Reliability Engineering and System Safety 217 (2022) 108024

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

An updated method identifying collision-prone locations for ships. A case study for oil tankers navigating in the Gulf of Finland

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A R T I C L E I N F O

Keywords:
Collision-prone locations
The Gulf of Finland
Ship-ship collision frequency
Oil Tankers
Verification Methods
IWRAP Mk2 Software

A B S T R A C T

To ensure the risk level associated with continuously increasing maritime traffic through particularly sensitive sea areas remains at acceptable level, a periodic risk assessment needs to be carried out by the relevant authorities. As a part of such assessment, allowing for proactive countermeasures to mitigate risk, the frequency of accidents is estimated along with the assessment of geographical locations where the accidents are most likely to happen.

To this end scientific literature offers a number of approaches, however only a few solutions are recognized by the maritime authorities and applied world-wide. One of such approach is a evidence-based, semi-dynamic, network-based model called IWRAP Mk2. Despite its advantages, the tool lacks the verification procedure of the model development process that governs the reliability of the results. This ultimately may undermine the reliability of the obtained results. This shortcoming seems to be quite common in the field of maritime risk assessment, as revealed by the recent analysis of the risk assessment method and tools.

Therefore, this article attempts to close this knowledge gap by providing a novel framework for ship-ship collision probability estimation and identification of the collision-prone locations, encompassing novel verification procedure suitable for network-based maritime risk models such as IWRAP Mk2 tool. As a results this new, wider modeling framework offers more reliable, evidence-based estimates of the probability of ship-ship collision and identifies more accurately the collision-prone locations in a given sea area. To demonstrate the usability of the framework a case study is performed, with the use of 10 months of ship traffic data recorded in the heavily trafficked and enclosed sea area of the Gulf of Finland during ice-free season with the special attention paid to the oil tankers.

The updated framework delivers the annual probability of ship-ship collision, where at least one ship is an oil tanker, which is higher by 16% compared to the results obtained from regular IWRAP Mk2 software, that lacks verification procedure. Also the framework identifies the most collision-prone locations in the Gulf of Finland, which are located in the eastern part of the Gulf, explaining over 60% of the total collisions in the whole GoF, for ice-free seasons.

1. Introduction

Safety of maritime transportation is recognized as one of the most essential elements when designing new maritime transportation system especially when introducing novel ship types to systems or planning new activities within existing systems [1,2]. To this end the International Maritime Organization introduced a systematic and rational way to analyze safety, called Formal Safety Assessment (FSA) [3–6]. Therein safety is measured with the use of risk, which is usually expressed quantitatively as a combination of two variables: the probability of an accident (P) and its consequences (C). The FSA documents have shaped the perspective on risk in the maritime domain, and the PxC notion still prevails, especially in the area of risk-based ship design [7–9]. The existing, however sparse, exceptions, tend to look behind the P and C numbers, claiming the need of uncertainty inclusion into the risk assessment and management process, thus prospective change in the risk

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https://doi.org/10.1016/j.ress.2021.108024
Received 18 December 2020; Received in revised form 23 August 2021; Accepted 3 September 2021
Available online 10 September 2021
0951-8320/

paradigm in maritime, [10,11]. Beyond maritime domain other definitions of risk can be found, as nicely summarized in [12], allowing for objective and subjective judgments of relevant elements of risk, such as probability, consequences, uncertainty and background knowledge. Moreover, a handful of approaches to the safety of socio-technical systems, also qualitative, can be found in the literature [13–16], including methods pertaining to Safety I and Safety II approaches.

Therefore, the research debate in the field of maritime transportation risk and safety can be divided into two main broad channels. First is related to the fundamentals, and second relates to application aspects of the adopted methods. A comprehensive review of risk analysis in the maritime transportation system, focusing on the conceptual issues, has recently been presented in [17–21], claiming a low level of scientific formalism when performing risk assessment studies for maritime transportation systems. Whereas the review of existing methods, from the perspective of their application capabilities, for risk assessment of maritime transportation are given, for example, in [20,22–29]. Particularly the findings presented in [23,30] demonstrate the limited applicability of the large group of existing methods applied for the risk management of selected accidents type in maritime transposrtation systems. Therein, claims are made that not all methods are proactive and are thus suitable for risk management, mainly due to lack of control over the input variables or adopted assumptions behind the methods, which render the methods passive, [31]. Moreover, recent claims have been made on the lack of validation procedures for maritime risk assessments and insufficient uncertainty handling, [19]. At the same time, the demonstration of possible ways to address those limitations, mainly in qualitative manner, have been carried out in [32–36].

Most of the existing methods and tools evaluating risk of accidents in maritime transportation systems adopt the similar view on risk, where the risk is defined as a combination of frequency and probability of the accident [37–40], or just the probability alone, [41–43]. Therefore, reliable estimates of the probability of collision are crucial, since these are further fed into a risk assessment procedure, directly affecting its reliability and validity, as pointed out in [19,44]. Additionally, the knowledge on tempo-spatial variation of the collision probability across an analyzed sea area is crucial, especially from the perspective of accident consequences mitigation, where the response capacity needs to be properly planned and distributed in the most effective manner, as shown in [32–34,36,45].

Despite the recent progress in the field of accident frequency estimation, both on the aspects of fundamentals [46–49], and methods application [43,50–55], the network-based approach discussed in details here is one of the most matured and widely used among maritime authorities all over the World, however the method is not free from drawbacks and limitations. Therefore, any improvement in this method may have large-scale effect, rising awareness among the potential end-users, thus contributing to maritime safety globally. One of the common deficiency of the existing solutions for accident frequency estimation based on traffic networks, including widely accepted software packages such as IWRAP Mk2, which has been adopted by maritime authorities in numerous studies worldwide, as presented in [56–65], is a lack of systemized verification procedures. The latter is understood as evaluation of the effect of model and data uncertainty as well as model settings (which often are left to the end-user's discretion without any explanation of their potential effect) on the model outcome. The need for the development of remedy for this has been strongly advocated in the recent literature of the subject, see for example [66,67], but the existing solutions are scarce, and often limited to input data handling, [68,69].

To close this gap, we propose here a three-stage, systematic, rational and evidence-based framework for the development of a model structure, suitable for semi-dynamic, network-based maritime traffic risk models, such as IWRAP Mk2, encompassing a verification process. The latter reduces the uncertainty associated with the following input parameters: the number of waterways to be included in the modeled traffic network, and their spatial fragmentation into shorter, manageable segments, thus better capturing the actual traffic characteristics of the network. The applicability of the framework is demonstrated with the case study, where the annual frequency of ship-ship collision is estimated, as well as the collision-prone locations in the analyzed sea area are identified. To this end, traffic data representing a period of 10 months of 2018 focusing on ice-free navigation in the Gulf of Finland is utilized, with the special focus on oil tankers, as obtained from AIS.

As a result, we update the knowledge on the probability of ship-ship collision in the Gulf of Finland, where at least one ship is an oil tanker. This information is currently outdated, mainly due to continuous growth of tankers traffic through the Gulf, which increased by 20% over the last decade, as indicated by independent studies presented in [58,59]. Therefore, continuous revision of this parameter is especially relevant in such enclosed and environmentally sensitive areas as the Gulf of Finland.

With the proposed approach we contribute to the field of maritime risk assessment in two-fold: first, to the foundational discussion on the uncertainty and a new way to handle it, suitable for semi-dynamic network-based maritime traffic models; second by delivering revised knowledge on collision frequency and collision-prone locations in a predefined sea area.

The rest of this paper is organized as follows. Section 2 elaborates on the methods adopted and data utilized to the collision frequency estimation. Section 3 presents the developed models and obtained results. Section 4 discusses the paper, while Section 5 concludes.

2. Methods and data

2.1. Adopted approach outline

To estimate the ship-ship collision frequency, as well as to evaluate the collision-prone locations in the sea area, we utilized IWRAP Mk2 software package. This package represents a semi-dynamic, network-based type of maritime accident risk estimation model that requires a traffic network to be developed, either manually or automatically, based on imported traffic data from external sources, such as Automatic Identification System - AIS. The model accounts for spatial variation of the traffic, while the effect of temporal changes of traffic on the outcome can be explained to some extent only, however it is tedious. This can be done for example by developing a series of temporarily narrower models, covering a set of shorter time spans, for example a week or a month, instead of one year. The traffic model takes a network structure, which is a commonly adopted concept to model transportation networks, see for example [60]. Within a network, there exist nodes and edges, where the former corresponds to waterways, while the latter, also called waypoints, denote the locations where the waterways meet or intersect. If a waterway experiences complex traffic, it can be further split into shorter, manageable parts, called legs. Such a network is used for further calculations of accident frequency over the analyzed sea area, one of such wide network, comprehensively covering the whole Baltic Sea is presented in [38,50].

Despite the convenient way of AIS data handling and translating them into spatial density maps of traffic, the IWRAP Mk2 features also some shortcomings. These relate to the way the traffic network is defined, and more precisely how the big dataset of ships positions scattered over the sea area is translated into shipping routes. One way is a manual drawing of the legs following the traffic density plots. As per the main routes there is no doubt about their importance for the model and need for including them, yet the question remains: does the extent of the less dense or even scarce traffic routes influence the model performance and outcome?

Therefore, we propose the following, novel three-stage framework for the maritime traffic network development, allowing for reliable estimates of ship-ship collision probability and identification of collision-prone locations, as depicted in Fig. 1. First, the initial structure of the

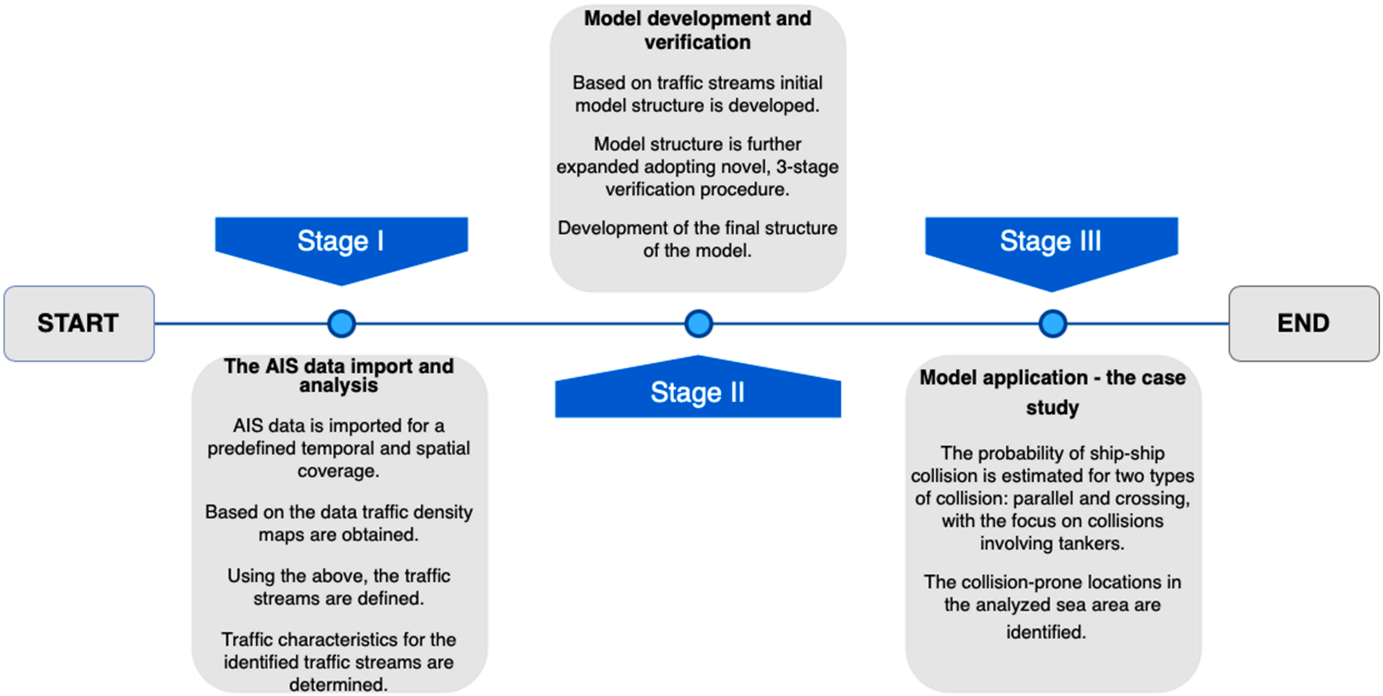


Fig. 1. A novel framework for collision frequency estimation and identification of collision-prone locations.

network is obtained, which is purely based on AIS data and manual, often intuitive, process of determining the legs and waypoints. During this stage, the routes that feature clear traffic patterns with significant density are incorporated into the network. While the locations where the waterway changes its direction, or merge with another route, are considered waypoints.

Second, the initial network is extended with all the routes of less dense traffic which can be visually distinguished in the data and could potentially affect the traffic flow in other areas, thus influencing the overall accident frequency. Subsequently, such an extended network is subject to a novel verification procedure, where the network is fine-tuned with respect to its legs and waypoints, so only those elements that contribute significantly to the explanatory power of the model are retained. At this stage the relevant legs are selected, their width is adjusted accordingly, and length is defined so the leg contains the relevant traffic.

Thirdly the model is instantiated, the ship-ship collision frequency is estimated and the collision-prone locations are identified adopting normalization process.

All these steps including methods and data are described in the following sub-sections.

