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SAFETY MANAGEMENT OF MARITIME TRAFFIC EFFECTS ON BALTIC NUCLEAR INFRASTRUCTURE

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Purpose: The aim of this article is to assess the impact of maritime traffic on the safety of a planned nuclear power plant located in the coastal zone of the Baltic Sea and to develop the principles of an integrated safety management system supporting decision-making processes in the field of critical infrastructure. The starting point is the assumption that the safety of a nuclear power plant in a coastal location should be considered not only in technical terms, but also as a management issue requiring data integration, risk assessment and the coordination of actions by multiple stakeholders.
Design/methodology/approach: The study utilised AIS data to reconstruct vessel trajectories, identify main traffic corridors and assess the fleet structure in the Lubiatowo–Kopalino area. Measurement sections LEG 1–LEG 7 and probabilistic modelling using the IALA IWRAP Mk2 software were applied. The results obtained were interpreted from a safety management perspective, with particular emphasis on the organisation of monitoring, the identification of high-risk zones and emergency response procedures.
Findings: The study showed that maritime traffic in the analysed area is highly spatially varied and concentrated in corridors running parallel to the coastline. The highest traffic intensity was recorded in the LEG 2 area, dominated by general cargo vessels and oil product tankers. IWRAP modelling confirmed that overtaking scenarios are the dominant hazard scenario, whilst the risk of head-on collisions remains relatively low. The results indicate that despite the power plant not being located directly on the main shipping route, its safety remains dependent on the indirect impacts of transit traffic.
Research limitations/implications: A limitation of the study is the use of AIS data and a probabilistic model that does not account for a full analysis of event consequences. Further research should cover the consequence component, extreme scenarios and the impact of variable hydrometeorological conditions on the level of risk.
Practical implications: The article outlines directions for the development of an integrated safety management system, encompassing AIS, radar and VTS monitoring, risk analysis and

response procedures. The results may assist maritime authorities, infrastructure operators and safety stakeholders in designing safety zones and organising traffic around strategic facilities.
Social implications: The study contributes to the debate on the safety of the energy transition and the social acceptance of nuclear investments. It demonstrates that effective security management of critical infrastructure requires a systemic, transparent and data-driven approach.
Originality/value: The originality of the article lies in combining maritime traffic analysis, probabilistic risk assessment and perspectives from management and quality sciences in relation to a planned nuclear power plant in Poland. The value of the work lies in demonstrating how analytical tools can support security management in organisations responsible for the operation of critical infrastructure.
Keywords: safety management; critical infrastructure; nuclear power plant; AIS; navigational risk.
Category of the paper: Research paper.

1. Introduction and Literature Review

The nuclear energy used in nuclear power stations is based on the process of nuclear fission, in which a neutron triggers the breakdown of a heavy element's nucleus, leading to the release of significant amounts of thermal energy. This process is a chain reaction, as it results in the emission of further neutrons capable of triggering subsequent reactions (Brennen, 2005; Todreas, Kazimi, 2011). The stability of reactor operation depends on maintaining a controlled chain reaction, described by the neutron multiplication factor k, which in a critical state takes the value of one (IAEA, 2016). In power generation, enriched uranium containing the U-235 isotope is used; its natural abundance in uranium ore is low, which necessitates enrichment processes, most commonly using gas centrifuges (World Nuclear Association, 2023). To increase the efficiency of the reaction, moderators such as water or graphite are used, which slow down the neutrons and increase the probability of fission (Duderstadt, Hamilton, 1976). The energy released in a nuclear reactor is mainly in the form of heat, which is absorbed by the coolant and transferred to the secondary system, where steam is generated to drive the turbines. Despite the advanced nature of nuclear technology, the final stage of electricity production is based on a classic thermodynamic cycle, analogous to that of conventional power stations (Brennen, 2005).

One of the key elements in the operation of nuclear power plants is the cooling system, which is responsible both for removing heat from the reactor and for maintaining safe operating conditions at the plant. Nuclear power plants are facilities with very high water requirements, and their location is heavily dependent on the availability of a stable cooling source (IAEA, 2016; World Nuclear Association, 2023; Macknick et al., 2012). In particular, for coastal power stations, a significant operational risk is posed by phenomena involving the blockage of cooling water inlets by biological material or suspended solids, which can lead to a reduction in the efficiency of cooling systems and pose a real risk to plant safety (Lin et al., 2023).

The importance of water resources in nuclear energy is also emphasised in the context of sustainable development. Nuclear power plants are among the most water-intensive facilities in terms of water usage, which requires the implementation of modern technological solutions to enhance water management efficiency and minimise environmental impact (Jayabal, 2025). In this context, locating power stations near large bodies of water, such as seas and oceans, enables efficient heat dissipation and stabilisation of the cooling system's operation. At the same time, the operation of nuclear power stations in a marine environment is associated with thermal impacts on coastal ecosystems. Long-term studies indicate that the discharge of heated water may affect local hydrological conditions and the biological structure of the marine environment, which should be taken into account in site selection and environmental assessments (Zhang et al., 2022).

