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NAVIGATIONAL RISK ANALYSIS IN THE AREA OF THE NEW CONTAINER TERMINAL IN ŚWINOUJŚCIE

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Purpose: The purpose of this study is to analyse and assess navigational safety in the area of the planned container terminal project in Świnoujście. Due to the strategic importance of the project, the safety assessment requires a multi-faceted approach, including mathematical modelling and simulation methods. The premise of the analysis is that the level of navigational risk in the analysed area depends on the intensity and structure of vessel traffic in the designated survey sectors. The hypothesis is based on the assumption the level of collision risk is strongly correlated with the number and type of vessels registered in the AIS data for each sector.
Design/methodology/approach: The research used a quantitative analysis of AIS (Automatic Identification System) data acquired for the Baltic Sea area for 2019-2022. The data was used to estimate the level of risk in terms of potential collisions and manoeuvring errors. The study is of a practical nature and is based on empirical data and analysis of local shipping conditions.
Findings: The use of simulation led to results that identified high-risk sectors and could form the basis for recommendations on navigational safety and the development of future maritime traffic management strategies.
Practical implications: The study aims to analyse current AIS data and local shipping conditions, which limits its application to wider geographical contexts. Further research is needed including forecasts of changes in traffic volumes and the impact of meteorological conditions. The analysis can be the starting point for more advanced risk simulations and cost-benefit analyses for shipping infrastructure investments.
Originality/value: The article brings new value by analysing navigational risk based on AIS data in a specific investment context. It identifies practical steps to enhance navigational safety in one of the key transport areas in the region. It is aimed at both decision-makers responsible for port infrastructure development and professionals involved in maritime safety and spatial planning.
Keywords: navigational safety, navigational risk analysis, AIS data, approach track, vessel traffic intensity, port spatial planning, port infrastructure, VTS.
Category of the paper: Viewpoint.

1. Introduction

Maritime transport in the Baltic Sea has been growing rapidly in recent years. Every year, more and more ships pass through this body of water and ports handle an increasing number of cargoes. This development necessitates investment in modern port infrastructure, especially in countries such as Poland, which have strategic access to the sea and want to maintain their position in a competitive market.

One of the key projects in this trend is the planned construction of a deep-water container terminal in Świnoujście. The new infrastructure is expected to enable the handling of the largest container vessels operating in the Baltic Sea and significantly increase the port's handling capacity. This is a major step forward from the point of view of the maritime economy, but also a challenge in terms of navigational safety in a busy area.

The South Baltic region, including the Świnoujście area, is one of the key intersections of shipping routes in this part of Europe. Based on AIS data from 2019-2022 (Figure 1), several major maritime corridors are clearly visible, leading, among others, through the Danish Straits to Western European ports, as well as routes connecting Poland, Sweden, Lithuania, Russia and Germany. Particularly intensive traffic is observed on the approaches to the Gulf of Gdansk, around Copenhagen and on the Karlskrona-Gdynia/Gdansk route. This traffic includes commercial vessels as well as passenger ferries and local vessels. In addition, there is increased recreational traffic during summer periods. The concentration of multiple vessel types, variable hydrometeorological conditions and the need to manoeuvre in a narrow approach lane means that the Świnoujście area requires special attention in terms of navigational safety.

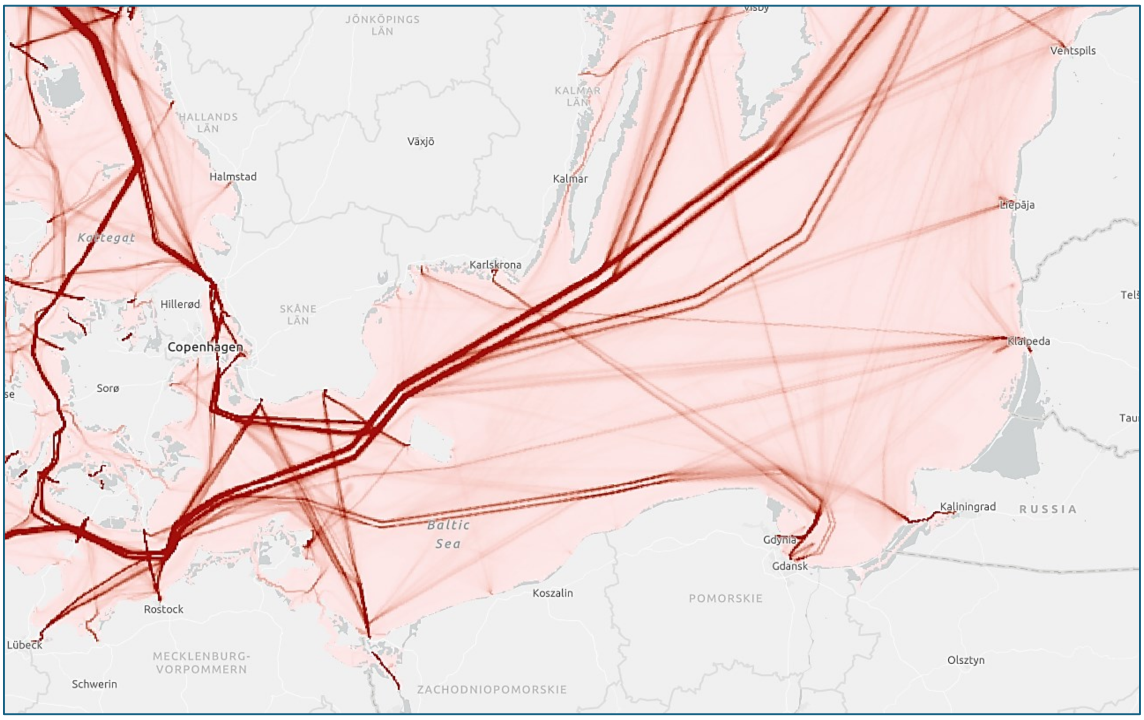

Figure 1. Main shipping routes in the Baltic Sea in 2019-2022 (compiled from AIS - Helcom data).

The planned construction of the container terminal will have a direct impact on the layout and intensity of ship traffic in the area. Consequently, it will not only be necessary to adapt the hydrotechnical infrastructure - such as the modernisation of the fairways or the construction of new breakwaters - but also to strengthen the maritime traffic management systems. This includes the expansion of the VTS system, the adaptation of pilotage procedures and the potential implementation of dynamic traffic separation systems (TSS) to safely integrate the new terminal with existing shipping traffic.

The new terminal is intended to serve as a significant transhipment hub, capable of handling the largest container vessels that can call at Baltic ports. This investment, while essential from an economic and logistical point of view, also poses serious challenges in terms of the organisation of maritime traffic and the safety of shipping. This is particularly important in the context of the current load on the waterways in the Świnoujście area, which is already characterised by a high volume of ferry, commercial and local traffic.

This article attempts to provide a comprehensive assessment of the potential risks associated with the operation of a container terminal. The analysis focuses on navigational safety and risks along different sections of the port approach route. Based on available AIS data, spatial and hydrographic analyses, as well as vessel traffic regulations, an assessment of the level of risk in the different sectors of the basin has been carried out. The conclusions of this analysis can be helpful for both the developer and the institutions responsible for maritime traffic management in the region.

The originality of the study stems from its practical and interdisciplinary nature. Given the dynamic development of the maritime infrastructure of the Polish Baltic coast - exemplified by the planned construction of the container terminal in Świnoujście - analyses are required that not only identify potential hazards, but also propose specific actions to enhance maritime safety. The article primarily responds to the need, which combines the analysis of AIS data with an assessment of local spatial and hydrographic conditions and existing regulations.

The study is characterised by dividing the study area into four survey sectors for which a separate risk assessment was carried out. In this way, local differences in traffic and spatial conditions were taken into account, and variability in the data was treated as a signal of possible risks. This approach allows the actual risks to be assessed and adjusted measures and recommendations to be proposed, which may be relevant in the context of the planned container terminal in Świnoujście.