2.2. Ship data

The applicability of the framework is demonstrated on a case study, where the traffic model is defined on the basis of AIS data describing maritime traffic in the Gulf of Finland, covering a period of 10 months of the year 2018, excluding two months of ice navigation season (February and March). Ice navigation peculiarities make the types of hazards and accidents present during ice navigation season very different from ice-free seasons, [61–67]. This is mainly due to ships navigating in convoys (thus following each other at close distance), icebreaker assistance and escorts in close proximity or deactivation of traffic separation schemes, [61,68,69]. All these cannot be properly captured by the adopted modeling approach and tool, [70,71]. Therefore, the data describing this particular type of navigation needs to be removed from the traffic database to avoid distortion. Due to this two-months gap in a one-year data, the obtained traffic distributions were recalculated to correspond to one year of ice-free navigation. This in turn allows the collision frequency to be calculated on a yearly basis.

The maritime traffic situation prevailing in the Gulf of Finland is depicted in Fig. 2, where there exist several dominating traffic flows. There are major shipping lines cutting the Gulf in east-west directions, where the majority of oil tankers steaming through the Gulf are present. Moreover, the N-S flows in western part of the Gulf are noticeable, these refers to the passenger traffic linking Helsinki and Tallinn. Additionally, the routes to the harbors along the coast on the Finnish (in the north) as well as Estonian and Russian side of the Gulf (in the south) are depicted. All these contribute to the probability of ship-ship collision in the area.

The ship data required for the traffic model development process is obtained from the automatic identification system – AIS. The system provides an automatic wireless exchange of information among ships (ship-to-ship) as well as between ships and the Vessel Traffic Services (VTS) centers (ship-to-shore). Primarily, it has been developed to increase the safety of navigation, however nowadays it is used in numerous areas covering a wide range of applications, for a relevant review in this subject, see for example [72–74]. The AIS message includes static, dynamic, and voyage-related information, as comprehensively described in an official documentation provided in [75]. The messages are transmitted with various temporal resolutions, depending on numerous factors, such as navigational status and dynamics of a ship, [76–78]. However, the resolution at which the messages are recorded in a database often depends on the purpose of the research and the level of automation at the stage of knowledge extraction from the data, [31,79]. If the research aims at identification of specific maneuvers of a ship, especially in restricted waters then ship positions should be recorded more frequently to capture the highly-dynamic phenomena, as demonstrated in [66,80–87]. However, if the aim is to obtain a big picture of the traffic over a wide spatial and temporal resolution, then a coarse data resolution suffices, as adopted in [88–91]. The latter is the case here, since the anticipated analysis focuses on low-dynamic objects, moving across a large sea area, and covering one year of navigation. Therefore, the time interval between consecutive AIS messages for a ship in the analyzed database is counted in minutes rather than seconds. This is done to decrease the size of database, to make the data handling by IWRAP Mk2 software easier and more effective, without any significant

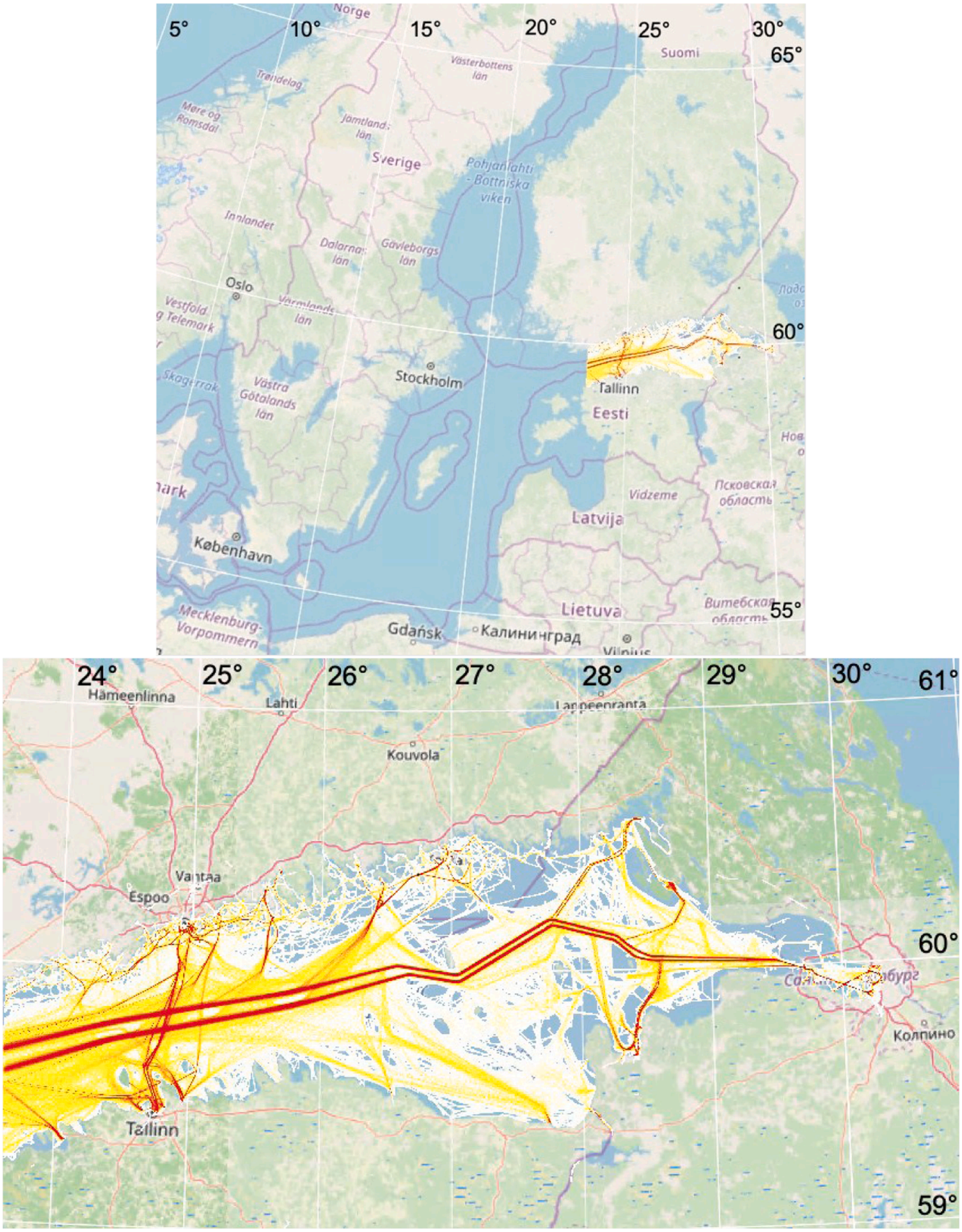


Fig. 2. Maritime traffic density map over the Gulf of Finland.

loss in explanatory power of the developed traffic risk model, mainly due to implemented algorithms therein, as described in [38,39].

Two exemplary AIS messages, as recorded in the database, are given in Table 1. Based on the recorded data the traffic database is developed, which is used as a crucial input for traffic model development. The tempo-spatial coverage of the developed database is given in Table 2. The time intervals' histogram of the recorded data in the traffic database is depicted in Fig. 3, while the share of vessel types is demonstrated in Fig. 4. It is noticeable in Fig. 3 that the time span between consecutive positions recorded in the database is not more than 5 min for the 90% of the records, while the remaining 10% records features time span of 20–25 min. While analyzing Fig. 4 it becomes evident that oil tanker traffic takes 18% of the total maritime traffic recorded in the area, however other ship types are also frequently observed there such as *general cargo* (19%) and *bulk carriers* (14%). The fourth most frequently recorded ship type is *other*, accounting for 16% of the overall traffic recorded in the GoF. This group includes small auxiliary vessels, such as bunkers, harbor tugs, pilot boats, and alike, operating primarily in close vicinity to harbors not affecting significantly the traffic along the routes in the model developed here. However, from the perspective of environmental consequences posed by the maritime traffic, the accidents where oil tankers are involved remain the most relevant for this

Table 1
An exemplary structure of AIS data used to develop the traffic model.

Type of AIS data		Sample 1 of AIS data	Sample 2 of AIS data
Static data	Maritime Mobile Service Identity (MMSI)	538,005,467	273,335,320
	IMO number (Ship ID)	9,242,625	9,031,624
	Vessel type	Container Ship	Oil Products Tanker
	Vessel length [m]	178	79
	Vessel width [m]	26	13
	Deadweight tonnage [t]	22,308	2774
	Gross registered ton (GRT)	17,189	1666
Dynamic data	TIMESTAMP, Date and Time (in UTC) when position was recorded by AIS	02/01/2018 12:35:46	03/01/2018 00:38:25
	Position: latitude and longitude [deg]	30.22786 59.89362	29.48026 60.02441
	Course over ground [deg]	000	094
	Speed over ground [kts]	0.0	7.2
	Heading [deg]	032	094
Voyage-related data	Navigation status (the possible values from 0 to 15 or from 95 to 99)	5 = moored	0 = under way using engine
	draft [m]	8.3	4.1

Table 2
Tempo-spatial coverage of the developed AIS database covering the maritime traffic over the Gulf of Finland.

Temporal	2018–01–01 00:00 - 2018–01–31 23:59and2018–04–01 00:00 - 2018–12–31 23:59
Spatial - latitude span	59.00 deg N - 60.80 deg N
Spatial - longitude span	023.58 deg E - 030.30 deg E

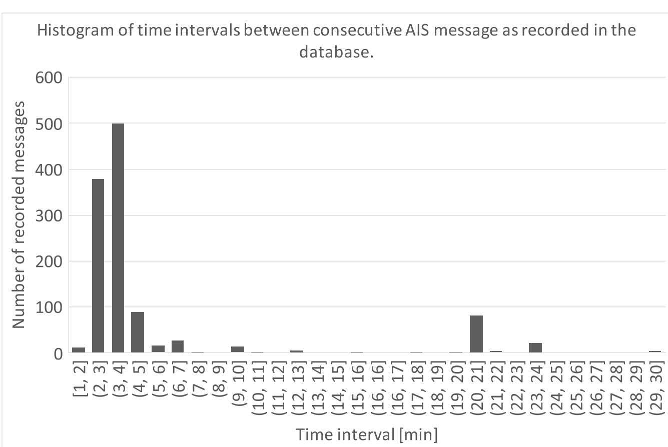


Fig. 3. Histogram of temporal resolution of recorded AIS messages, that are used to develop the traffic model.

particular sea area. Therefore, the histograms of their relevant parameters, that are taken as input to the traffic model (except ship draft), are depicted in Figs. 5-7. Therein the histograms of ship speed and course are shown in Fig. 5, while the main dimensions of the ships, attributed to a ship type are visualized across Figs. 6-7.

By studying those figures, it became clear that there are dominating size groups of tankers navigating in the GoF. For oil product tankers there are two identifiable groups, one with length of around 200 m and the other spanning roughly from 70 m to 180 m. While for the crude oil tankers there is one dominating group of ships of length around 250 m. Similarly analyzing the histograms of speed and courses, the dominating

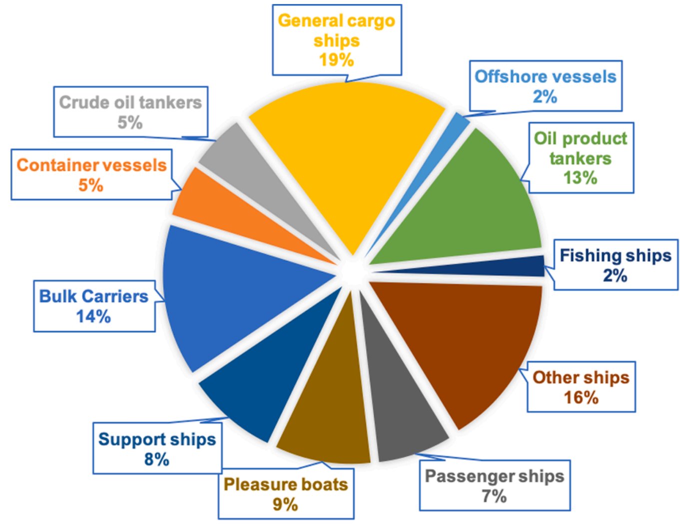


Fig. 4. Breakdown of ships navigating in the Gulf of Finland per their type, as recorded in the traffic database for 2018.

values can be outlined. The figures provide coarse and generic information about the AIS data used for this study, while the in-depth analysis of ship types and sizes along given routes and their contribution to the accident probability is performed with the use of IWRAP Mk2 software.

Based on the recorded data the network structure and parameters can be defined, leading to the estimation of the ship-ship collision frequency, as elaborated in depth in the following sections.

2.3. *Transforming ship data into model structure*

Model structure is developed based on heuristics, which tend to reflect our understanding of the subject supported by visualization of AIS big dataset. Such approach is acceptable for the given purpose, since the relevant literature of the topic is lacking generic, rigorous, repeatable thus scientific way of transforming scattered data of ship trajectories into a solid traffic network, except just a few recent work in this field, [83,92].

The traffic network is created with the traffic density plot in the background, as depicted in Fig. 2. It consists of edges (straight segments, also known as legs) and nodes (known as waypoints, where the traffic flow alter its directions or two or more legs merge). Firstly, the waypoints are visually determined, for which the legs are drawn between each consecutive waypoint. In case of two-way, parallel traffic the leg width is adjusted accordingly, so it captures traffic in both directions, as depicted in Fig. 11. However, if the traffic streams in opposite directions are not parallel, these need to be considered as separate legs, and the width of each leg shall be set up properly, encompassing one stream per leg.

Secondly the major legs are drawn, capturing the traffic on the densest routes, in the case study presented the backbone of the network resembles a cross with longer arm lying along the east-west directions and shorter along north-south. Subsequently the legs adjacent to the main traffic line are added, according to their contribution to the scope of the study. For example, if the focus is on accidents involving oil tankers, then all the tankers traffic must be included in the first place. Secondly all the traffic streams interacting with the tanker traffic must be added too. While the traffic streams that are located away from the tanker routes, and are not merging or crossing with those, may be found obsolete, thus not included in the traffic network.

