framework is to be used for day-to-day navigation, visibility conditions are determined visually and a proper mode for the framework can be selected. Additionally, the framework assumes favourable sea conditions, which can be easily justified for the ship types analyzed here, since those usually operate under decent weather conditions, as revealed in

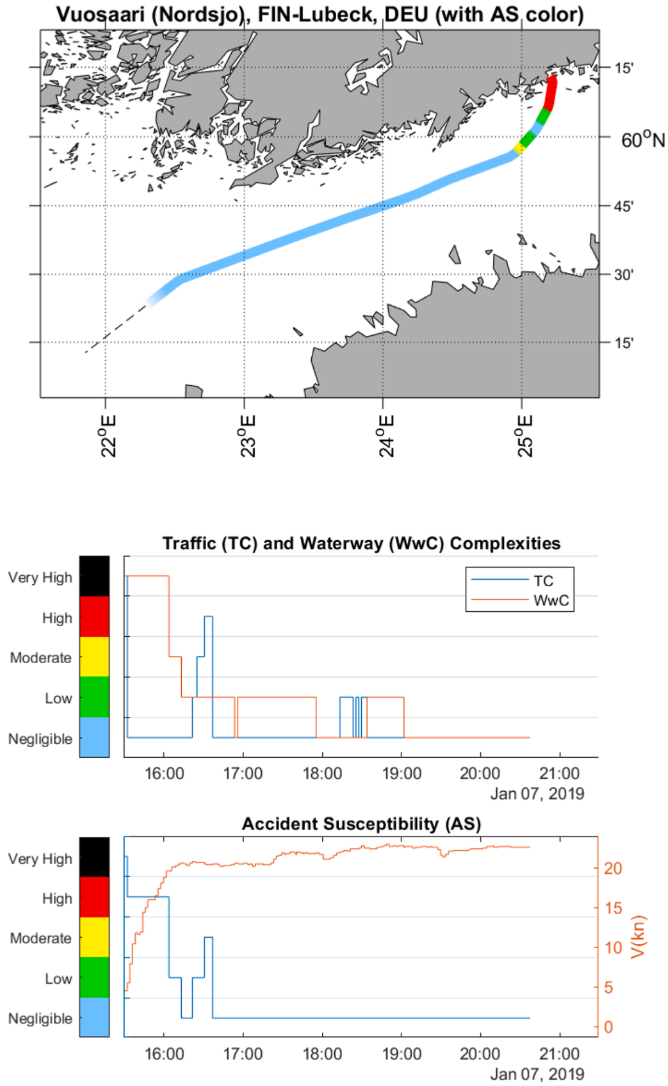

Fig. 24. Close-up of the legs of the voyage from Vuosaari (Finland) to Lubeck (Germany) located in the Gulf of Finland, including departure from Vuosaari. High traffic and waterway complexity at departure and low otherwise, make accident susceptibility high at the initial stage of voyage, subsequently dropping to low and negligible in the remaining part of the voyage. Along with the values of accident susceptibility index ship speed is depicted.