2. Literature review

Shipping safety is a rapidly developing field that combines engineering practice with risk analysis and new technologies such as VTS systems or predictive tools based on AIS data. Increasingly, there is a shift away from purely traditional methods, with researchers and practitioners introducing probabilistic solutions, machine learning models and advanced analysis of vessel trajectories. One important aspect influencing the safety of manoeuvring in ports is adequate manoeuvring support, which significantly reduces the risk of collision and improves the efficiency of vessel berthing, especially in difficult hydrometeorological conditions (Paulauskas, et al., 2021). Such measures are complemented by advanced risk models based on fuzzy logic, which enable collision risks to be assessed taking into account the angle of intersection of vessel routes and the characteristics of the navigational environment (Shi et al., 2022).

Due to their intensive operation and the nature of passenger transport, ferries are among the units for which safety analysis must be carried out in a way that specifically considers operational risks. The models used in this context take into account both technical aspects and human factors (Hsu et al., 2022). A similar approach has been adopted in analyses for container ships, where Bayesian networks have been used to identify critical risk points along the operational chain (Zhou et al., 2022).

In inland waters, as the example of the Songhua River in China shows, navigational risk is particularly dependent on local hydrographic conditions and the intensity of vessel traffic. Methods for risk assessment in such environments are based on historical data and adverse event analysis (Xia et al., 2023). An interesting approach has also been proposed for the analysis of AIS data - by comparing vessels involved in accidents with those that avoided incidents, key risk indicators have been identified (Aalberg et al., 2022). Another factor affecting safety levels is the presence of hydraulic works. Studies have shown that construction works carried out in the vicinity of shipping lanes can temporarily increase navigational risk, which requires detailed analysis and compensation measures (Paulauskas et al., 2023).

Particular importance is also given to incidents that are not accidents, but only potentially dangerous situations detected by analysing AIS data. This approach allows hazards to be identified before an actual incident occurs, thus increasing the effectiveness of prevention efforts (Du et al., 2020).

The Baltic Sea region, especially its northern part, has also been the subject of maritime risk analyses based on AIS data. The results of these studies point to the need to adapt maritime traffic management systems to regional specificities (Du et al., 2021). Similar conclusions have been drawn from studies of navigation in Arctic waters - conditions there require particularly precise decision support tools (Yang et al., 2021).

There are also studies in the literature that focus on the accessibility of selected sites in the southern Baltic Sea region, which are relevant to the planning of environmental studies (Kubacka et al., 2024), and on the risks associated with marine traffic in the vicinity of wind farms (Rutkowski, Kubacka, 2023). Developed Bayesian network methods (Kong et al., 2024), as well as artificial intelligence techniques that can support analyses for different transport modes (Tselentis et al., 2023), are effectively used for risk assessment in such cases.

There is also no shortage of multi-criteria approaches, such as FAHP-entropy-VIKOR, used for risk management at container terminals (Khorram, 2020), or synthetic reviews of available risk assessment methods in maritime transport (Huang et al., 2023).

From a port risk management perspective, the organisation and operation of container terminals is of significant importance. Pallis (2017) draws attention to the specificity of risk management in these units, pointing out the need to integrate multiple sources of information and implement operational safety procedures. In addition, it is worth citing studies dedicated to the impact of the shore effect on fairway width, which show the importance of precise hydrodynamic analysis to ensure the safe passage of vessels with fragile hulls (Baric et al., 2019).

In recent years, increasing attention has been paid to the development of tools to enable ongoing safety management. Li et al. propose an integrated vessel traffic management system based on dynamic collision risk analysis in congested ports and fairways (Li et al., 2023). This approach significantly improves the efficiency of traffic management and allows rapid response to changing conditions. In automated container terminals, a significant challenge is the allocation of storage yards - an issue addressed by He et al. who proposed a dynamic allocation algorithm that indirectly affects the safety of port operations (He et al., 2022).

Li and co-authors, on the other hand, provide an overview of wharf management methods, showing how modern approaches can improve the operation of marine terminals while enhancing their safety (Li et al., 2023). An interesting perspective is presented by Yu et al. who proposed optimising ship routes taking into account local traffic patterns, resulting in increased predictability and safety in ports (Yu et al., 2021).

Documents from the PIANC organisation provide a series of design guidelines for channels leading to ports and how they deal with the impacts of climate change and unpredictable weather events - which is crucial for long-term port infrastructure planning (PIANC, 2014a, 2014b, 2020). This is complemented by USACE design guidelines, which apply to both deepwater navigation and general coastal engineering (USACE, 2006, 2018).

Authors such as Gucma have developed a number of tools to assist in the analysis of fairway shunting safety. Kinematic and simulation approaches for determining the width of fairway bends have been developed (Gucma et al., 2020, 2022; Artyszuk et al., 2016), as well as comprehensive approaches for formal assessment of shunting safety (Gucma, Ślączka, 2018). Their work contributes significantly to the development of methodologies for the design and assessment of waterway infrastructure in the Baltic Sea region (Gucma et al., 2022).

Zalewski presented an analytical concept for determining fairway design parameters, based on algorithms that can be useful under conditions of limited data availability (Zalewski, 2012). On the other hand, Artyszuk and co-authors presented methods for optimising the width of fairway bends using computer simulation, which allows the infrastructure to be fine-tuned to meet the requirements of specific vessel types (Artyszuk et al.,2016).

Rodrigue's work presents a systems analysis of container terminal layouts, focusing on their functional layout and its impact on operational safety (Rodrigue, 2025). Similarly, Emery analyses the costing approaches used by the USACE in estimating dredging works, which is relevant to sound investment planning (Emery, 2024).

Autonomy is playing an increasingly important role in modern approaches to collision avoidance in confined waters, with research by Cho et al. showing how autonomous systems can operate in accordance with maritime regulations while ensuring safe manoeuvring in tight spaces (Cho et al., 2023)

The development of port infrastructure in Poland is also becoming an important topic of analysis, especially in the context of increasing competitiveness and increasing the potential of transshipment (Ministry of Infrastructure, 2023). It is also worth noting that textbook economic approaches, such as the one presented by Mankiw, can also provide a useful background for assessing the profitability of investments in maritime transport safety (Mankiw, 2020).

3. Navigation analysis methodology

The navigational analysis was based on AIS (Automatic Identification System) data acquired for the Baltic Sea area in the period 2019-2022. The data contained information on the positions, direction and time of passage of vessels through spatially defined survey gates, distributed in four sectors (A-D). QGIS software was used to preprocess and visualise the spatial data, while further analytical and statistical operations were carried out using the Python language (libraries: pandas, numpy, scipy, matplotlib).

A probabilistic approach was used to quantify collision risk, where the primary measure was the expected value of the number of collisions for a given vessel type. Risk (R) was defined as:

$$R = N \times Pk, \tag{1}$$

where N is the number of vessel passages through the sector in the year under consideration and Pk is the assigned probability of collision, estimated on the basis of HELCOM reports and the contribution of the vessel type in question to the total number of marine casualties in the region.

Due to the random nature of collision events, a Monte Carlo simulation was used to map the distributions of the potential number of collisions. For each year and unit type, 10,000 samples were generated from a Poisson distribution in which the mean corresponded to R. The simulations made it possible to estimate not only mean risk values, but also standard deviations, minimum-maximum ranges and detection of outliers, indicating potentially extreme cases.

The results of the collision risk analysis carried out are directly dependent on the number of vessels passing through the measurement area, reflecting the volume of maritime traffic in sectors A-D. Collision probability values (Pk) were estimated based on the number of recorded accidents involving specific vessel types in the sectors analysed, according to AIS data provided by HELCOM. This approach takes into account the empirical proportions between traffic volume and the frequency of incidents involving specific vessels. Thus, the Monte Carlo simulation was based on realistic assumptions regarding traffic patterns and recorded incidents, ensuring the reliability of the results obtained. The accuracy of AIS data can affect the location and identification of maritime traffic, but the HELCOM system provides high data reliability due to its dense network of land-based receiving stations, as documented in official HELCOM material (2024)

The results of the analyses were presented in graphical form (e.g. bar, scatter and box plots), which enabled clear interpretation of spatial and temporal patterns of collision risk and comparison of the dynamics of change between sectors and classes of units.

4. Characteristics of the study area

The study area is located in the western part of the southern Baltic Sea, in the immediate vicinity of the planned container terminal in Świnoujście. The basin is characterised by varied bottom morphology, dynamic hydrometeorological conditions and increased vessel traffic, which makes it particularly important from the perspective of assessing navigational conditions.