Such approach seems suitable for organized traffic, where the ships navigate along easily distinguishable routes. Therefore, regular traffic of varying level of density can be accounted for and its contribution to the

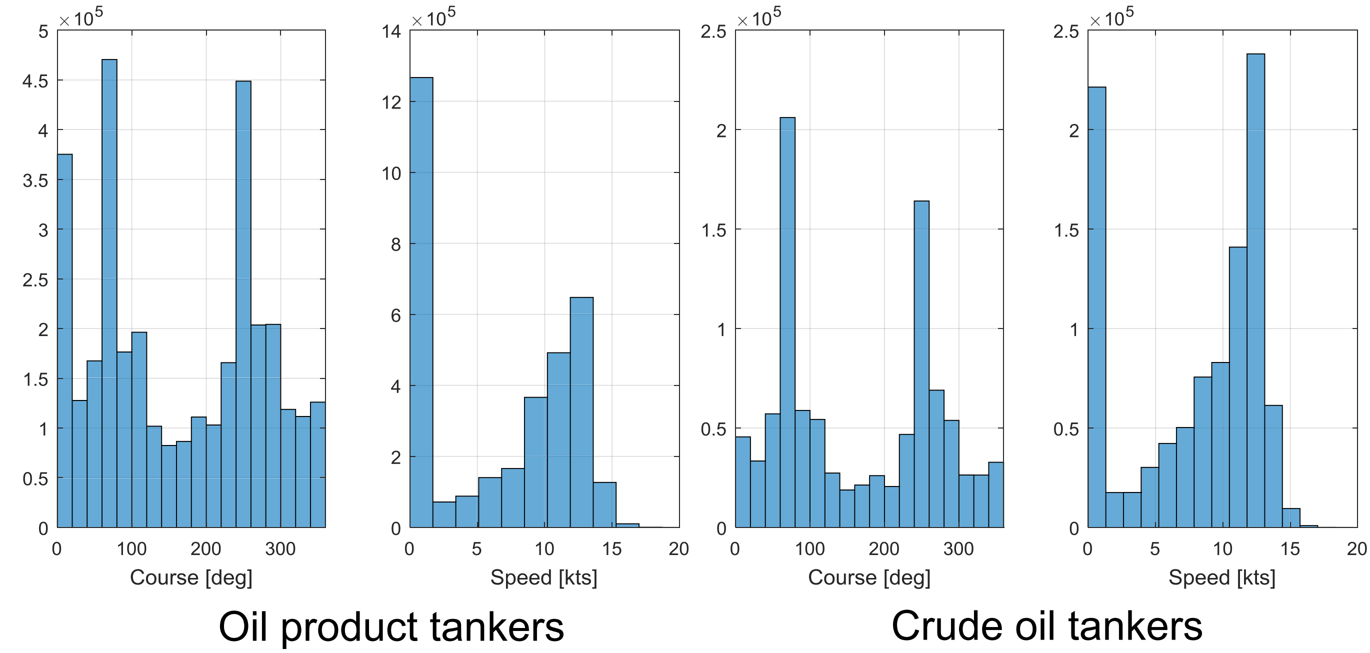


Fig. 5. Histograms of speed over ground and course over ground for the main ship types navigating in the Gulf of Finland in 2018.

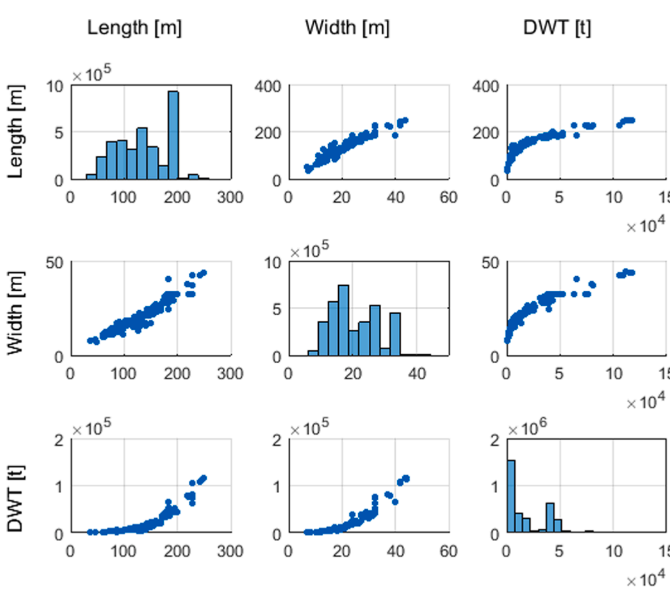


Fig. 6. The main characteristics of oil product tankers navigating in the Gulf of Finland in 2018.

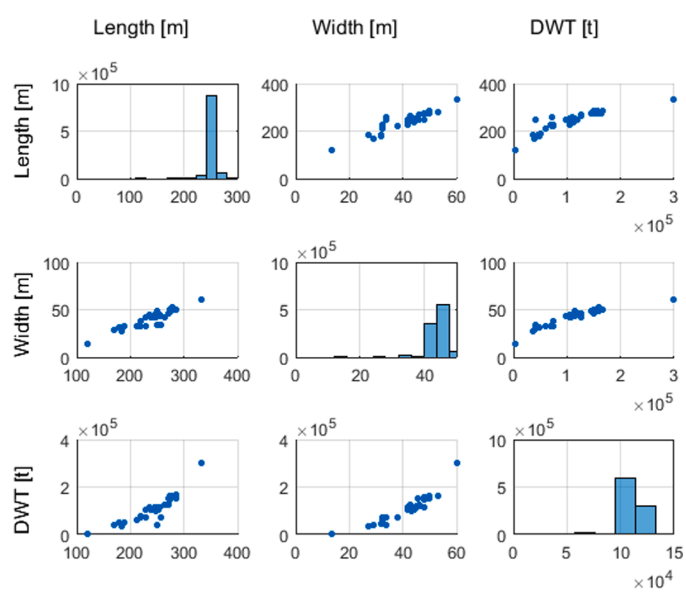


Fig. 7. The main characteristics of crude oil tankers navigating in the Gulf of Finland in 2018.

overall accident probability along the network examined. The latter is the aim of new verification procedure proposed in the Section 2.6, which guides the level of details of the traffic network by not allowing the noninfluential legs to the network.

However, the challenge remains when it comes to modeling the irregular traffic where it is not feasible to distinguish dominating directions. In theory, probability of accident associated with such irregular traffic can be modelled, assuming the traffic random. Such random navigation assumption may hold for small crafts, such as pleasure boats, fishing boats, that tend to keep away from the main traffic lanes. However, the merchant ships usually follow the routes, thus random navigation assumption may not be the best choice there. Therefore, the irregular traffic is not accounted for in the presented case study.

The maritime traffic in a network is described by the following characteristics: probability density functions of a ships' positions across each leg, ship type and main dimension (length, breadth), as well as speed distribution according to the ship type. A ship is counted on a given leg and assigned to the traffic associated with this particular leg if the two following counting criteria are met, as depicted in Fig. 8, otherwise it is not classified by an algorithm and remains nonexistent, [38]:

- her course does not deviate more than 5° from the direction of the leg, referred to as the 5 deg limit criterion. This value is taken as default in IWRAP Mk2 software package, however it can be adjusted according to the needs and prevailing traffic. In case of organized traffic flow this value seems sufficient, however when the traffic is more scattered, setting up this parameter may require some initial

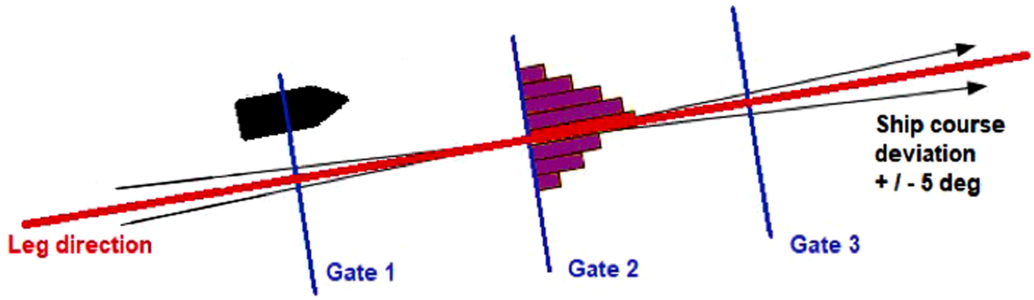


Fig. 8. *Ship counting criteria* [38].

precheck with the traffic data, to ensure all relevant traffic is accounted for.

- The ship needs to steam along the leg for a major part of it; technically she has to pass through two, out of three, virtual gates that are automatically set up along the leg, referred to as the 2 gates passed criterion.

If the counting conditions are met for a group of ships navigating along the leg, they are assigned to this leg. While all the ships not meeting the conditions are removed from the traffic distributions for the particular leg. Obviously, such removal may affect the final results of the analysis, since it is sound to expect, that the ships exceeding 5 deg limit, would have created additional crossing type of encounters, hadn't they been removed. Once they are removed, certain number of crossing type of encounters "vanishes" from the given area. However detailed quantification of this effect remains out of the scope of this paper, nevertheless it is worth further studies.

Several exemplary situations are depicted in Fig. 9, where the adopted logic is presented on a series of case studies. Since the conditions depend on the layout of legs against the ship trajectories, therefore it is important to properly adjust leg length and its direction.

2.4. Collision frequency estimation

To estimate the ship-ship collision frequency (F), a well-established approach is applied, as presented in [40,93]. Therein the F is governed by the two following factors: first, is the spatial distribution of the ships' trajectories, determining a number of collision candidates (N_G), second, is the human error probability, referred to as causation factors - P_c.

$$F = N_G \cdot P_c \tag{1}$$

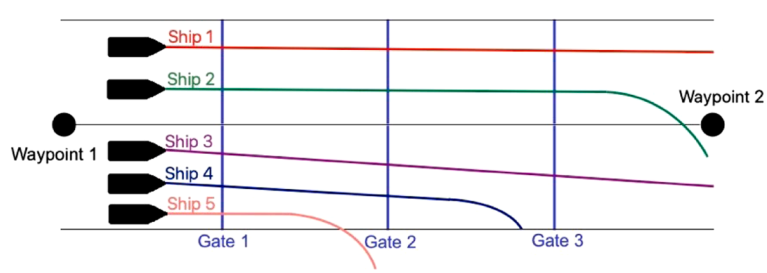
A collision candidate refers to a vessel that is on a collision course with another vessel, that may result in an accident if no evasive action is taken by the bridge crew onboard the ships. The number of collision candidates is a result of an overlap of the traffic density distributions on the analyzed legs, [38], as obtained from the AIS data. Therefore, the spatial aspect of the issue is well covered, however the temporal dimension of the topic is not directly accounted for. The causation factor reflects the chances of not performing an evasive action by a navigator onboard a ship in a collision situation.

Five collision types are anticipated in IWRAP software, as depicted in Fig. 10, which can be gathered into two groups, as follows:

- Parallel type of collisions, that happen along the leg:
  - Head-on - Fig. 10a – the difference in headings of two ships falls in a range of (from 170 to 190 deg).
- Overtaking - Fig. 10b – when the absolute value of difference in headings is less than 10 deg.
- Crossing type collisions in waypoints, where:
  - Two routes intersect - Fig. 10c.
  - Two routes merge - Fig. 10d.
  - The single route bends - (Fig. 10e).
  - The intersecting angle falling in the range of 010–170 deg and 190–350 deg.

Each of the collision type is associated with a corresponding causation factor, that is based on earlier studies conducted for various regions worldwide, see for example [39,40,94–96]. Since this parameter features a spread, which depends on the geographical area, [97], the IWRAP Mk2 software allows the end-user to modify it accordingly.

For the case study presented here we adopt the values of this parameter from the earlier work, where the causation factor was defined specifically for the Gulf of Finland, as shown in Table 3, and reported earlier in [98,99].



Ship no	1	2	3	4	5
Is criterion 1 met -*5 deg limit*	Yes	Yes	No	No	Yes
Is criterion 2 met - *2 gates passed*	Yes	Yes	Yes	No	No
Ship assigned to the traffic along the leg?	Yes	Yes	No	No	No

Fig. 9. Exemplary situations of trajectories of 5 ships steaming along the leg between two waypoints, and application of counting criteria, resulting in acquisition or not of a ship to the traffic data.

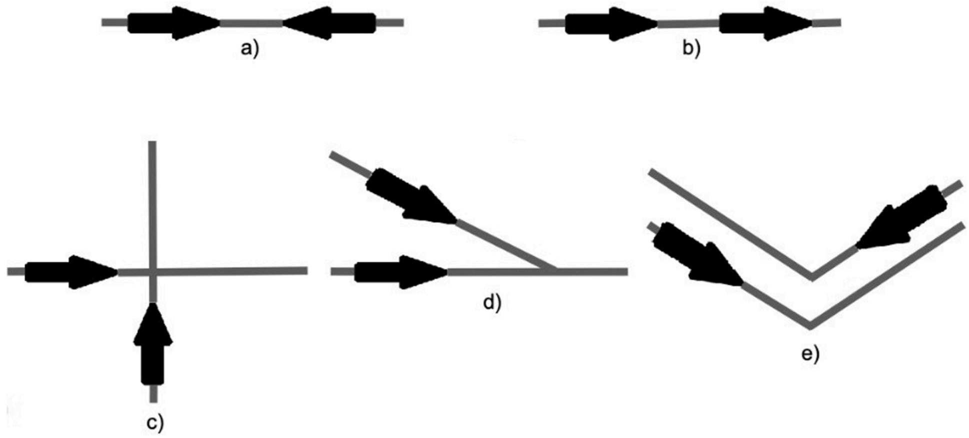


Fig. 10. Types of collisions: a) head-on, b) overtaking, c) crossing, d) merging, e) bend.