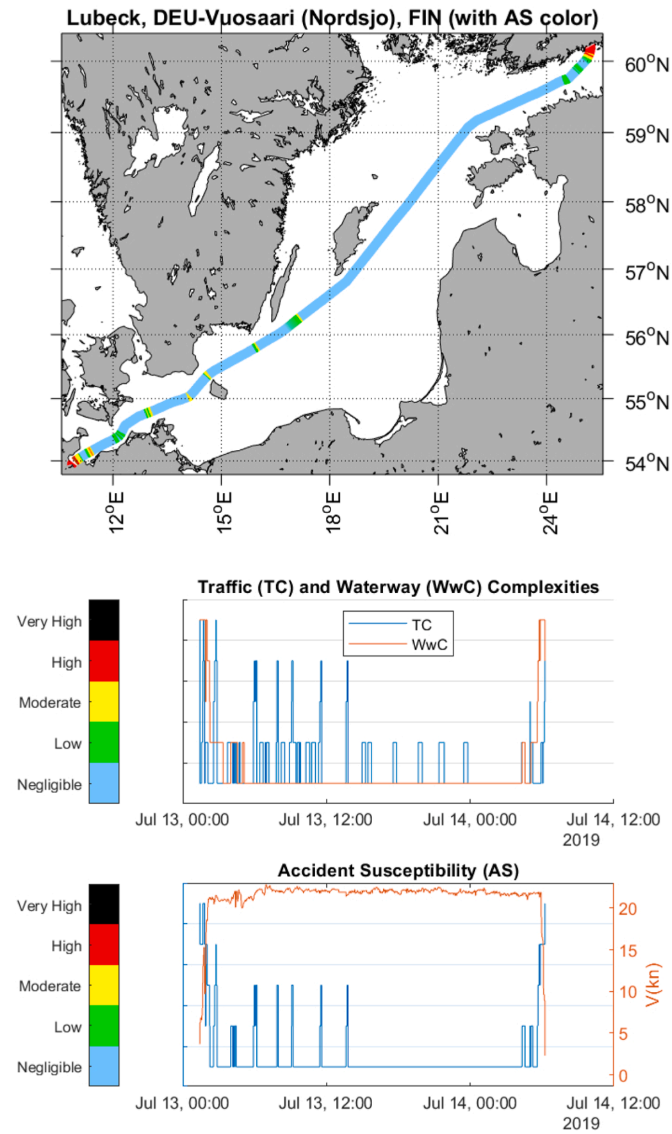

Fig. 25. Summer time voyage from Lubeck (Germany) to Vuosaari (Finland), with high traffic and waterway complexity at departure and arrival. The upper image shows the track of the voyage with colors indicating Accident Susceptibility, the dashed line shows a gap in the AIS data longer that 40 min. In the lower image, two time histories show Traffic and Waterway Complexities and Accident Susceptibility Index. In the time history of ASI also the ship speed is shown. No values are shown for gaps in AIS data.

[64]. However, this element may deserve a more in-depth consideration for other ship types exposed to various conditions, including harsh weather, affecting their maneuverability and so - collision avoidance strategies. Smaller ships are more badly affected by deteriorating hydro-meteorological conditions than large vessels. Additionally, elements pertaining to environment, posing threats to navigation, such as ice condition or unreliable depth soundings (quite relevant to cruise ships operating in polar waters) - could be considered in future works.

Moreover, at the stage of framework aggregation, it becomes evident that the framework tends to slightly prioritize waterway complexity over traffic complexity. This is explained by the fact that the proximity to shallow grounds limits the maneuvering space for a ship, thus complicating evasive actions and increasing task demands / mental workload, as per Figs. 1 and 3. Since, the parameters describing waterway and traffic complexity adopted here are chosen for a large cruise ship and a RoPax vessel, they may differ for small and medium sized ships. This is mainly due to less space required for maneuvering, making the threshold adopted here excessive for them.

As presented, the framework may assist in defining navigational situations to be avoided. For example, the officer should steer the own ship clear from very high values of accident susceptibility index. Alternatively, if such situation occurs or is expected to occur, based on experience and/or the analysis of past voyages, bridge manning could be increased in advance in order to distribute the mental workload among a larger number of bridge team members. However, the issue of setting the limiting levels for accident susceptibility index, which depends on numerous factors and can be organization-dependent [88,89], is left out of the scope of this study.

Last but not least, other modeling techniques can be adopted in the future with an intention to transform the framework from deterministic into probabilistic, to encompass the uncertainty associated with the input parameters and reflect their effect on the outcome better. To this end, Bayesian Networks or similar tools can be found suitable.

The overall intention of the introduced accident susceptibility framework is to act as a natural extension of the existing onboard solutions for ship vulnerability assessment. Trough continuous assessment