In the area in question, the prevailing factor shaping the hydrodynamic conditions is the winds, particularly from the west and south-west. Storm events, especially in winter (December-February), lead to a significant increase in wave intensity and intensification of coastal currents. Maximum wind speeds during this period exceed 30 m/s, resulting in waves over 5 m high and significant displacement of bottom sediments and variability of coastal zones (Dąbrowska, Torbicki, 2024). Data from long-term observations indicate an increasing intensity of westerly winds, which is associated with an increase in the unidirectional transport of debris along the shore - from west to east (BioConsult Ltd., 2022). The currents in this area are longshore in nature and are strongly dependent on meteorological conditions, especially with winds exceeding 5°B (BioConsult Ltd., 2022).

Observations in the vicinity of the future container terminal indicate that local variability in the direction of currents - due to the curved shoreline, among other things - can lead to the formation of areas of sediment accumulation or flushing. In the context of navigational safety, this is crucial, as it affects the risk of shoal formation and changes in bathymetry, which can lead to collisions or subsidence of ships (BioConsult Ltd., 2022).

According to the analysis in the environmental report, the average annual wind speed in the Świnoujście area is about 5.9 m/s, while maximum speeds recorded in winter reached 30-35 m/s. Wave heights in the coastal zone are typically 1-2 m, while during storms they exceed even 5 m. Seasonally, the greatest hazards occur from November to February (BioConsult Ltd., 2022).

In terms of the characteristics of coastal currents, it is worth noting that in the south-western part of the Baltic Sea, the average speed of currents is between 0.1 and 0.4 m/s (i.e. about 0.2-0.8 knots), and these values can increase in strong winds (Krek et al., 2016). Coastal sea currents, shaped mainly by wind waves, directly influence sediment transport and changes in shoreline shape. The variability of these processes - especially in the Świnoujście area - is important from the point of view of navigational safety, as it may lead to local shallows, increasing the risk of collisions or grounding of vessels.

In order to carry out a detailed analysis of the navigational risks associated with the planned construction of the container terminal in Świnoujście, the fairway area was divided into four separate sectors, corresponding to the successive stages of the ship's approach to the port. This division allows for a differentiated assessment of risks depending on the characteristics of a given section of the route and the prevailing navigational conditions there.

For each sector, two basic risk parameters were identified: the probability of a hazardous event (P) and the potential consequences of that event (S). The assessment was carried out qualitatively, based on available source data, including vessel traffic intensity maps (HELCOM AIS 2019-2022), hydrometeorological characteristics (IMGW), operational data (VTS, szczecinpilot.pl) and reports of the State Commission for the Investigation of Marine Accidents (GDPWM). The values assigned to the two parameters are illustrative and form the basis for further, more precise analysis based on quantitative data.

In the analysis of navigational safety, it is also necessary to take into account the number of maritime accidents in the time period from which the data for the study was extracted. An area was delimited on the map, which covered four sectors A-D.

Figure 2. Characteristics of marine incidents with pollution incidents 2019-2022.

Source: HELCOM.

Figure 2 shows a map of the intensity of ship traffic in the southern Baltic Sea, based on AIS data from 2019-2022. This data enables the identification of the main shipping routes, the points of concentration of vessels and the places where sea routes cross. As part of this study, four distinct approach sectors to the port of Świnoujście were marked on the map, which were used to carry out a navigational risk analysis in the context of the planned construction of the container terminal (Figure 3).

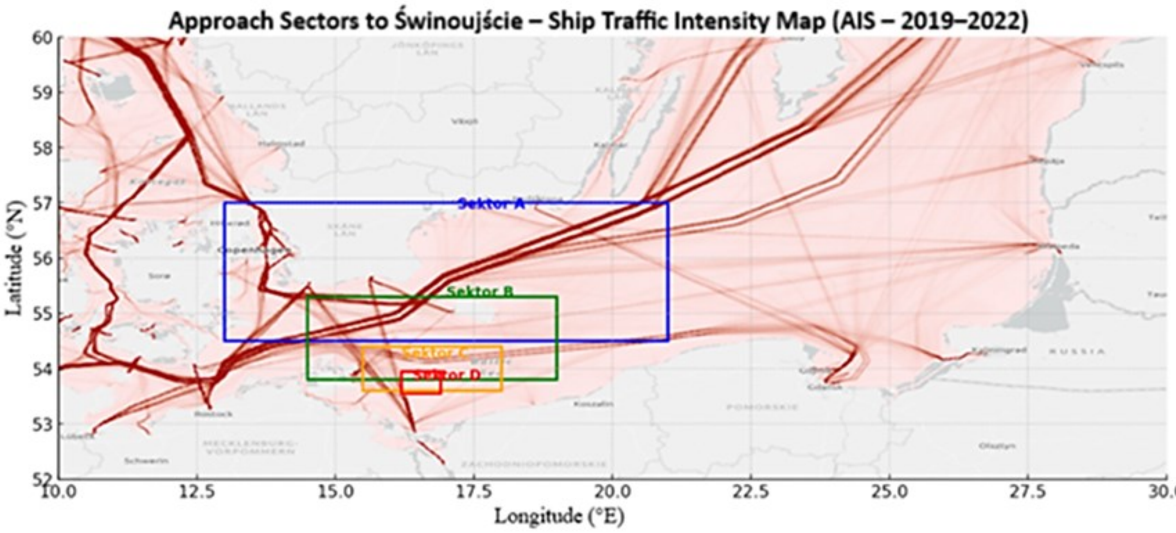

Figure 3. Map of vessel traffic intensity in the southern Baltic (AIS 2019-2022) with a breakdown of the four approach sectors to Świnoujście.

Source: HELCOM.

This division makes it possible to take into account the different navigational conditions in the different parts of the route, which differ in terms of traffic density, hydrographic conditions, infrastructure and typical manoeuvres carried out by vessels. The approximate geographical coordinates for each sector are summarised below, together with a brief description of their functions, which are presented in table 1.

Table 1.
Gate coordinates for each sector

Sector	Gateway	Latitude	Longitude	Description
A - open sea	**Gate 1:** between the western exit of Sassnitz and the northern point towards Bornholm (near Arkona).	Goal start position: 54,5546 N	Position of start of goal: 013.7076 E	Main trade routes, high volume of transit traffic
		Goal end position: 55,139 N	Goal end position: 014,8186 E	
B - external approach	**Gate 2:** between Kolobrzeg and the exit to Rønne/ Bornholm.	Goal start position: 54,9931 N	Starting position of goal: 015.1226 E	Region of convergence, approach manoeuvres
		Goal end position: 54,5007 N	Goal end position: 016,3496 E	
C - track approach	**Gate 3:** East of Świnoujście in the direction Greifswald (for local traffic/ Pommeranian Bay).	Goal start position: 54,3433 N	Goal start position: 013,800 E	Narrow track leading to Swinoujscie, heavy ferry traffic
		Goal end position: 54,3437 N	Goal end position: 014,2569 E	
D - internal track	**Gate 4** (if any): At the entrance to the fairway to Swinoujscie (for port traffic).	Goal start position: 53,9920 N	Goal start position: 14,1880 E	Approach to the terminal, impact of the weather. Mooring manoeuvres
		Goal end position: 54,0003N	Goal end position: 014,3503 E	

The analysis of vessel traffic on the basis of AIS (Automatic Identification System) data is an important element of modern shipping monitoring. The use of measurement gates makes it possible to quantify the intensity of maritime traffic in selected sections of water bodies. This technique makes it possible not only to count passing vessels, but also to classify them according to type and direction of flow (IN/OUT). Figure 4 shows four survey gates that have been placed at key locations in the approach to Świnoujście harbour and in the transit areas of the Pomeranian Bay and the western Baltic Sea. Each of the gates will be used to carry out an analysis of the intensity of vessel traffic in a given cross-section, based on AIS data.