Table 3
Causation factor in the Gulf of Finland, adopted from [98].

Type of collision	Parallel		Crossing		
	Head-on	Overtaking	Crossing	Merging	Bend
Causation factor [-]	0,101E-4	0,562E-4	2,560E-4	2,560E-4	2,560E-4

In order to estimate the collision frequency, the ship traffic data is organized and presented to the end-user in the following manner:

1 The ships are classified according to their type and size.
2 For each leg, a number of ships in each class is counted.
3 For each leg the histogram of lateral position of ships across the given leg are determined and to this data the distributions are fit, as depicted in Fig. 11.

Based on this information, the geometric number of collision candidates can be calculated for each collision type separately, as explained below.

2.4.1. Parallel type of collision

This type of collision encompasses the head-on and overtaking collisions. For the head-on type of collision, the following formula is adopted from [39]:

$$N_G = L_w \sum_{i,\ j} P_{Gi,j}^{\text{collisiontype}} \frac{V_{ij}}{V_i^{(1)} V_j^{(2)}} \left(Q_i^{(1)} Q_j^{(2)} \right) \tag{2}$$

Where, L_w is the length of a leg, $Q_i^{(1)}$and $Q_j^{(2)}$are the number of ships passing through the given area in a time unit for each ship type and size in each direcion (1) and (2), $V_i^{(1)}$and $V_j^{(2)}$are their speed, while $f_i^{(1)}(y)$ and $f_j^{(2)}(y)$ denote the distributions of ship positions across the leg, as depicted in Fig. 12, and $P_{Gi,j}^{collisiontype}$ is the probability that two ships of a class i and j collide in a head-on encounter, described by Eq.3, as follows [39]:

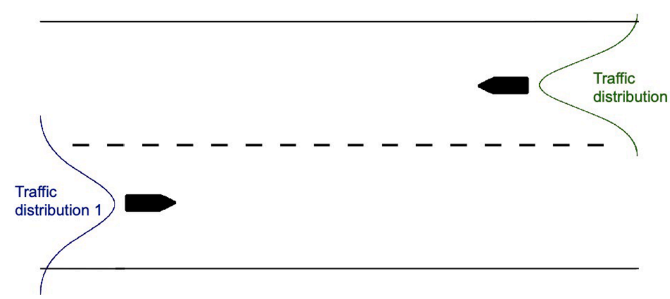


Fig. 12. Collision along the route and traffic distribution.

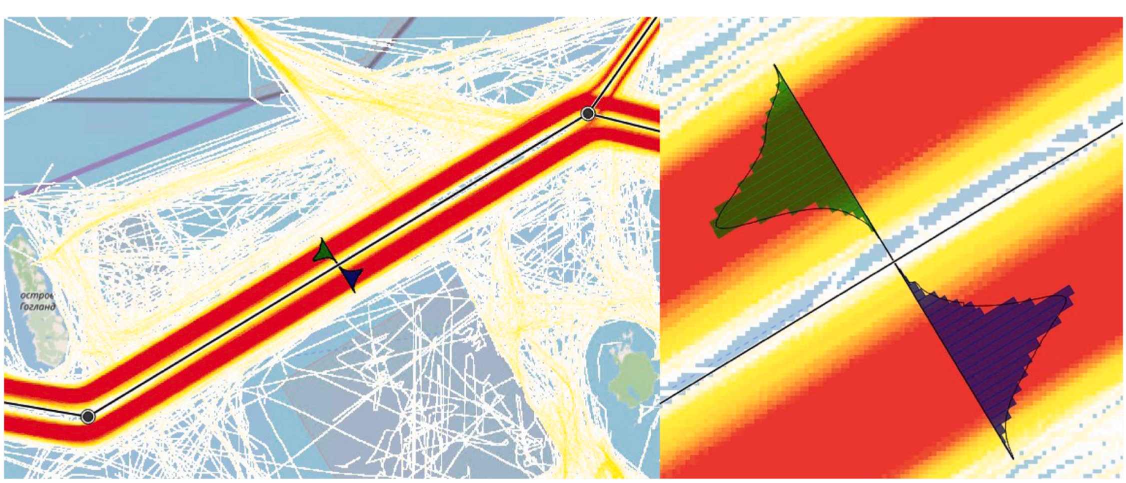


Fig. 11. Sample traffic density plot with the density distribution fitted.

$$P^{head-on}_{Gi,j} = P\left[y_i^{(1)} - \frac{B_i^{(1)}}{2} < -y_j^{(2)} + \frac{B_j^{(2)}}{2} \cap y_i^{(1)} + \frac{B_i^{(1)}}{2} > -y_j^{(2)} - \frac{B_j^{(2)}}{2}\right]$$

$$= P\left[y_i^{(1)} + y_j^{(2)} < \frac{B_i^{(1)} + B_j^{(2)}}{2}\right] - P\left[y_i^{(1)} + y_j^{(2)} < -\frac{B_i^{(1)} + B_j^{(2)}}{2}\right] \quad (3)$$

$$= \int_{-\infty}^{\infty} \int_{y_j=-y_i-\overline{B}}^{-y_i+\overline{B}} f_{Y_i}(y_i) f_{Y_j}(y_j) dy_i dy_j = \int_{-\infty}^{\infty} f_{Y_i}(y_i)\left[F_{Y_j}\left(-y_i+\overline{B}\right) - F_{Y_j}\left(-y_i-\overline{B}\right)\right] dy_j$$

where $B_i^{(1)}$ and $B_j^{(2)}$ are the widths of a ship for each ship type and size in each direction (1) and (2), and $\overline{B}_{ij} = \frac{B_i^{(1)}+B_j^{(2)}}{2}$ is the average width.

To estimate the frequency of overtaking type of collisions, formula Eq.1 and formula Eq.2 are used, with the modified parameter $P^{\text{collisiontype}}_{Gi,j}$ described by Eq.4, as follows [39]:

$$P^{\text{overtaking}}_{Gi,j} = P\left[y_i^{(1)} - y_j^{(2)} < \frac{B_i^{(1)} + B_j^{(1)}}{2}\right] - P\left[y_i^{(1)} - y_j^{(2)} < -\frac{B_i^{(1)} + B_j^{(1)}}{2}\right] \quad (4)$$

2.4.2. Crossing type of collision

This type of collision comprises of accident between ships on intersecting courses. The number of collision candidates for this collision type is considered independent of the distribution of ship positions across a leg [37,39], but depends on the following – as depicted in Fig. 13: angle between the two legs (θ), collision diameter (D_{ij}), number of ships in a given class and their speeds, as well as relative speed of encountering ships – V_{ij} in the following manner, [39]:

$$N_G = \sum_{i,\,j} \frac{Q_i^{(1)} Q_j^{(2)}}{V_i^{(1)} V_j^{(2)}} D_{ij} V_{ij} \frac{1}{\sin\theta} \quad (5)$$

$$V_{ij} = \sqrt{\left(V_i^{(1)}\right)^2 + \left(V_j^{(2)}\right)^2 - 2V_i^{(1)} V_j^{(2)} cos\theta} \quad (6)$$

$$D_{ij} = \frac{L_i^{(1)} V_j^{(2)} + L_j^{(2)} V_i^{(1)}}{V_{ij}} \sin\theta + B_j^{(2)}\left[1 - \left(\sin\theta \frac{V_i^{(1)}}{V_{ij}}\right)^2\right]^{\frac{1}{2}} + B_i^{(1)}\left[1 - \left(\sin\theta \frac{V_j^{(2)}}{V_{ij}}\right)^2\right]^{\frac{1}{2}} \quad (7)$$

where $L_i^{(1)}$ is the length of the ship i in waterway 1, $L_j^{(2)}$ is the length of the ship j in waterway 2, and B is the width of the vessel.

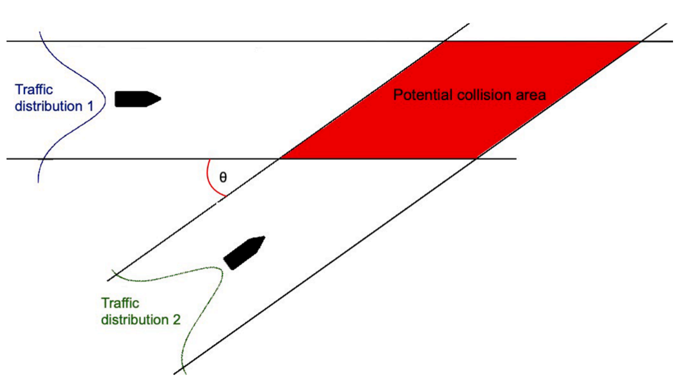


Fig. 13. Collision on crossing waterways and potential collision area.

2.5. Collision-prone locations identification

This section introduces a procedure resulting in the definition of the collision-prone locations over an analyzed sea area, based on normalization of the accident frequency as obtained through Eq.2.

The proposed procedure bounds linearly the collision frequency on parallel courses with the length of a leg (Eq.2). Since, each leg has different length, the resultant collision frequency will be also different, and the reason can simply be the length of the leg. This leads to a situation, where the obtained accident frequencies cannot be directly compared among the legs, as the longer legs will probably feature higher collision frequency than the shorter legs. To close this gap, a normalization procedure is applied, resulting in the collision frequency being expressed per length unit (nautical mile), instead of per leg. Only then, the most collision-prone areas of the traffic network (edges and nodes) can be reliably defined.

2.5.1. The most collision-prone edges in the network

To define the most collision-prone edges (legs) in the traffic network, the collision frequency coefficient called the normalized annual collision frequency - $\overline{F}_{l_j}$ - defined as follows:

$$\overline{F}_{l_j} = \frac{F_{l_j}}{|l_j|} \qquad \text{(collision per year / NM)} \quad (8)$$

where F_{l_j} is the annual collision frequency along the leg l_j, which length is denoted by $|l_j|$ (NM), while $L = \{l_1, l_2, \dots, l_n\}$ is a set of legs belonging to a model structure.

As the normalization is a division of the obtained annual collision frequency by the length of each considered leg, thus, the normalized annual collision frequency is expressed in collisions per year per one nautical mile. According to the formula Eq.8 the leg l_j is the leg with the highest normalized annual collision frequency if

$$\bigvee_{l_j \in L} \bigwedge_{l_i \in L, l_i \neq l_j} \overline{F}_{l_j} \geq \overline{F}_{l_i} \quad (9)$$

Next, we develop a following set comprising the normalized collision frequencies for all the legs belonging to the traffic network:

$$\left\{\overline{F}_{l_1},\ \overline{F}_{l_2},\ \dots,\ \overline{F}_{l_n}\right\} \quad (10)$$

Subsequently the set is sorted in descending order, as follows:

$$\left\{\overline{F}_1,\ \overline{F}_2,\ \dots,\ \overline{F}_n\right\} \quad (11)$$

where $\overline{F}_1 \geq \overline{F}_2 \geq \dots \geq \overline{F}_n$.

From such developed set we remove all the items lower by one order of magnitude than the item of the highest value - $\overline{F}_1$ in this case. Finally, the following set is retained:

$$\left\{\overline{F}_1,\ \overline{F}_2,\ \dots,\ \overline{F}_k\right\} \quad (12)$$

Where the highest value yields $\overline{F}_{max} = \overline{F}_1$, and the lowest is $\overline{F}_{min} = \overline{F}_k$.

Finally, the obtained set is split into three sub-sets, according to their values, as follows:

$$\left[\overline{F}_{\min},\ \overline{F}_{\min} + \delta\right],\ \left[\overline{F}_{\min} + \delta,\ \overline{F}_{\max} - \delta\right],\ \left[\overline{F}_{\max} - \delta,\ \overline{F}_{\max}\right] \quad (13)$$

where

$$\delta = \frac{\overline{F}_{max} - \overline{F}_{min}}{3} \quad (14)$$

While $[\overline{F}_{max} - \delta,\ \overline{F}_{max}]$ denotes the set of legs considered as the most collision prone.

2.5.2. The most collision-prone nodes in the network

The frequency of crossing-type collision (crossing, merging and bend) is calculated only in network nodes, since – by definition - the edges intersect or merge there. Since the node is defined as an area of a constant size, and there is no reference to its size in the equations estimating frequency of collision (Eq.5-7), the obtained values can be directly compared across all the nodes without the need of normalization. The procedure for finding the most collision-prone nodes (waypoints) is analogical to the one presented for edges.

The waypoint w_j features the largest annual collision frequency if:

$$\bigvee_{w_j \in W} \bigwedge_{w_i \in W, w_i \neq w_j} F_{w_j} \geq F_{w_i} \tag{15}$$

Where $W = \{w_1, w_2, \ldots, w_m\}$ is a set of waypoints belonging to a model structure and F_{w_j} is the collision frequency of waypoint w_j.

Similarly, to the legs, first we define the set comprising of all annual frequencies of accident for all the waypoints belonging to the traffic network:

$$\{F_{w_1}, F_{w_2}, \ldots, F_{w_m}\} \tag{16}$$

Next, the set is sorted in descending order:

$$\{F_1, F_2, \ldots, F_m\} \tag{17}$$

where $F_1 \geq F_2 \geq \ldots \geq F_m$.

From such developed set all items are removed that are lower by one order of magnitude than the item of the highest value - F_1 in this case, yielding:

$$\{F_1, F_2, \ldots, F_k\} \tag{18}$$

where $F_{max} = F_1$, and $F_{min} = F_k$.

Subsequently, the set is split into sub-sets by the values comprised in each sub-set, as follows:

$$[F_{\min}, F_{\min} + \gamma], [F_{\min} + \gamma, F_{\max} - \gamma], [F_{\max} - \gamma, F_{\max}] \tag{19}$$

where

$$\gamma = \frac{F_{max} - F_{min}}{3} \tag{20}$$

The sub-set $[\overline{F}_{max} - \gamma, \overline{F}_{max}]$ comprises the highest values of accident probability among all the waypoints, denoting thus the waypoints that are considered the most collision- prone for the given traffic network.