An example of a nuclear power plant utilising the advantages of a coastal location is the plant in Greifswald (Lubmin), which operated using VVER-440 reactors (GRS, 1992). This system employed a multi-circuit cooling system in which seawater was used to remove heat from the condensers and to support auxiliary systems. The primary circuit was responsible for directly cooling the reactor core, whilst the secondary circuit enabled steam production and turbine drive. In addition, there were component cooling systems and emergency systems, such as the ECCS, ensuring safety in the event of a coolant loss (GRS, 1992).

For nuclear power plants located in coastal areas, maritime traffic is also a significant external factor, as it may pose a risk of collision, vessel drift or accidents in the vicinity of critical infrastructure. The literature emphasises that the analysis of vessel traffic based on AIS data is an effective tool for assessing navigational safety and identifying potential hazards (Goerlandt, Kujala, 2014; Montewka et al., 2012). The highest risk of collision occurs in areas with high traffic density and during overtaking manoeuvres resulting from speed differences between vessels (Goerlandt, Kujala, 2014).

A review of the literature indicates that the location of nuclear power plants in coastal zones is primarily determined by access to water resources, which are essential for the efficiency and safety of cooling systems. At the same time, the presence of maritime traffic in such areas constitutes a significant risk factor, requiring the use of advanced analytical methods and safety management systems. The integration of AIS data with probabilistic models is currently one of the key approaches in assessing navigational risk in areas of critical infrastructure.

2. Study Aea and Context

2.1. Planned location of a nuclear power plant in the vicinity of the Baltic Sea

The study area covers the site of the planned first nuclear power plant in Poland, situated in the Lubiatowo–Kopalino region, in the municipality of Choczewo (Pomeranian Voivodeship), in the immediate vicinity of the Baltic Sea. This site was officially designated under the Polish Nuclear Power Programme (PPEJ) as the construction site for the country's first facility of this type (Ministry of Climate and Environment, 2023).

The choice of this location was not accidental – it resulted from a comprehensive analysis that took into account environmental, technical and social factors. As research indicates, the siting of a nuclear power plant is based on a multi-criteria analysis, covering, among other things, environmental, infrastructural and socio-economic aspects (Susiati et al., 2025). Furthermore, this process may involve anywhere from a few to as many as several dozen detailed criteria, which are divided into biophysical, social and regulatory groups (Dede et al., 2024).

One of the most important factors determining the choice of location was the availability of water for cooling the reactors. Nuclear power plants are facilities with very high water requirements – consumption can reach tens of millions of litres per day, making access to large water reservoirs a key element in planning such investments (Jayabal et al., 2025). For this reason, a location in the immediate vicinity of the Baltic Sea provides a stable and efficient cooling source, which directly translates into the operational safety of the power plant.

It is also significant that a large proportion of the world's nuclear power plants are built precisely near large bodies of water, such as seas or major rivers (Kumar, Singh, 2023). Access to a stable cooling system is one of the fundamental conditions for their safe operation – its absence or disruption can lead to serious operational problems (Zhang et al., 2023).

Another key criterion was the low population density of the analysed area. The literature emphasises that when selecting sites for nuclear power plants, efforts should be made to minimise potential risks to the population, which translates into a preference for areas with scattered development (Ahmed et al., 2023). The municipality of Choczewo meets these conditions, characterised by a relatively small number of inhabitants and a limited degree of urbanisation.

Geological and environmental conditions also played a significant role. The most important site selection criteria include geotechnical stability of the ground, low seismic activity and a limited risk of natural hazards (Ahmed et al., 2023). Analyses carried out for the Lubiatowo–Kopalino region indicate that this area meets these requirements, making it suitable for the siting of nuclear infrastructure (PGE EJ1, 2022).

From an environmental perspective, the impact of the project on coastal ecosystems is also of particular importance. The location on the Baltic Sea requires consideration of the impact on the marine environment and protected areas; however, as available analyses indicate, it is possible to limit the negative effects of the investment by applying appropriate mitigation measures (General Directorate for Environmental Protection, 2023).

In terms of infrastructure, this location also offers the opportunity for effective integration with the national electricity system and the development of transmission networks, which is crucial for the operation of the power plant on a national scale (Ministry of Climate and Environment, 2023).

More broadly, this investment forms part of Poland's energy transition, which aims to reduce dependence on fossil fuels and limit greenhouse gas emissions. Given the dominance of coal in the national energy mix, the development of nuclear energy is one of the key tools for enhancing energy security and implementing the European Union's climate policy (European Commission, 2020; Ministry of Climate, 2021).