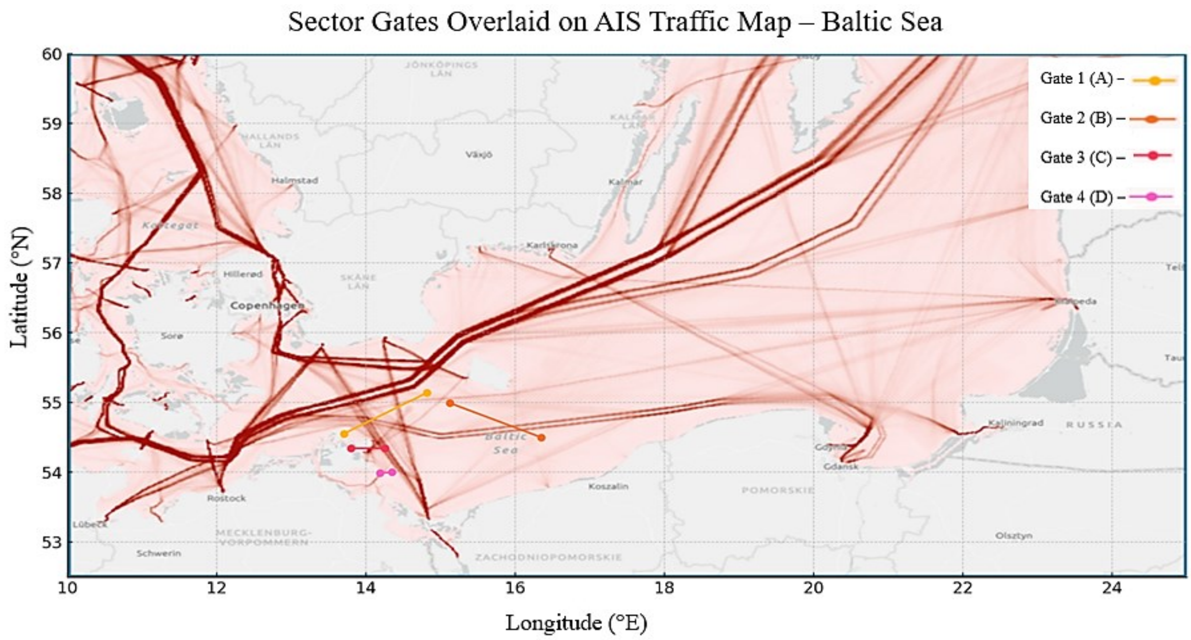

Figure 4. Distribution of sector gates on the background of the AIS traffic map in the Baltic Sea. Source: HELCOM.

For each survey gate, a detailed analysis of the intensity of vessel traffic is carried out. Firstly, the number of vessels that crossed a given gateway during the analysed period is determined - this includes the number of unique vessels identified by the AIS signal. The survey also takes into account the direction of movement of vessels. Vessels are classified as either inbound (IN) or outbound (OUT) to determine the predominant directions of navigation in the port approach area.

Another aspect is the breakdown of vessels by type, using the classification used in AIS. A distinction is made between passenger ships, commercial vessels, tankers, fishing vessels, and special vessels such as tugboats or rescue craft. Yachts and smaller recreational craft are also analysed in a separate group.

The analysis also includes the temporal distribution of traffic - data can be aggregated on a daily, weekly or monthly basis to identify cyclical patterns and seasonality in traffic volumes.

The use of survey gates is not only aimed at monitoring and forecasting the volume of maritime traffic in approach and transit areas, but also at identifying potential collision points and bottlenecks in the shipping system. The data also support the processes of manoeuvre planning, traffic control and environmental management, especially in specially protected areas (e.g. Natura 2000). The results of the analysis can be successfully used in maritime traffic surveillance (VTS) systems and operational management of seaports.

5. Results

This section presents the results of an analysis of ship collision risk in selected shipping sectors in the Baltic Sea. The tabular and graphical summaries show the variation in risk over time and between vessel types. The highest values were recorded for passenger and cargo ships, reflecting their dominant share of maritime traffic. The results presented allow for a better understanding of the distribution of risks and identify areas requiring special attention in the context of navigational safety.

5.1. Sector A - Gate 1

Sector A comprises one of the key shipping sections, characterised by a high proportion of passenger and cargo type vessels. This area is characterised by stable and intensive maritime traffic, which makes it particularly relevant for collision risk assessment. Figure 5 shows the number of ship crossings through Sector A in 2019-2022, broken down by vessel type (e.g. container ships, passenger ships, service ships, etc.).

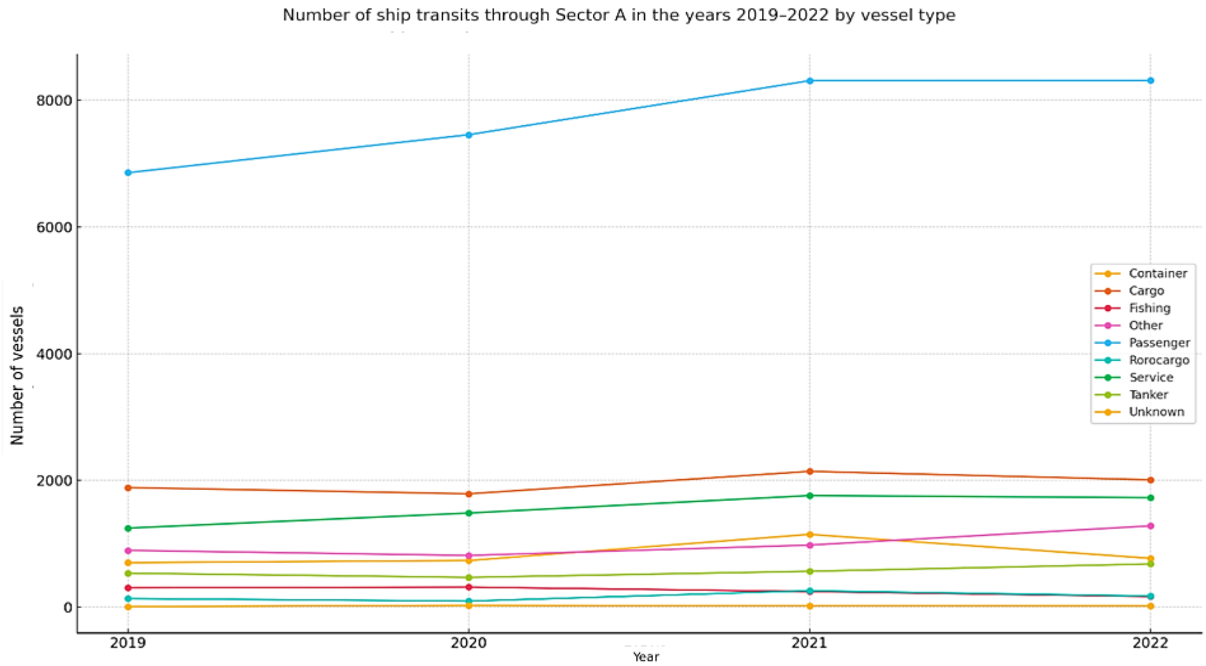

Figure 5. Number of vessel transits through Sector A in 2019-2022 by vessel type.

Source: own compilation based on AIS data.

- Passenger units are the dominant type, with overruns of more than 8000 per year (peak in 2022).
- Cargo and service units also have a significant share, with service traffic growing steadily.
- Tanker and container units show moderate increases with minor fluctuations.
- The 'Unknown' and 'Rorocargo' units appear less frequently, but their numbers are also increasing.

The increase in the number of vessel passages, especially passenger and service types, translates into an increased likelihood of collisions in the sector under study. It was therefore important to estimate the collision risk for individual vessel types, taking into account both their numbers and their variability over time. A statistical summary (Table 2) is presented below, taking into account the average risk values, standard deviations and minimum and maximum ranges for the years 2019-2022.

Table 2.
Summary of average collision risk values, standard deviations and minimum and maximum values for Sector A for the period 2019-2022

Collision risk statistics by vessel type for 2019-2022 for sector A				
Ship type	**Average**	**Deviation std.**	**Min**	**Max**
Cargo	6,325	0,495745341	5,781009585	6,925571885
Container	0,4125	0,102430898	0,345165622	0,56477171
Fishing	0	0	0	0
Other	2,8875	0,594322831	2,369977313	3,729657172
Passenger	3,575	0,328203004	3,169561423	3,842480851
Rorocargo	0	0	0	0
Service	0	0	0	0
Tanker	0,6875	0,108475112	0,5730187	0,832591273
Unknown	0	0	0	0

Monte Carlo simulations confirmed that cargo and passenger ships are among the groups of vessels most vulnerable to collisions, as a result of their relatively high unit collision probability Pk. The Pk value for cargo vessels remained at 0.0034 in all years, representing a 0.34% risk of collision for each passage through Sector A. Similarly, for passenger vessels, the Pk was 0.0026, or 0.26% per passage. Moderate Pk values were observed for other (0.0028) and container vessels (0.0020). In contrast, units such as rorocargo (0.0018), service (0.0015) and tanker (0.0018).