2.6. Verification procedure of the model

The structure of a base traffic model is developed according to the method described in Section 2.1, with the use of default IWRAP Mk2 settings. However, it remains unclear whether the given structure is the most appropriate, especially in terms of the coverage of all relevant routes, both their lengths and widths. With the 3-step verification procedure, we help to provide the end-user knowledge on the gain or loss they may be experienced when continuing development of the base model, by adding more information to the model, thus spending more resources and incurring higher costs. By introducing this procedure to the development process of maritime traffic risk modeling with the use of IWRAP Mk2 we assist the end-user in achieving the cost-benefit balance of the analysis as well as the particular traffic model reliability criteria, as proposed in [100] and postulated further in [19,101,102]:

- R2. The degree to which risk analysis produces identical results when conducted by different analysis teams but using the same methods and data.

The approach proposed here ultimately leads to more reliable risk model and consists of the three following tests applied consecutively, as depicted in Fig. 14:

1) the leg relevance – test A;
2) the leg width – test B;
3) the leg length – test C.

After each test the model structure is adjusted accordingly, and following the completion of all three tests the final structure of a model is obtained.

2.6.1. The leg relevance test - A

At this stage we expand the base model with additional legs representing low density traffic that was not initially translated into distinct routes.

The maritime traffic, mainly due to the paradigm of freedom of navigation, is partly regular as the routes can be easily distinguished and identified, where the majority of ships follow the same directions. To

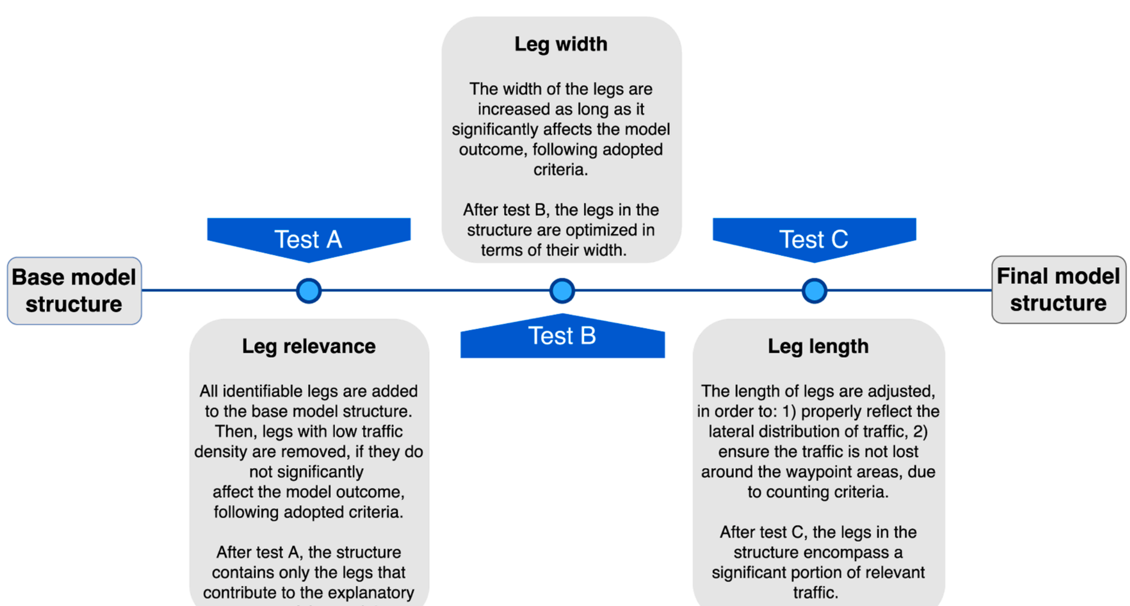


Fig. 14. A three-step verification procedure of the traffic model structure.

some extent the traffic can be irregular, especially in areas where it is temporarily scarce or spatially dispersed. The shares of those two types of traffic depend on the sea area. For example, the traffic over the sea with traffic separation schemes (TSS) or between important harbors is expected to be regular and only ships navigating outside the TSS, calling to less frequently visited harbors, or remaining outside the major routes will form irregular traffic. Therein the share of ships navigating regular routes are higher than those in irregular traffic. On the contrary, on the areas where traffic is not organized its irregularity is expected to be high. This can be seen on approaches from the ocean to land where routes converge from various directions and traffic is highly dispersed or areas ships infrequently navigate along a given route.

However, the IWRAP Mk2 software leaves it up to the end user to decide what routes shall be included in the traffic model, without any feedback on the effect of too simplistic model structure on the risk model outcome. To close this gap we propose test A.

The first step of test A is an extension of the base model with the routes that are infrequently visited by ships or are dispersed. Such a model, which is intentionally excessive, in terms of the number of legs and waypoints, is called an extended model. Subsequently, all the legs are examined applying consecutively four traffic density thresholds, to evaluate their expected influence on the outcome of the model (annual collision frequency *f*). The following traffic density thresholds are adopted:

1 T_1 - less than one ship per week (52 per year).
2 T_2 - less than two ships per week.
3 T_3 - less than four ships per week.
4 T_4 - less than seven ships per week (365 per year).

The procedure run by test A is iterative, and consists in removing from the extended model a set of legs meeting a given threshold until the outcome of the model at a particular iteration differs from the previous iteration by more than 5%. Then the removal of legs ceases, and all the remaining legs are considered relevant for the given analysis. In practice we remove from the extended model all the legs meeting T_1, and the resulting annual frequency of accidents are compared with the former value as calculated for the extended model. If the difference in the annual accident frequency (*df*), between actual and previous network, is more than 5% we exit and restore the previous shape of the network – the shape it had prior to this threshold. Otherwise, the new network is saved, and we move on to T_2, where the removal/checking procedure is repeated. The legs meeting T_2 are removed, and if *df* does not exceed 5%, we move on to T_3, otherwise we exit. The exit condition can be set-up individually, as it informs the end-user when to stop simplifying the network, as the loss of information becomes relevant. The flowchart of the test A is presented in Fig. 15.

The 5% criterion that is applied in this and other two tests is based on engineering judgment, however supported by good practices in uncertainty handling and expression in probabilistic risk assessment (PRA) - [103] - as well as results of PRA from other domains, where the difference in consequences of this size are considered minimal, see [104]. Therefore it is value is justified, even though it can be adjusted according to the needs.

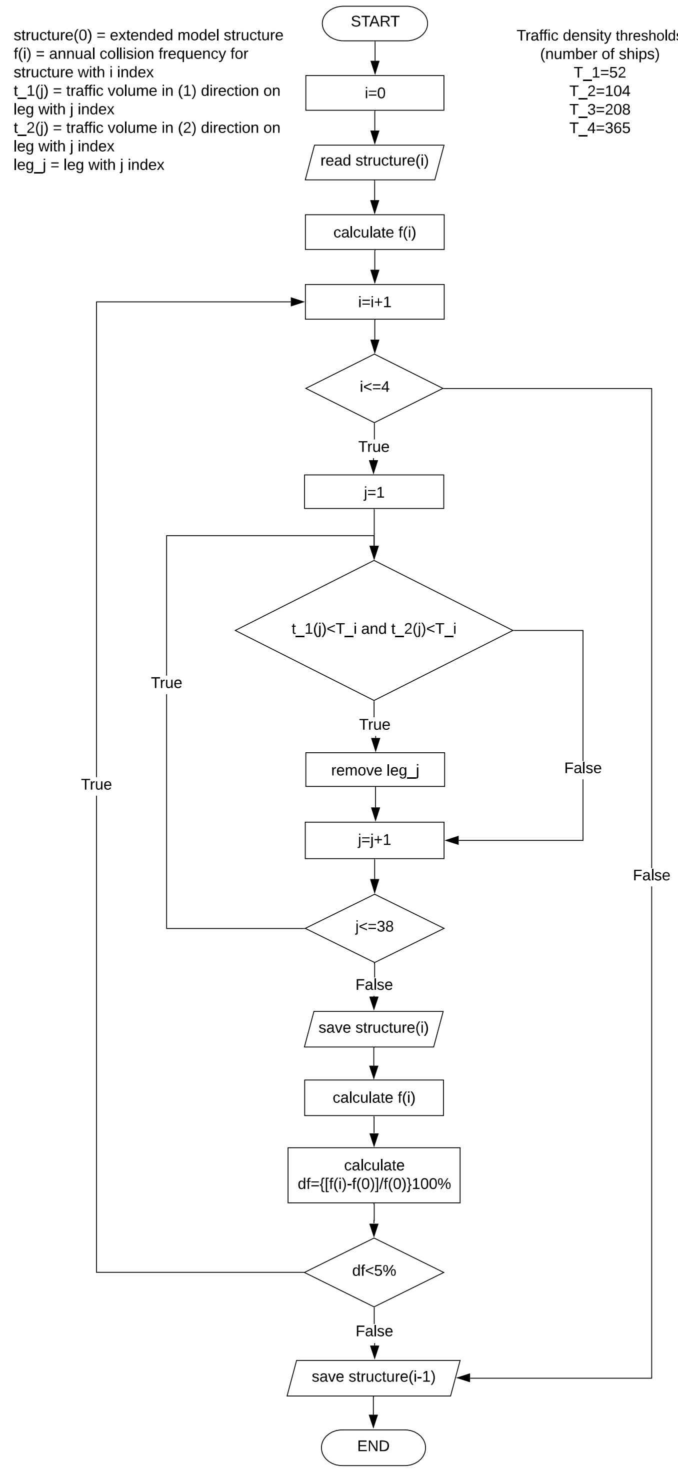


Fig. 15. The flowchart for test A.

2.6.2. *The leg width test – B*

Test B aims to assess the most effective and informative width of each leg. The initial width was set on the basis of the traffic density plot as produced by IWRAP. It unfortunately does not provide any insight into a possible impact of arbitrary settings of this parameter on the annual frequency of collisions. Therefore, test B is designed to examine how the increase of the leg width affects two parameters: 1) the calculated traffic intensity, 2) annual collision frequency on this particular leg and the adjacent waypoints. To this end, the width of a leg is gradually increased by 10% of its initial width until the change in the number of ships (*dt*) covered by the leg and the resulting annual collision frequency (*df*) becomes less than 5% compared to their previous values. Then, the given leg is no longer widened. The flowchart of the test A is presented in Fig. 16.

2.6.3. *The leg length test - C*

The distributions describing the traffic characteristics on each leg are key to the adopted method of collision frequency estimation. These distributions shall be relevant to the leg and have to reflect the dynamics of the traffic along the given leg properly, without significant loss of information. Therefore, two issues are identified here and addressed by

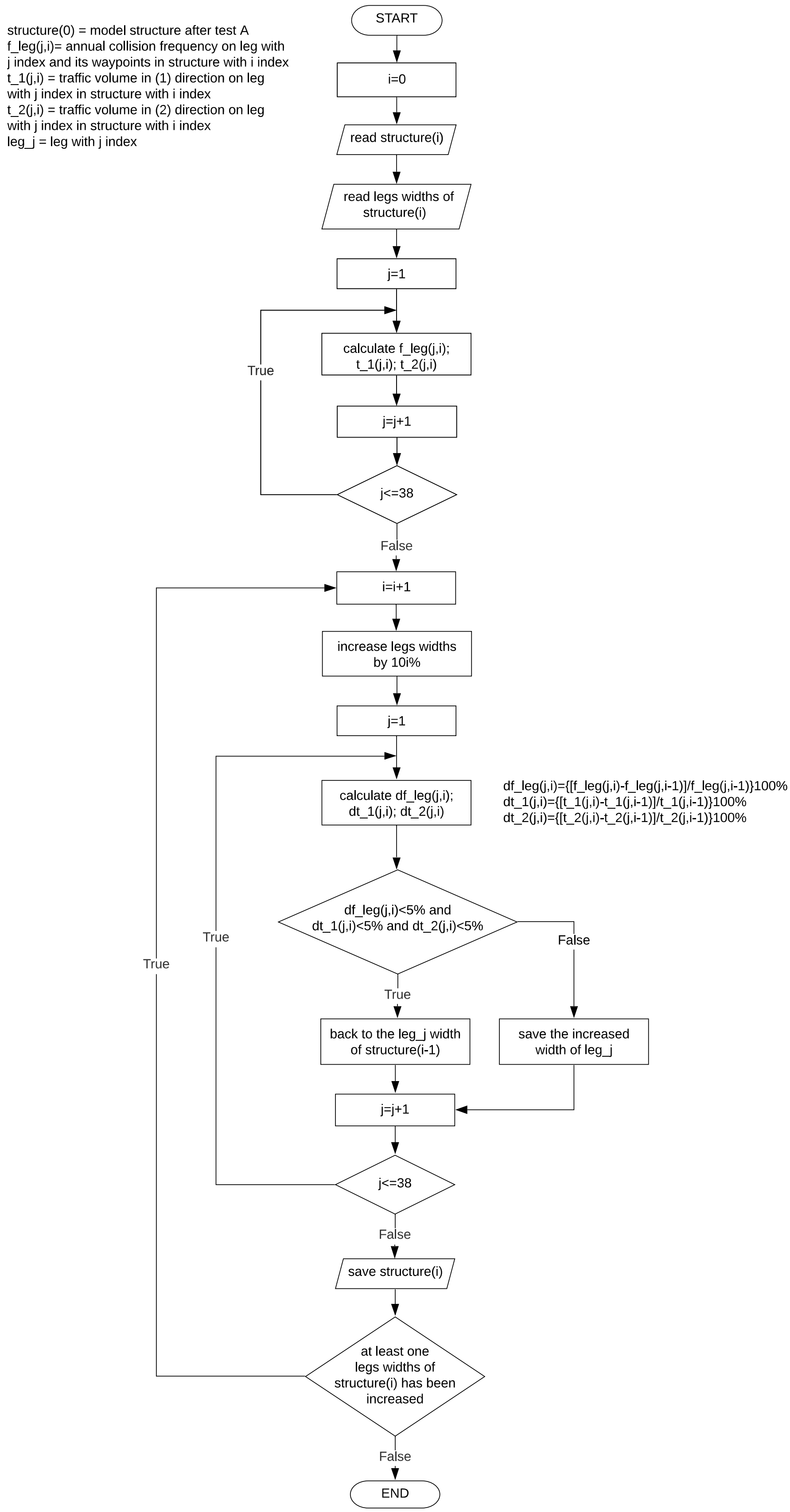


Fig. 16. The flowchart for test B.

test C.