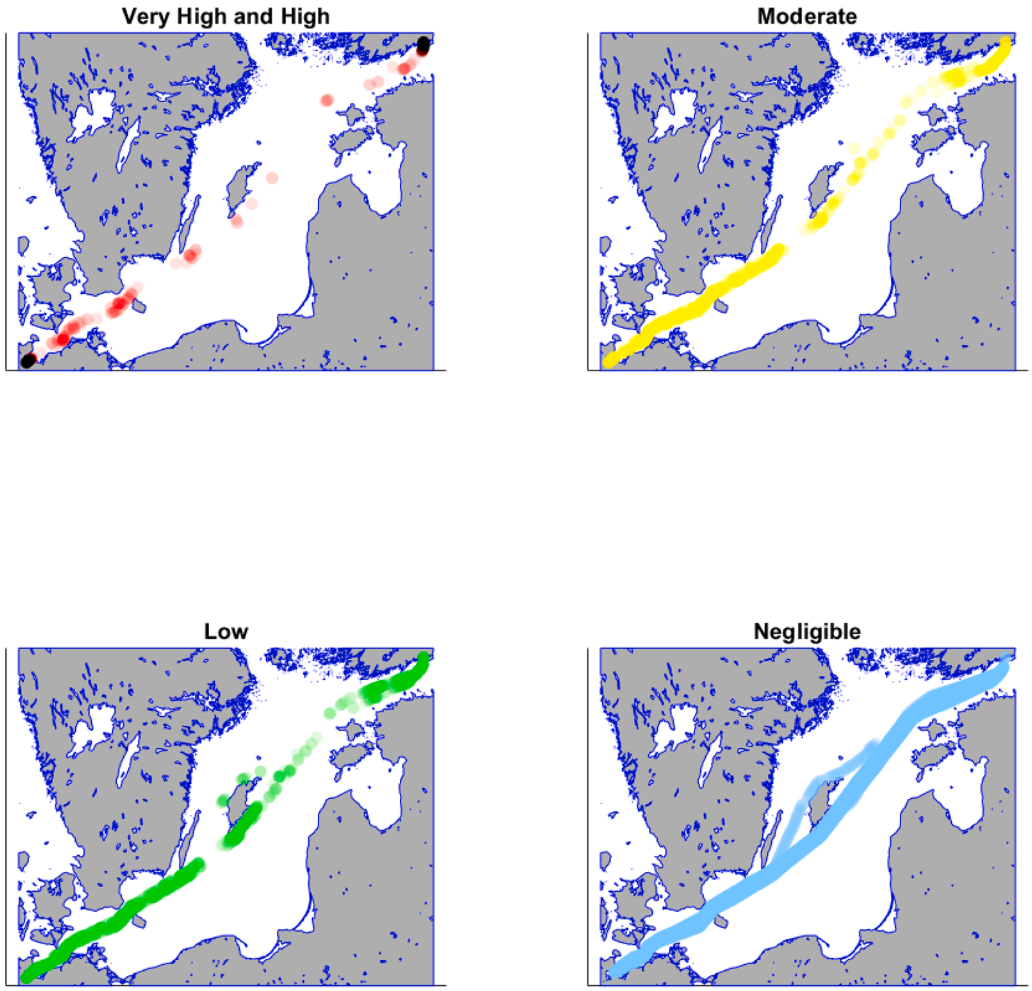

Fig. 26. Breakdown of accident susceptibility levels for the analyzed RoPax route covering 8 months (January–August) of 2019.

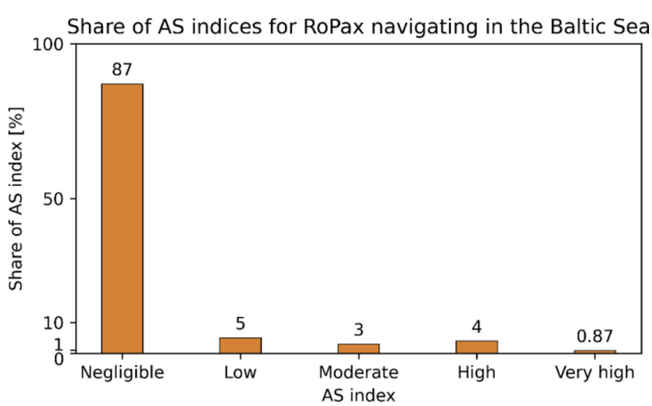

Fig. 27. Distribution of the accident susceptibility indices for the analyzed RoPax.

of vulnerability and susceptibility of a ship in operation, the framework is meant to increase the crew's situational awareness, thus supporting safe operation of watertight doors onboard ships carrying passengers, contributing to an overall increase in navigational safety of the passenger ship in operation.

6. Conclusions

The aim of this paper is to introduce a framework and model for the evaluation of accident susceptibility index, appropriate for a large cruise vessel and a RoPax involved in high seas and coastal navigation. Subsequently, the developed method is applied to several case studies.

The framework's foundation is laid on a workload/human performance relation widely discussed in the literature on human reliability analysis. The relation is governed by a set of factors obtained in the course of integration of background knowledge from aviation and maritime. The latter encompasses wide literature review and experts' knowledge elicited specifically for this particular purpose.

The results obtained in the course of the case studies show that the framework properly reflects the actual navigational situation. Consequently, the suitability of the solution for the given purpose is demonstrated and the framework can be used as intended.

As it is, the framework can be applied two-fold. First, to support decision making process onboard passenger and RoPax ships, especially when combined with a system for real-time monitoring of operational vulnerability to flooding, thus supporting safer operation of passenger ships. Second, to evaluate historical ship traffic data when determining the sea areas that may require increased situational awareness from the crew, due to high or very high level of accident susceptibility index.

The presented framework is generic and is developed under the assumption of the conditions of solo watch on the bridge, yet it is easily transferable and expandable to encompass a wider set of factors and operational conditions that may be found relevant for a different context. Also, being deterministic, the framework, has huge potential to become probabilistic, to better account for associated uncertainties, given appropriate modeling techniques are applied, such as Bayesian

Networks.

CRediT authorship contribution statement

Jakub Montewka: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision. **Teemu Manderbacka:** Methodology, Resources, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing. **Pekka Ruponen:** Methodology, Resources, Writing – original draft, Writing – review & editing. **Markus Tompuri:** Software, Investigation, Visualization, Data curation. **Mateusz Gil:** Software, Visualization, Resources. **Spyros Hirdaris:** Funding acquisition, Project administration, Writing – original draft, Writing – review & editing.

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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