Figure 6 shows the results of the Monte Carlo simulation, illustrating the distribution of the number of potential collisions for different vessel types in Sector A from 2019 to 2022. The highest risk values and their variability were observed for passenger and cargo (Cargo) vessels, which is related to their dominant share of maritime traffic. The graph also shows the presence of outliers, indicating incidentally increased risk. Tanker and Container vessels show moderate risk, while the other types have minimal exposure to collisions. The results highlight the need for further analyses of shipping safety in the context of traffic intensity and vessel typology.

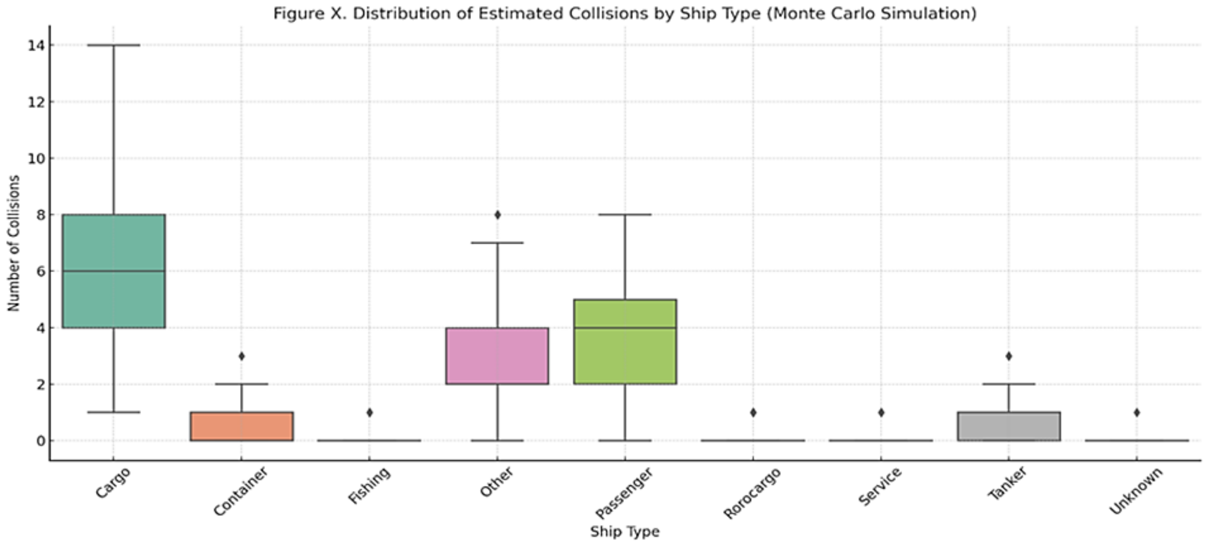

Figure 6. Distribution of number of simulated collisions by vessel type in sector A (Monte Carlo method).

5.2. Sector B - Gate 2

The maritime traffic in Sector B is characterised by a greater diversity of vessel types, with a distinct proportion of cargo, passenger and service vessels. Compared to Sector A, there is slightly less traffic here, but greater annual variability. Figure 7 shows the number of ship transits through Sector B from 2019 to 2022 by vessel type (e.g. container ships, passenger ships, service ships, etc.). The data has been mapped from the table provided by you and the vessel types have been visualised as separate series.

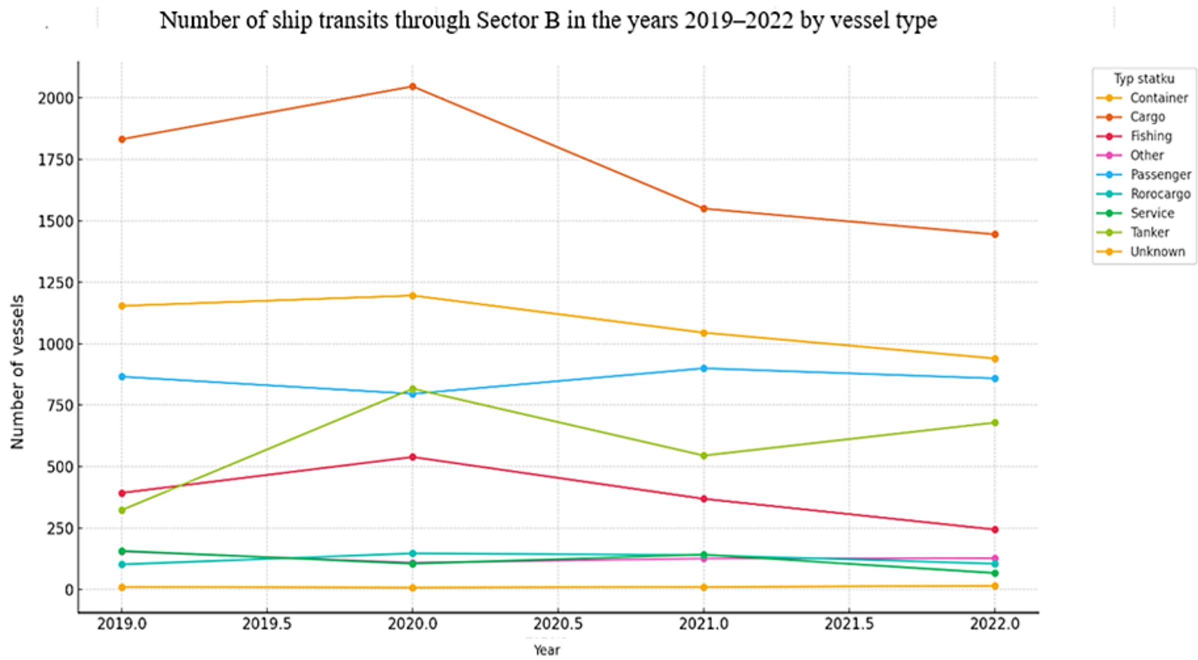

Figure 7. Number of vessel transits through Sector B in 2019-2022 by vessel type.

Source: own compilation based on AIS data.

Below is Table 3 with the results of the Monte Carlo simulations for each vessel type in Sector B, calculated using data from 2019-2022. It includes the average numbers of potential collisions, standard deviations and minimum and maximum values from the 1000 trials carried out.

Table 3.
Summary of average collision risk values, standard deviations and minimum and maximum values for Sector B for the period 2019-2022

Collision risk statistics by vessel type for 2019-2022 for sector B				
Ship type	**Average**	**Deviation std.**	**Min**	**Max**
Cargo	5,927	0,474	5,311	6,801
Container	0,373	0,096	0,312	0,503
Fishing	1,334	0,313	1,011	2,088
Other	2,018	0,475	1,671	3,193
Passenger	2,959	0,278	2,622	3,611
Rorocargo	0,426	0,107	0,351	0,579
Service	0,406	0,104	0,312	0,551
Tanker	1,994	0,283	1,732	2,602
Unknown	0,036	0,015	0,016	0,064

The probabilistic analysis carried out for sector B using Monte Carlo simulation confirmed the variation in collision risk levels between the different types of units, with the assessment based on the value of the unit collision probability Pk, regardless of the average number of events R.

The highest Pk values throughout the 2019-2022 period were consistently attributed to cargo vessels, for which the probability of collision per passage remained at 0.0034, or 0.34%. Similarly, passenger vessels were characterised by a value of Pk = 0.0026 (0.26%). Moderate probability values were present for container (0.0020) and other (0.0028) units. Units such as rorocargo (0.0018), service (0.0015) and tanker (0.0018). In contrast, units such as unknown and fishing, with Pk = 0.0005.

Below is Figure 8 showing the results of the Monte Carlo simulation for Sector B, showing the distribution of the number of potential collisions between 2019 and 2022 by vessel type.