First, the leg should not be excessively long, as it is likely that the obtained traffic density distribution from such a long leg will not reveal the local variation of traffic, that may be essential for the calculations of the collision frequency. Such a situation is depicted in Fig. 17, where a distribution of lateral positions of ships determined for the long leg (left image in Fig. 17) significantly differs from the distributions if the leg is split into two shorter segments (right image in Fig. 17).

Second, it is essential to adjust the length of two adjacent legs at a waypoint where ships alter their courses. Such legs shall be long enough to allow the majority of traffic to be included in the leg. If the leg is long enough the majority of ships will navigate along the leg direction and not exceed the 5 deg criterion prior to reaching the waypoint area (according to the counting criteria presented in Section 2.3). Therefore, the ships will pass through the majority of virtual gates set on the leg and will be assigned to this leg. When reaching the waypoint area, at the end of the segment, the ships will alter their courses, thus exceeding 5 deg criterion, but this will not affect the number of counted ships, since they already have met the counting criteria in the earlier sections of the leg. However, if the leg is too short, covering mainly the area where the ships alter their courses around the waypoint, the majority of trajectories may not meet the 5 deg criterion, thus the counting algorithm will remove them from the traffic data for this particular leg. In fact, for the legs that are too short, the loss of traffic may reach up to 70%, which significantly affects the obtained results in terms of collision frequency.

Therefore, test C intends to examine the effect of the adopted level of spatial resolution of legs on the collision frequency associated with the given traffic model.

3. Case study

The applicability of the novel framework introduced in Section 2 is demonstrated on a case study presented in this section. This includes the following: the model structure, ship-ship collision frequency estimates, identified collision-prone locations in the studied area of the Gulf of Finland, reflecting the period of ice-free navigation, with the focus on oil tankers. While the process of 3-stage verification applied to the model structure allows for an in-depth assessment of the modeling choices on the resulting annual collision frequency.

3.1. Model structure and ship-ship collision frequency

Structure of a base model, which is the initial step of the model development process is created with the use of the IWRAP Mk2 software tool adopting the AIS dataset as visualized in Fig. 2. The AIS dataset comprises all the traffic and ship types recorded in the area over the analyzed period of 2018, excluding February and March, and it yields the model structure presented in Fig. 18. Therein the main legs, and the waypoints between them, are visualized. Subsequently, three verification tests are carried out, as introduced in Section 2.6, to ensure the developed structure reflects the observed traffic in the optimal manner.

3.1.1. Expansion of the base structure – test a

The base traffic model structure is expanded according to the traffic density map obtained in the course of AIS data processing only for the oil tankers. Narrowing down the dataset, made the traffic picture much clearer, and facilitated the process of legs identification. Such a developed model is referred to as an extended model - Fig. 19- and is considered a canvas for test A. The latter checks the relevance of the legs based on their traffic density. In the course of test A, it becomes evident, as tabulated in 4, that the removal of the legs experiencing more than 2 ships per week (threshold 3) leads to a drop in the resulting annual collision frequency of 11.8%, compared to the extended model, as presented in Table 4. However, if the model is stripped from the less trafficked legs, with less than 2 ships per week (thresholds 1 and 2), the drop in annual collision frequency, in comparison to the extended model, is less than 5% (see Table 4). Since the adopted criterion for this test is 5%, we decide to exclude those less trafficked legs from the model. Thus the resulting model structure consists of 38 legs and 39 waypoints, as presented on the lower image of Fig. 20.

3.1.2. Estimation of the model leg width - test B

With this test we estimate the appropriate width of legs. To this end traffic density plots are used as background picture, and based on those, the width of each leg is set up, so the leg covers the majority of the plotted trajectories. Subsequently, all the legs are incrementally widened as long as the increase in the resulting annual collision frequency does not exceed 5%, compared to the value obtained in the previous step.

The exemplary results, for two sample legs, are shown in Fig. 21. Therein the relative changes in annual frequency of collision and traffic intensities in East (E) and West (W) directions are provided as a function of the leg width increase (compared to the initial value). On the left pane of Fig. 21 the width increases by 10% leads to the rise in the annual collision frequency and traffic intensities in both directions by more than a 5% criterion. Subsequently, the width was increased by another 10%, resulting in a 6% rise in one of the observed parameters. Then a widening of the leg by another 10% led to smaller increase of the observed parameters, less than a 5% criterion, and it was concluded that increase of the leg width by 30% of its initial size does not contribute significantly to the model outcome. Therefore, the width of the leg was set as 120% of its initial width. While the final width of another leg is set as 130% of its initial width, as depicted on the right pane of Fig. 21, since only when reaching a 30% increase in the width all the relative changes in observed variables become less than 5% criterion.

In a similar manner, the width of all the legs was evaluated and updated accordingly.

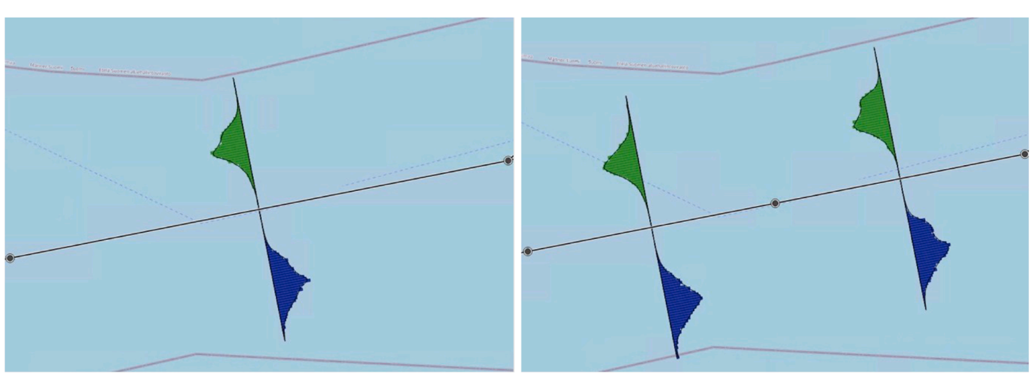


Fig. 17. Inaccuracy in traffic modeling due to the improper selection of leg length. Too long leg generalizes significantly different distributions (left) while splitting that leg into segments allows for more relevant traffic distribution estimation (right).

Fig. 18. Base model structure.

Fig. 19. Extended model structure.

3.1.3. Estimation of the model leg length - test C

Finally, test C is applied to the already updated traffic model structure, aiming at setting an appropriate length of the legs, after their number and width was fixed. For the sake of practicality all legs are classified as "long," "medium," and "short" which is a relative measure defined on the case-by-case basis. The model developed here contains six legs significantly longer than the remaining ones, so they are classified as "long". Then the median of all remaining legs was evaluated, and the legs longer than median are labelled as "medium" while the others are classified as "short".

Subsequently, the legs in each group are kept splitting into a number of segments, and for each new segment the annual collision frequency is estimated. The splitting process ceases as the relative change in the annual collision frequency does not exceed 5%.

The obtained results reveal the following, as depicted in Figs. 22-24-

- the short legs existing in our traffic model can remain unchanged,
- the long legs need to be split into 4 segments;
- the medium legs shall be split into 2 segments.

Any denser splitting of legs into segments does not add any significant amount of new information to the model, thus is obsolete. Based on those findings, the legs in the model are modified, resulting in a new model structure, comprising 69 legs and 70 waypoints - compared to 38 legs and 39 waypoints in the previous version of the model.

3.1.4. Summary of the verification procedure

The effect of each test on the resulting annual frequency of collision is presented in Table 5. It is evident that tests A and test C are the most influential, since they contribute to a 15% increase in the annual collision frequency, while test B contributes to a 2% increase. Therefore, it is of high importance to pay close attention to the proper inclusion of traffic (the waterways with less than 2 ships per week can be omitted in this case), and the analyzed legs need to be properly split, avoiding excessively long legs.

After completion of all tests, this new, improved model structure is considered final, and consists of 69 legs and 70 waypoints, as depicted in Fig. 25. Subsequently, this structure is used as a canvas to estimate the frequency of ship-ship collisions, involving an oil tanker, and to determine the most collision-prone locations in the analyzed area for this ship type.

Table 4
Changes in the model annual collisions frequency in the course of test A.

Type of model	Annual frequency of collisions	Relative change of the annual collisions frequency, with respect to **the extended model**
Base model – include only routes with moderate and high traffic density as revealed by the traffic plots.	0.162	–
Extended model, include all definable legs recorded in AIS data, regardless of traffic density along the legs	0.188	–
Extended model excluding the legs accommodating less than 1 ship per week (threshold 1)	0.184	−2.3%
Extended model excluding legs accommodating less than 2 ships per week (threshold 2)	0.179	−4.9%
Extended model excluding legs accommodating less than 4 ship per week (threshold 3)	0.166	−11.8%
Extended model, excluding legs accommodating less than 7 ships per week (threshold 4)	0.161	−14.5%

3.2. Evaluation of the collision-prone locations

The presented model yields two types of information. First, the frequency of collision is calculated separately for the legs and waypoints, and refers to the analyzed sea area for all or predefined types of ships. Second, the spatial distribution of the collision frequency across the analyzed sea area is shown, defining the most collision-prone locations.

Identification of the most collision-prone areas for oil tankers requires estimation of the collision frequency for this type of ships in the first place. Such results for all 69 legs and 70 waypoints are depicted in Figs. 26 and 27. Therein the normalized annual frequency of collisions involving at least one tanker is presented, expressed as the annual number of collisions per 1 nautical mile of a leg. The annual collision frequency estimated for waypoints does not require normalization, and the value obtained for all the waypoints can be directly compared between them.

Following the formulas Eq.8-14 described in section 2.5.3, the most collision-prone legs are determined, as depicted in Fig. 28, while a color code applied there corresponds to the colors bars in Fig. 26. The dark red represents the highest values of the normalized annual collision frequency while the yellow color denotes the opposite. The most collision-prone legs (marked with the dark red) are labelled with arrows showing the associated value of the normalized annual collision frequency.

Following the formulas Eq.15-20 the most collision-prone waypoints

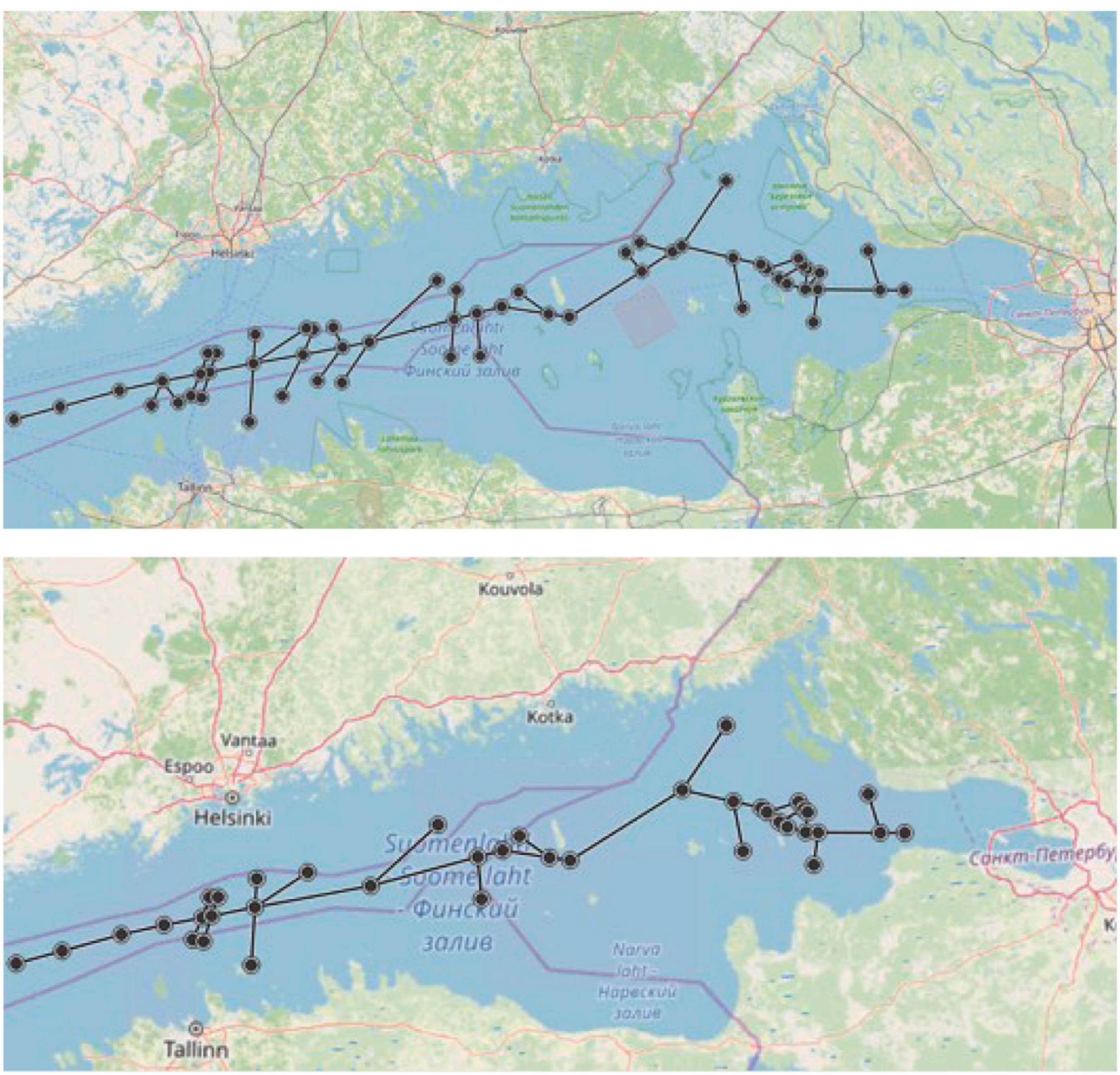


Fig. 20. Model structure prior to (upper image) and after (lower image) test A.