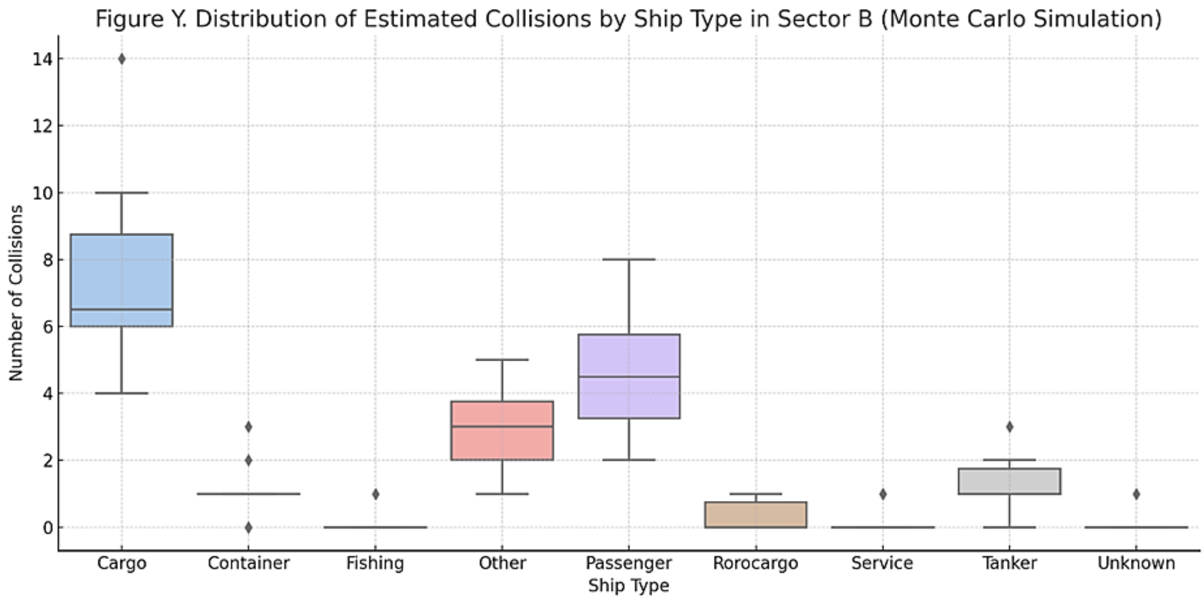

Figure 8. Distribution of number of simulated collisions by vessel type in sector B.

As can be seen in the graph, the highest collision risk values in Sector B were observed for Cargo and Passenger units, which is consistent with their high presence in the study area. Outliers can also be seen, especially for Cargo units, indicating possible incidental increases in risk. In contrast, types such as Service, Fishing and Unknown are characterised by minimal exposure to collision risk.

5.3. Sector C - Gate 3

Sector C comprises a region of moderate traffic volume, where transit passenger and freight units dominate. In the years under review, characteristic fluctuations in the number of crossings and an increase in the share of specialised vessels could be observed. Figure 9 shows the variation in the number of transits of the different vessel types (e.g. Container, Cargo, Passenger, etc.) in Sector C from 2019 to 2022. The data shows the dominant presence of passenger and cargo vessels, with varying trends in other vessel types.

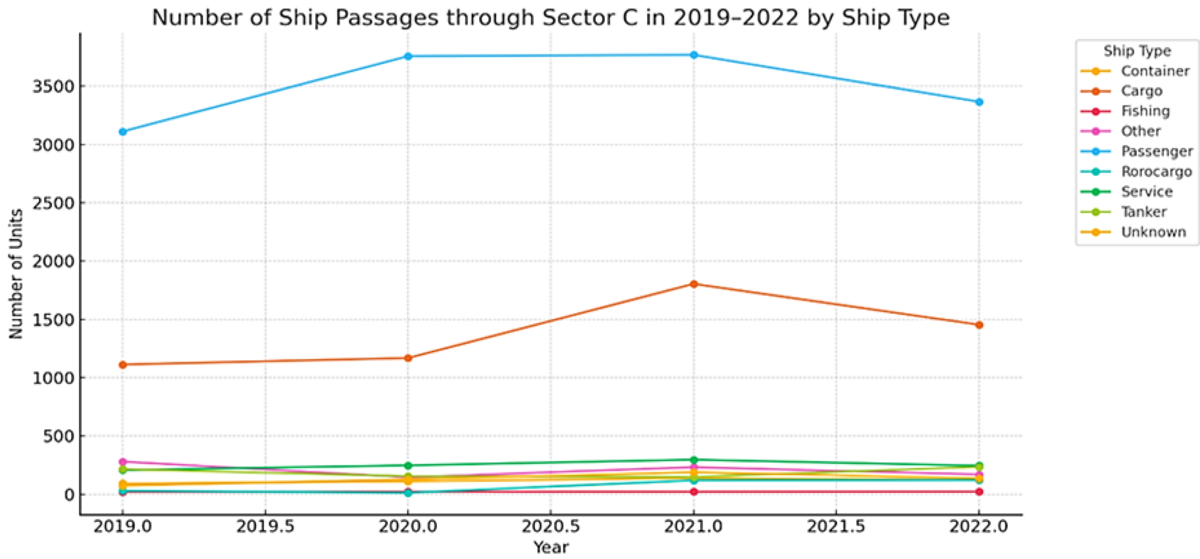

Figure 9. Number of vessel transits through Sector C in 2019-2022 by vessel type.

Source: own compilation based on AIS data.

Table 4 presents collision risk statistics for different vessel types from Monte Carlo simulations for Sector C (years 2019-2022).

Table 4.
Summary of average collision risk values, standard deviations, and minimum and maximum values for Sector C from 2019 to 2022

Vessel type	Average	Deviation std.	Min	Max
Cargo	6,371	0,498	5,789	7,125
Container	0,405	0,092	0,321	0,512
Fishing	1,041	0,267	0,851	1,988
Other	2,176	0,441	1,651	3,305
Passenger	3,182	0,307	2,682	3,709
Rorocargo	0,448	0,112	0,336	0,574
Service	0,367	0,085	0,295	0,522
Tanker	2,275	0,299	1,734	2,823
Unknown	0,043	0,013	0,021	0,067

For cargo vessels, for the entire period analysed (2019-2022), a collision probability of Pk = 0.0034 or 0.34% per passage was assigned. Passenger vessels showed a collision probability of Pk = 0.0026. For container vessels Pk = 0.0020 while for the other class Pk = 0.0028. These vessels had collision probabilities assigned between 0.0015-0.0018. For fishing vessels Pk = 0 while for unidentified vessels Pk = 0.0005.

The following Figure 10 shows the distribution of the number of estimated collisions by vessel type in Sector C, based on a Monte Carlo simulation (1000 trials). The values were generated from the number of vessel transits and the collision probabilities assigned to them. There is a clear dominance of passenger and cargo (Cargo) vessels in terms of risk of collisions, which is reflected in the wide range of values and numerous outlier points.

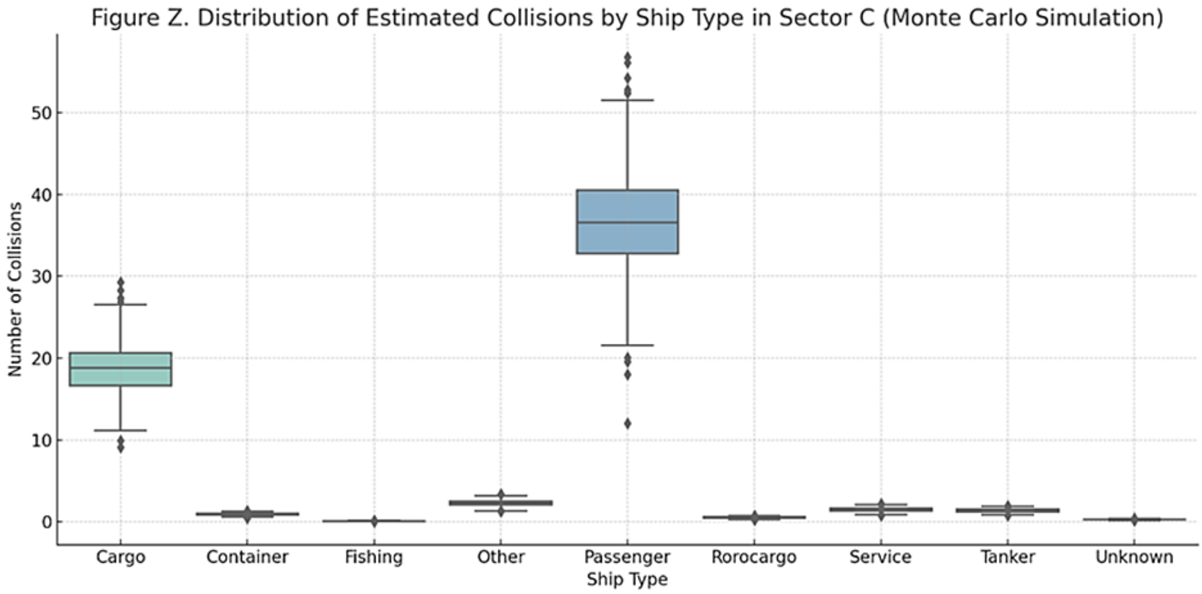

Figure 10. Distribution of number of simulated collisions by vessel type in sector C.