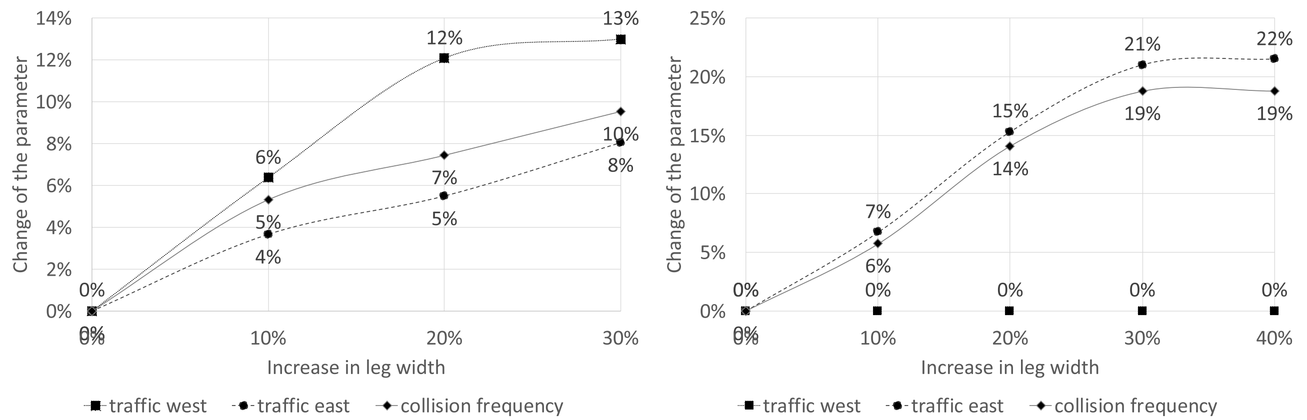


Fig. 21. Results of test B for two exemplary legs.

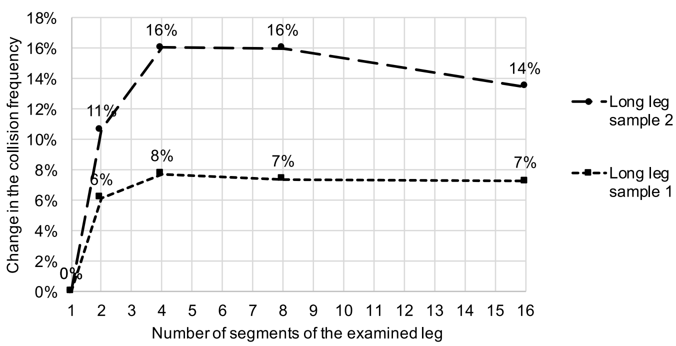


Fig. 22. Change in annual collision frequency (in percent) due to splitting of the leg into segments - results of the test C for the leg classified as long one.

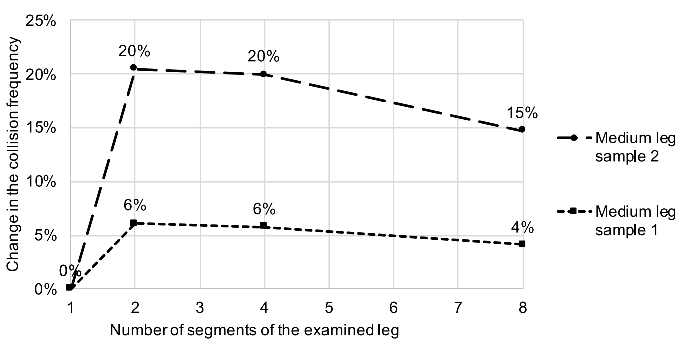


Fig. 23. Change in annual collision frequency (in percent) due to splitting of the leg into segments - results of the test C for the leg classified as medium one.

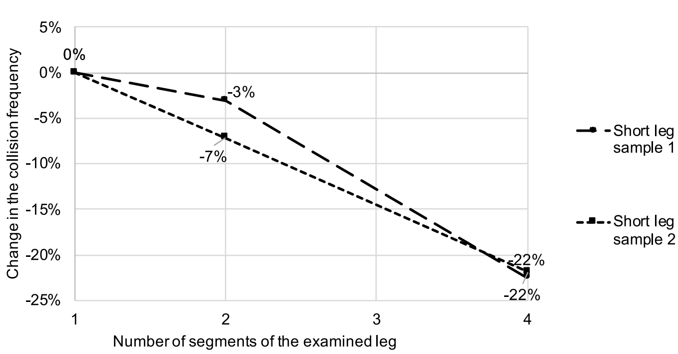


Fig. 24. Change in annual collision frequency (in percent) due to splitting of the leg into segments - results of the test C for the leg classified as short one.

Table 5
The effect of changes in the model on the collision frequency in the subsequent stages of model development.

Model development stage	Annual frequency of collision	Relative change in the annual collision frequency, compared to previous value	Cumulative change in the annual collision frequency, compared to the base model
Base model - using IWRAP default settings	0.162	–	–
Stage I - test A for the relevance of legs	0.179	10%	10%
Stage II - test B for the leg width	0.182	2%	12%
Stage III - test C for the leg length	0.190	4%	16%

are determined, which locations are shown in Fig. 29, marked with the dark blue color and additionally labeled with the arrow and associated numerical value. These are based on the results depicted in Fig. 27, where dark blue represents the highest values of the frequency and green refers to the lowest values.

The estimated annual collision frequency for the whole Gulf of Finland, for all ship types yields 0.190, which means one collision per 5.3 years. While the annual frequency of collisions involving at least one tanker yields 0.078, with the recurrence time of almost 13 years. However, the presented analysis does not account for the ice-navigation and resulting accident frequency, which in reality may shorten the recurrence period.

The most collision-prone locations, with respect to head-on and overtaking collision types, for tankers steaming through the Gulf of Finland during ice-free seasons, explaining over 63% of the collision frequency in the Gulf, as depicted in Fig. 28, are the following:

- On the main route around the Gogland Island, where the normalized annual collision frequency reaches up to 1.1E-4 per one nautical mile (NM).
- The routes adjacent to those legs, heading east and west, reveal the normalized annual collision frequency falling in a range of (0.5–0.8) E-4 per NM.
- In the eastern part of the GoF, at the split of waterways towards Vyborg and St Petersburg the normalized annual frequency of tankers collision is around 0.4E-4 per NM.

The results obtained for the crossing-type collisions reveal a similar

Fig. 25. The final structure of the model, after completion of test C.

pattern as in the case of the parallel types of collision, as shown in Fig. 27 and 29. The areas with the highest frequency of crossing-type of collision are located on the main route, as follows:

- South of Gogland Island, annual collision frequency of 1.8E-2.
- West of Gogland Island, close to the junction with a route to Estonian oil terminal of Sillamäe, annual collision frequency of 1.6E-2.
- In the eastern part of the GoF, at the split of waterways towards Vyborg and St Petersburg, annual collision frequency of 1.0E-2.

4. Discussion

The presented study aims to introduce a framework allowing more reliable estimation of ship-ship collision frequency and identification of the collision-prone locations. While the case study demonstrating the applicability of the framework refers to oil tankers navigating in the Gulf of Finland during ice-free season.

To this end, a traffic model is developed adopting commercial IWRAP-Mk AIS 2 software package, that is a recognized tool among users around the world and recommended by the maritime associations and authorities, employing a three-step verification procedure intending to increase the model reliability.

There are few points worth discussion here. First is the way to evaluate the reliability of the traffic model, developed from AIS data. This is a typical question in the risk analysis community, however often missed in the domain of maritime risk analysis. Despite the wide use of the adopted software and semi-dynamic network-based models, the problem of model reliability and proper selection of parameters remains an open issue. This aspect is an intrinsic part of modeling, as it refers to the quest for a trade-off between modeling effort and achievable accuracy. In practical application of the network-based traffic models, it is unrealistic to expect from the end-user to include in the model all possible nodes and edges belonging the traffic network. Therefore, evidence-based guidelines facilitating the evaluation of trade-off are sought, since IWRAP Mk2 tool is lacking those. To close this knowledge gap we propose a threshold-based verification process.

The parameters of the model structure obtained in the wake of the process, like number of legs, their width and length are justified based on tests, which made the overall model less prone to local variations, leading to more stable estimates of the collision frequency.

The process is objective and remains generic, the adopted value of 5% for the tests criterion tends to reflect the standards existing in the guidelines given by the maritime authority and industry as well as in the approaches to deal with the uncertainty in the probabilistic risk analysis.

Second discussion point refers to the idea of normalization of accidents frequency over the length unit of the analyzed legs. It is simple yet allows for direct comparison among various sea areas using the same quantity. This leads to the identification of the most collision-prone areas in reliable fashion.

Altogether, such developed model improves in the following generic reliability criterion, giving some hints on the proper use of this particular method, [19,101,102]:

- R2. The degree to which risk analysis produces identical results when conducted by different analysis teams but using the same methods and data.

The results of the 3-stage verification process, for the case-study presented here, revealed the following:

- Test A - a traffic model should account for any leg where the traffic intensity is higher or equal 2 ships per week - as presented in Table 4. Removal of legs with traffic intensity smaller than 2 ships per week leads to the underestimation of the collision frequency below 5%. While removal of the legs with traffic intensity less than 4 ships per week would cause the underestimation of collision frequency by 11.8%. The latter exceeds the adopted threshold, thus those legs are retained in the model.
- Test B - the leg width increase is sometimes also needed, but it does not contribute the most to the outcome of the model.
- Test C - the resolution of the leg length needs to be properly adjusted, to this end long legs in the model shall be split into 4 segments each, moderate into 2 segments, while the short legs can remain unchanged. Any denser splitting of the legs does not bring any benefit, since a significant fraction of ships become excluded from the traffic distributions, especially from the sectors close to the waypoints, as they do not meet the 5 deg criterion, as pointed out already in Section 2.6.3.
- All three tests led to a considerable modification of the base model, yielding the following changes in the annual collision frequency as follows – see Table 5:
- 10% increase in the wake of test A.
- 2% increase as a result of test B.
- 4% increase resulting from test C.

Although only two verification tests out of three markedly influence the developed model, all three are justified, clearly contributing to the overall improvement of the model reliability. Among the three test, test B showed the lowest influence of the leg width on the annual collision frequency and proved that IWRAP correctly adjusts leg widths based on the AIS dataset. However, special attention needs to be paid to the proper translation of the traffic density plot into the models' structure in terms of the number of legs and their length, since the majority of uncertainty stems from there.

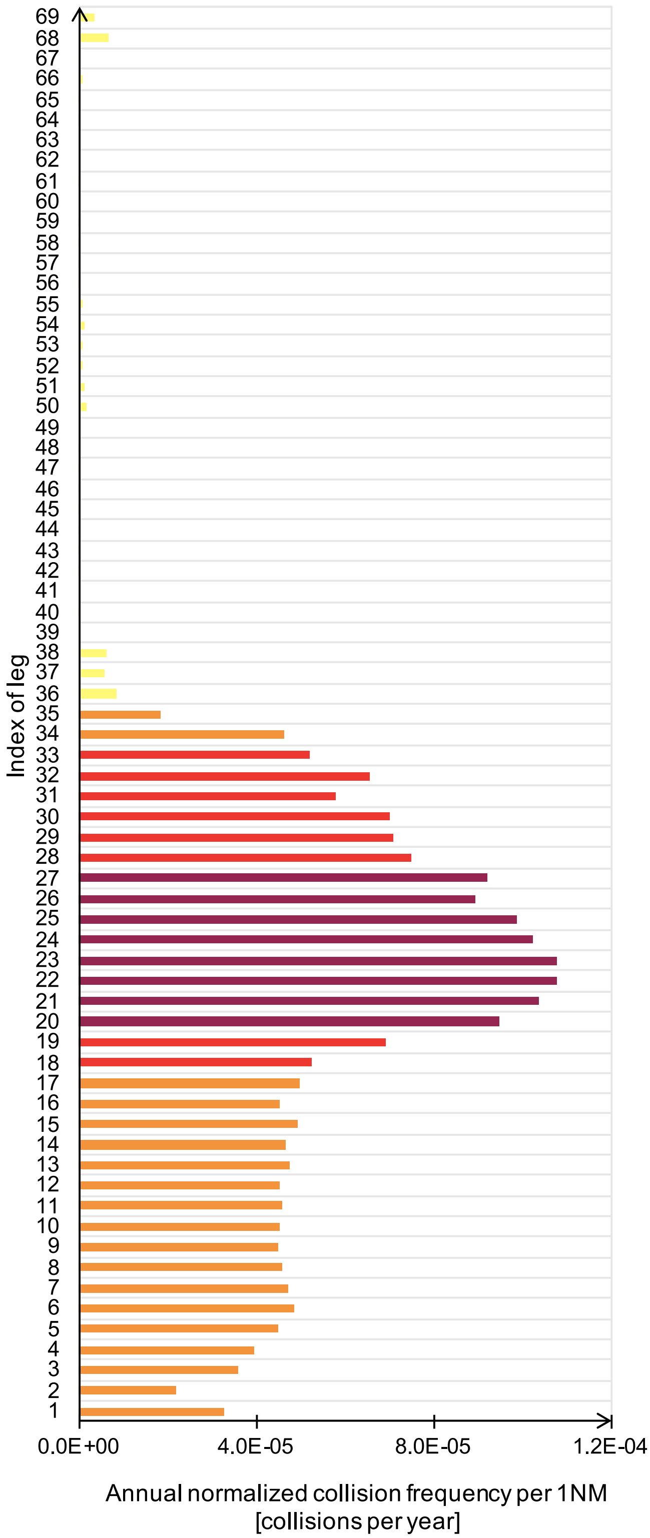


Fig. 26. The normalized annual frequency of collisions on legs for tankers.