5.4. Sector D - Gate 4

Sector D is the most heavily trafficked section of those analysed, with the dominant presence of large passenger vessels. The high intensity of shipping in this area is reflected in the values of the estimated collision risk.

Below Figure 11 shows the variation in the number of vessel transits through Sector D between 2019 and 2022 by vessel type. Passenger vessels dominate the traffic, showing a clear increase. Types such as 'Cargo' and 'Unknown' also present significant changes, while 'Fishing', 'Rorocargo' and others show little variation.

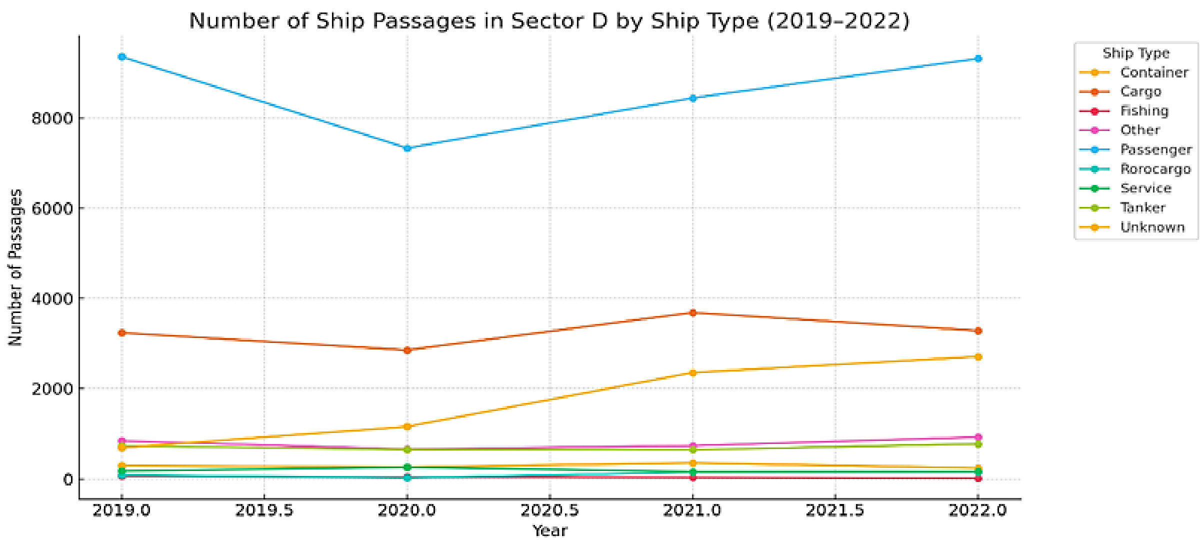

Figure 11. Number of vessel transits through Sector D in 2019-2022 by vessel type.

Source: own compilation based on AIS data.

Table 5 illustrates how the collision risk developed for the different vessel types in Sector D, based on the results of the 2019-2022 Monte Carlo simulations.

Table 5.
Summary of average collision risk values, standard deviations and minimum and maximum values for Sector D from 2019 to 2022

Vessel type	Average	Deviation std.	Min	Max
Container	2,324	0,226	1,556	3,028
Cargo	44,699	4,546	30,309	59,836
Fishing	0,162	0,016	0,114	0,212
Other	8,917	0,855	6,107	11,82
Passenger	89,262	9,09	57,49	122,83
Rorocargo	0,74	0,075	0,479	0,996
Service	1,161	0,114	0,799	1,564
Tanker	5,094	0,492	3,653	6,939
Unknown	3,468	0,352	2,509	4,507

Analysis of the data for Sector D from 2019 to 2022 reveals that cargo and passenger vessels showed the highest collision probability values. For cargo vessels throughout the analysis period, Pk = 0.0034, or 0.34%. Passenger vessels with an assigned probability of Pk = 0.0026. Their abundance (e.g. more than 9300 passages in 2019 and 2022) makes them one of the key categories in the hazard structure. Values of Pk = 0.0020 (for container ships) and Pk = 0.0028 (for the other category). Due to the different number of crossings (e.g. 927 in other in 2022). Rorocargo, Service, Tanker have assigned collision probabilities ranging between Pk = 0.0015 and 0.0018. Fishing vessels have the lowest Pk = 0.0005 values, while some unknown (unidentified) vessels also have Pk = 0.0005.

Below is Figure 12 showing the variation in collision risk for different vessel types between 2019 and 2022. The box plot shows the estimated collision risk by vessel type in Sector D between 2019 and 2022, based on Monte Carlo simulations. The highest and most variable risk values were observed for passenger and cargo (Cargo) vessels, while the other vessel types had low and stable risk levels.

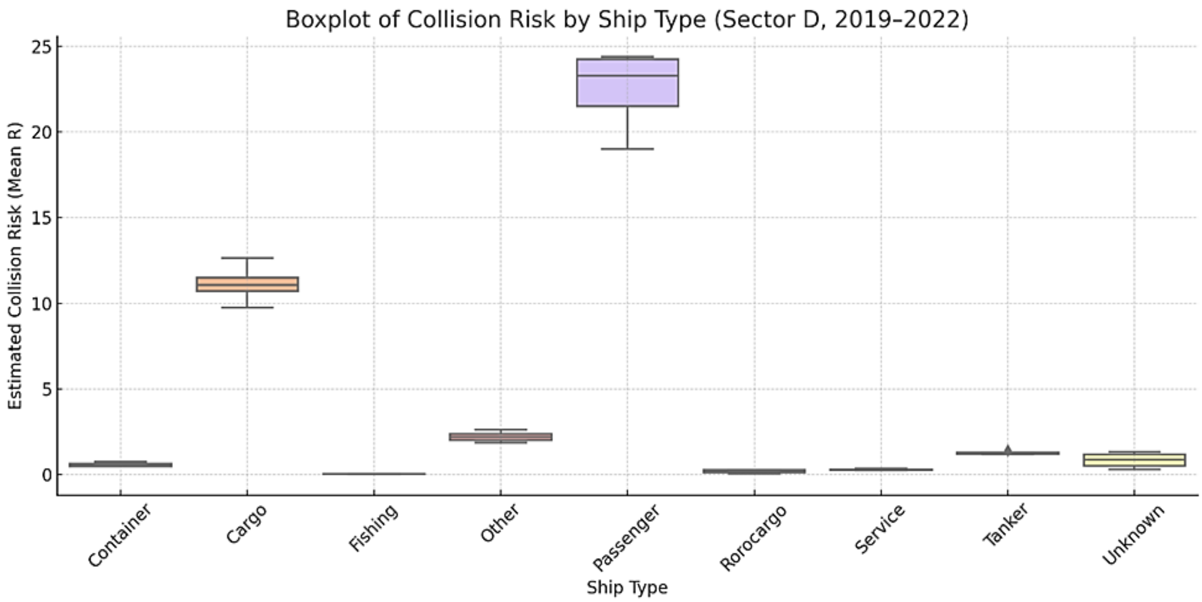

Figure 12. Distribution of number of simulated collisions by vessel type in sector D.

6. Recommendations for maritime traffic management and prevention activities

The results of the analysis carried out indicate a number of areas where it is possible and reasonable to implement measures to improve maritime traffic management and reduce the risk of vessel collisions. First of all, due to the high risk values attributed to passenger and cargo vessels, it is recommended to focus preventive measures on these two types of vessels. This is particularly the case in Sector D, where the volume of traffic and the variability of risk parameters were the highest.

As a first step, it is advisable to implement dynamic traffic management systems (Vessel Traffic Services - VTS), with priority given to the most congested and sensitive sections of the fairway. Such systems should be integrated with real-time analysis of AIS data, enabling automatic identification of potential collision hazards and provision of shunting recommendations. In parallel, the introduction of speed restriction zones (Traffic Separation Schemes) in the most congested sectors is recommended, especially for vessels with high tonnage and less maneuverability. Reducing speed at sensitive points can effectively reduce both the likelihood and consequences of potential collisions.

An important preventive aspect should also be the provision of regular education and training campaigns for vessel operators, with particular emphasis on the crews of passenger craft and vessels serving busy ports. Training should include elements of situational awareness, interpretation of navigational data and emergency procedures in collision situations.

In addition, due to the observed variability of risk over time, it is advocated that collision risk maps should be updated periodically, using both historical data and current observations of maritime traffic. Such maps can be a valuable tool to support shipping route planning and the allocation of patrol and rescue services.

Finally, consideration should be given to the further development and integration of predictive tools, based on Monte Carlo simulations and machine learning models, which will enable risk forecasting depending on weather conditions, seasonality or infrastructure changes. Implemented on a continuous basis, these solutions can make a real contribution to increasing shipping safety and reducing maritime accidents in the Baltic Sea region.

7. Discussion

The analysis of collision risk in Sectors A-D of the Baltic Sea shows a clear correlation between traffic intensity and risk level. Passenger and cargo vessels were found to be particularly vulnerable to collisions, the dominant presence of which in the surveyed sectors translates into the highest risk values. The highest risk intensity was identified in Sector D, which may be due to its geostrategic importance and traffic concentration.

Although marginal vessels - such as fishing or service vessels - generate little risk, their impact in certain situations (e.g. limited visibility or navigational errors) should not be underestimated. This suggests the need for an in-depth qualitative analysis that also includes human factors and the operational context.

Dynamic variables such as weather conditions, seasonality or the technical condition of vessels are worth considering in further studies. Extending the model to include data from radar systems, onboard sensors and real-time observations could significantly improve the accuracy of risk forecasting.

From a practical point of view, the results of Monte Carlo simulations can be used as a basis for decision support in maritime traffic management, port infrastructure planning or the deployment of VTS systems. In the future, it is worth considering the use of hybrid predictive models, combining statistical analysis with artificial intelligence methods, which can help to improve the safety of shipping and the resilience of maritime transport systems to disruptions.

Given the calculated values and the potential concentration of risk at selected spatial points, it makes sense to use module 4 of the IWRAP (Geographical Risk Mapping) system in further detailed studies to identify local collision foci and the spatial distribution of risk, which will enable precise planning of countermeasures as part of navigation safety management.

8. Conclusions

An analysis of AIS data from 2019-2022, supplemented with statistical indicators from HELCOM reports, allowed the estimation of vessel collision risk in selected sectors of the Baltic Sea. The study used a Monte Carlo simulation, the results of which were directed at estimating collision probabilities for individual vessel types. A Poisson distribution, suitable for rare events such as marine accidents, was used as the basis for modelling.

Calculations were carried out separately for the four sectors (A-D), based on the number of passes of the units through the survey gates and the collision probability factors assigned to them. The risk value was defined as the product of the number of passes (N) and the collision probability (Pk), individually assigned to each type of unit.

Sector A showed a clear predominance of passenger units with more than 8000 crossings per year. The high volume of traffic in this category translated directly into elevated collision risk values at the peak (2022). Significant values were also recorded for cargo units. Fluctuations in the results, especially the presence of outliers, indicate the occurrence of incidental situations.

Sector A showed a clear predominance of passenger units with more than 8000 crossings per year. The high volume of traffic in this category translated directly into elevated collision risk values at the peak (2022). Significant values were also recorded for cargo units. Fluctuations in the results, especially the presence of outliers, indicate the occurrence of incidental situations immediate action, but should be taken into account in long-term marine traffic safety planning. In contrast, vessels with the smallest share of traffic - such as fishing vessels or indeterminate vessels - have a very low probability of collision, allowing them to be considered as a category with a negligible impact on overall safety in the sector.

Despite their relative stability, the high deviations in some groups of units may suggest periodic increases in risk, linked, for example, to seasonal increases in traffic or complex route patterns. This points to the validity of an in-depth spatial analysis to identify areas of particular risk and tailor preventive measures accordingly. Such an approach is in line with the recommendations of international standards for the analysis of shipping safety.

Sector C saw intensive traffic of cargo and passenger units, which were assigned collision probabilities of 0.0034 and 0.0026 respectively. Although these are the same values as in the other sectors analysed, their consequences in terms of spatial conditions and local traffic distribution have a noticeable specificity. Although these are the same values as in the other sectors analysed, their consequences in terms of spatial conditions and local traffic distribution have a noticeable profile - Sector C is characterised by lower total traffic intensity but higher variability in risk scores, which may indicate local route intersections, limited manoeuvring space or seasonal traffic congestion. The large variation in results is indicative of dynamic factors such as variability in traffic volumes over time, route intersections, manoeuvring restrictions or seasonality. Although many vessel types - including container ships, tankers, service vessels or ro-ro - remain in the moderate risk range, the elevated variability in the data for the dominant groups can be considered a warning signal. It is also a worrying feature of the C-sector that the unit risk remains within limits that are considered by international analyses to be elevated or in need of further control, even if the average number of collisions does not exceed the limits (Čorić et al., 2021). Further analysis of the operational context of the sector is therefore recommended, taking into account geographical and temporal factors that could explain the observed volatility.

Sector D showed the highest level of collision risk of all the areas analysed. This was mainly due to the intensive volume of passenger and freight units, which dominated the traffic pattern and had a high probability of collision. Although the risk levels attributed to these classes of units remained consistent with the other sectors, their impact was particularly noticeable due to the very high number of crossings during the period analysed. This situation indicates the need for special consideration for this sector in the context of planning shipping safety measures and given the proximity of the planned container terminal in Świnoujście. In addition, the simulations carried out showed considerable variability in the results, suggesting the presence of complex traffic configurations - such as route intersections, uneven distribution of activity over time or spatial constraints. The distribution of uncertainty observed in these analyses indicates that sector D may contain local danger points with increased collision risk, which require more in-depth assessment. For other vessel types, such as support vessels, fishing vessels or unspecified vessels, the risk was assessed as relatively low and stable, with no significant impact on the risk level. Due to the dominance of passenger and cargo traffic, this sector should be treated as a priority area for future analytical work

The analysis clearly shows that passenger and cargo vessels play a key role in determining the level of collision risk in the Baltic Sea areas studied. Regardless of the sector studied, it is these two types of vessel that generate the highest risk values, due to both their numbers and the intensity of use of the main shipping lanes. This relationship is particularly pronounced in Sector D, which, due to the highest cumulative risk values and high variability of results over time, requires special attention from maritime safety institutions. This may imply the need to implement additional preventive measures, reorganise navigational infrastructure or improve traffic management systems.

The results of the analysis made it possible to formulate priority recommendations that can support the maritime traffic management policy in the area of the planned investment. In terms of immediate actions, it is recommended to implement additional AIS monitoring in the areas with the highest traffic and to introduce local procedures for separation of vessel traffic with high collision risk (e.g. passenger and cargo vessels).

In the long term, on the other hand, it is recommended to include risk modelling in cyclical assessments of the impact of infrastructure investments on maritime safety and to develop digital decision support systems for port managers and navigational operators that are based on AIS data and predictive analyses. This approach is in line with the direction of EU policy development on intelligent maritime transport systems and adaptive safety management.

In conclusion, the Monte Carlo-based simulation methodology used has proved not only accurate, but also flexible and effective in the context of maritime collision risk modelling. The results obtained not only allow the identification of high-risk sectors, but also provide a sound basis for making recommendations on shipping safety and designing future maritime traffic management strategies.

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