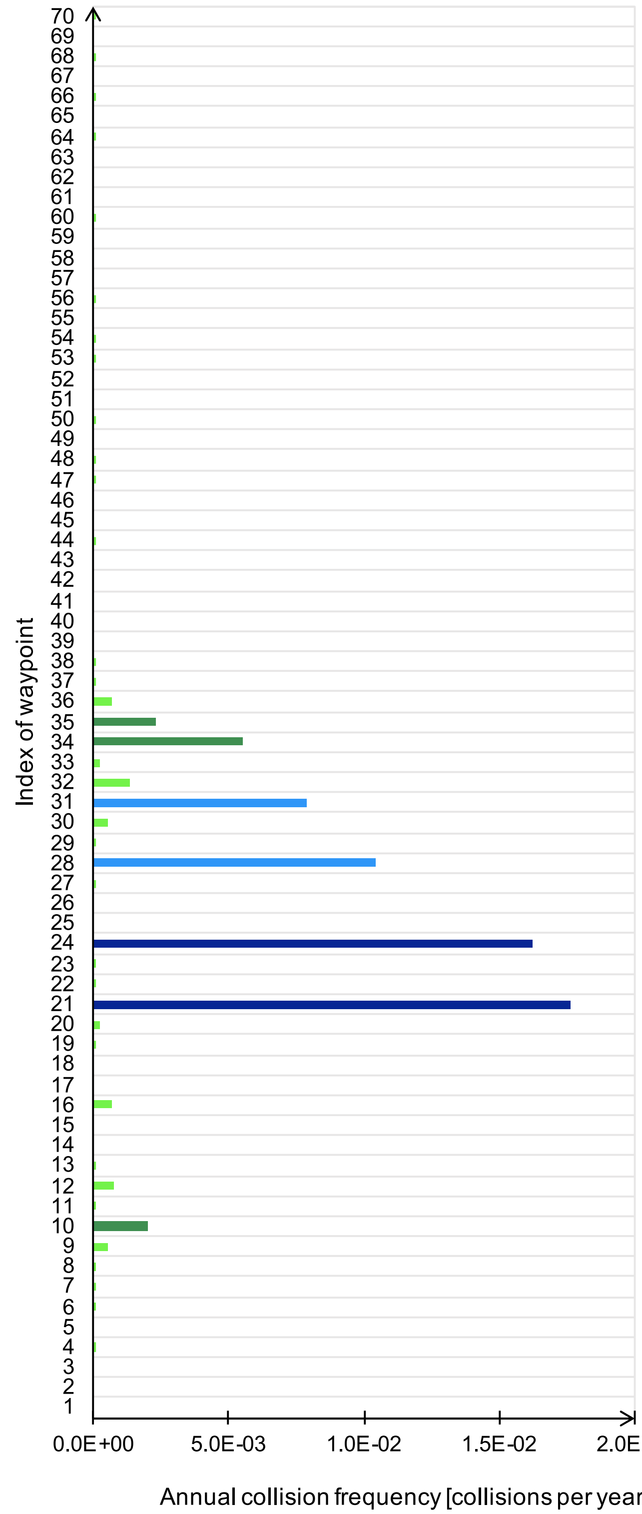


Fig. 27. The annual frequency of collisions on waypoints for tankers.

The results obtained from the IWRAP Mk2 base model and the proposed framework are presented in Table 6 for comparison. What is important is not only the comparison of pure numbers, but the fact, that by applying the framework introduced here the end-users are gaining the confidence in the model outcome, through its increased reliability. Also the uncertainty bounds are established, through the iterative, evidence-based verification process. All these were not available to the end-user when just using base model.

Another aspect, that is crucial for the reliability of risk assessment of maritime transportation, is the proper translation of the tempo-spatial variation of traffic over the and its effect on the collision frequency, [105]. The presented study does not account for that fully, since the yearly traffic data are imported all at once, thus the resulting estimates are given as a single number, and the effect of traffic variability is averaged out. However, dividing input data into smaller datasets, covering narrower time spans, would yield month-specific results, where each month is attributed with the collision frequency. Such an

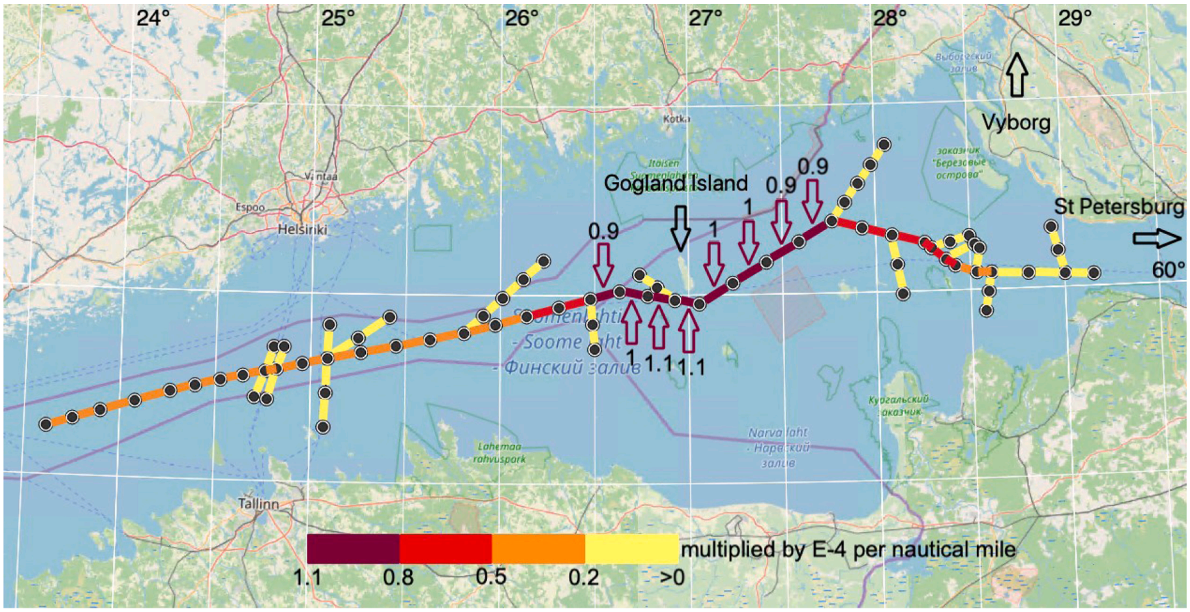


Fig. 28. The map of the annual normalized collisions frequency for tankers - the most collision-prone legs. The color code corresponds with Fig. 26.

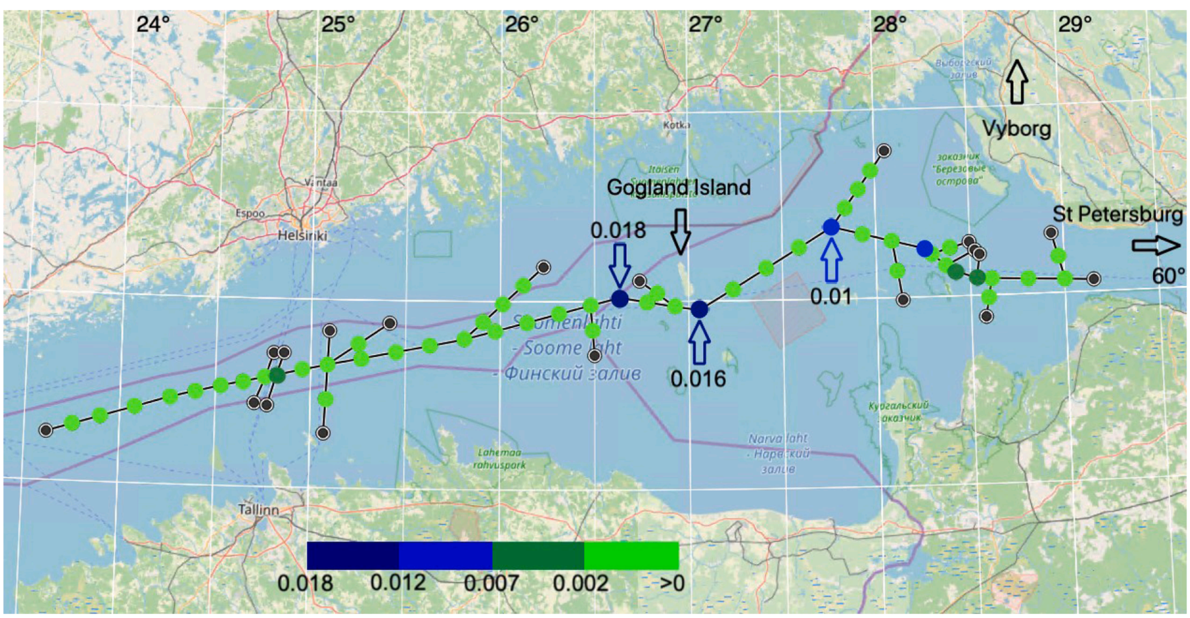


Fig. 29. The map of the annual collisions frequency for tankers - the most collision-prone waypoints. The color code corresponds with Fig. 27.

Table 6
The comparison of results generated by the IWRAP Mk2 base model and the proposed framework.

	IWRAP base model using default settings	Proposed framework
Annual collision frequency	0.162	0.190
Model reliability	Unknown	Assessed

approach would express accident frequency in a form of interval rather than a single tone, which would provide better insight into annual variation of this parameter, which is intuitive, since the traffic composition is far from constant, especially in the areas with scheduled and season-dependent traffic, such as the Gulf of Finland. This will allow one to account for another source of uncertainty and present it in an informative manner.

Last but not least, the quality of traffic data needs to be assured. To this end relevant data, in this case AIS data, must be screened for inconsistencies and outliers, as those may significantly affect the outcome, [106]. For example, in the case presented here we found the number of samples with erroneous information on ship draft, e.g. the draft equals the half of ship width, which is obviously impossible for conventional ships. Since this parameter is irrelevant for the risk of collision analysis, it is not corrected in the database. However, it will become crucial for the risk of grounding assessment, thus appropriate methods need to be employed to correct this wrong and misleading information.

Finally, since the focus here was on estimation of collision frequency, a similar approach including verification process can be taken to estimate grounding frequency in the future.

5. Conclusions

The objective of the presented study was two-fold. First, at the foundational level, we propose a three-stage, systematic, rational and evidence-based framework for the development of a model structure, suitable for semi-dynamic, network-based maritime risk traffic models, such as IWRAP Mk2, encompassing a verification process assisting the traffic model structure development. To facilitate direct comparison of the accident frequency across the areas, or waterways, and to determine the collision-prone locations, we introduce the concept of a normalized collision frequency. It can be easily applied in any future quasi-dynamic network-based models aiming at the identification of accident frequency or accident-prone locations.

Second, at the application level, a case study is performed, resulting in the estimates of the collision frequency between ships navigating in the Gulf of Finland (GoF), focusing on oil tankers. Additionally, we identify the most collision-prone locations in this sea area during ice-free periods. As a result of the case study the annual frequency of collisions involving at least one tanker for the whole area of the GoF yields 0.078. This is tantamount to the return period between collisions of 13 years. The most collision-prone areas are found along the main E-W route cutting through the GoF, on the traffic lanes to the east and west of Gogland Island. This area is expected to account for more than 63% of all the collisions involving tankers in the Gulf, while the remaining 27% is spread across the remaining routes in the GoF.

The outcome of this study could be relevant to several groups of stakeholders. First is the scientific community, since the paper provides a novel, clear, coherent, and rational framework encompassing verification process, that intends to reduce the uncertainty of the model structure, which earlier remained to a large extent unidentified and was thus unmanageable. The verification process is generic and applicable to any collision frequency model to be developed with the use of IWRAP-like tools.

The second group of potential end-users of this study are maritime administrators, especially those from the Baltic Sea rim, which focus on the improvement of maritime safety or mitigation of accident consequences. The former encompasses, for instance, traffic regulation modifications in the analyzed sea area (Gulf of Finland), while the latter may cover planning, developing, and distribution of oil spill response capacity.

Future work could focus on more detailed representation of temporal aspects that the maritime traffic features, to reflect better the temporal changes and their effects on the collision frequency.

On an application side of the framework, it is essential for the Northern Baltic Sea to account for harsh weather conditions, such as ice cover, and different modes of navigation, such as ice navigation. The evident diversity in traffic characteristics as well as significant differences in the mode of ship navigating deserve a completely new approach to model frequency of accidents during winter navigation.

6. Author agreement

All authors have seen and approved the final version of the manuscript being submitted. I warrant that the article is the authors' original work, hasn't received prior publication and isn't under consideration for publication elsewhere.

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.

Acknowledgments

The work is supported by SIMREC project. The South-East Finland-Russia CBC 2014-2020 programme is the main contributor.

The authors are grateful to three anonymous reviewers for their useful comments and suggestions to earlier versions of this paper.

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