2.2. Navigational conditions at the site of the planned nuclear power plant (Lubiatowo–Kopalino)

The analysed area of the planned nuclear power plant site in the Lubiatowo–Kopalino region is situated in the coastal zone of the Baltic Sea, characterised by a relatively straight coastline and a shallow continental shelf. From a navigational point of view, this is a body of water of moderate difficulty, but one requiring consideration of a number of significant bathymetric and hydrographic conditions. The navigational conditions of the analysed area are presented on a navigational chart (Fig. 1), showing depth distribution, isobaths and navigational markings in the coastal zone.

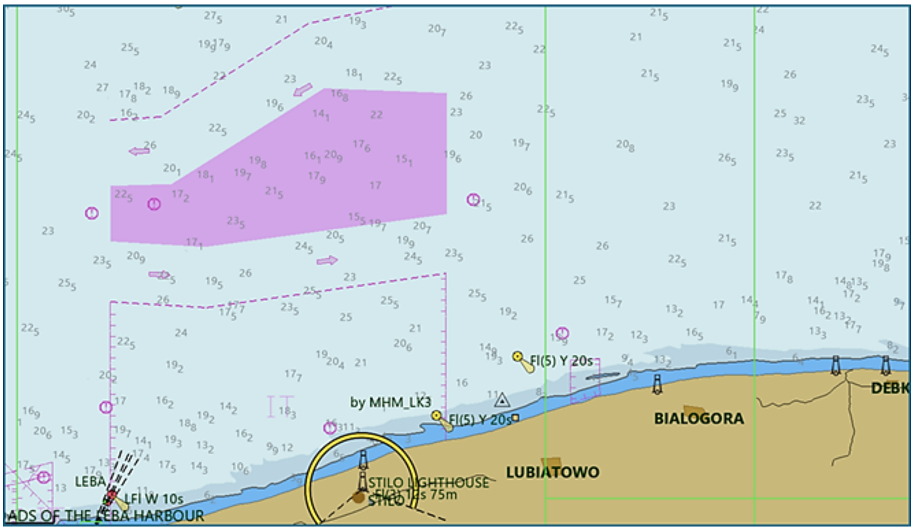

Figure 1. An extract from a navigational chart of the Lubiatowo–Kopalino area showing bathymetric conditions, navigational markings and the coastal zone of the Baltic Sea in the vicinity of the planned site of the nuclear power plant.

Source: own compilation based on navigational charts.

In the immediate vicinity of the shore lies a shallow water zone, where depths gradually increase from around 1-2 m at the shoreline to around 10-20 m a few kilometres offshore. This bathymetric profile is typical of the southern Baltic Sea and necessitates precise navigation, particularly for vessels with greater draught and those transporting large-scale cargo. The charts show numerous point depth marks and isobaths, indicating a relatively uniform, sandy seabed, occasionally interspersed with local shallows. The presence of these seabed features may constitute a significant restriction to navigation and require the designation of approach channels or dredging works. An important element of the navigation system in this area are navigation marks and light buoys, including Fl(5) Y 20s marks, which designate safe approaches from the sea. The system is supplemented by coastal marks, including the Stilo lighthouse, which serves as a distinctive landmark for coastal navigation. From the perspective of maritime traffic management, the analysed water area lies outside the main shipping routes of the Baltic Sea, which results in relatively low vessel traffic. Nevertheless, local shipping routes and approaches to the port of Łeba run in its vicinity, which means the presence of fishing vessels and smaller commercial ships. The map also highlights areas of special purpose (marked in purple), which may include restricted zones, naval training grounds or other areas of limited use. Their presence is of significant importance for the planning of maritime infrastructure and the organisation of future traffic of vessels serving the power plant. Furthermore, the hydrometeorological conditions of the Baltic Sea, including wave action, sea level variability and ice conditions during the winter, constitute a significant factor affecting navigational safety. These factors must be taken into account, particularly when designing hydrotechnical infrastructure and cooling water intake and discharge systems.

2.3. Characteristics of maritime traffic in the Southern Baltic

Maritime traffic in the Southern Baltic region, particularly in the coastal zone of the Pomeranian Voivodeship, is characterised by varying intensity and directionality, depending on the course of the main shipping routes and local coastal routes. The analysed area covers the waters in the Lubiatowo–Kopalino region and the vicinity of the port in Łeba. Based on the data presented in the (Fig. 2), it is possible to identify the dominant directions of vessel movement and areas with a higher concentration of ship trajectories. The measurement points (transects) used allow for the analysis of vessel flow in specific spatial cross-sections, which enables an assessment of traffic intensity and its directional structure.

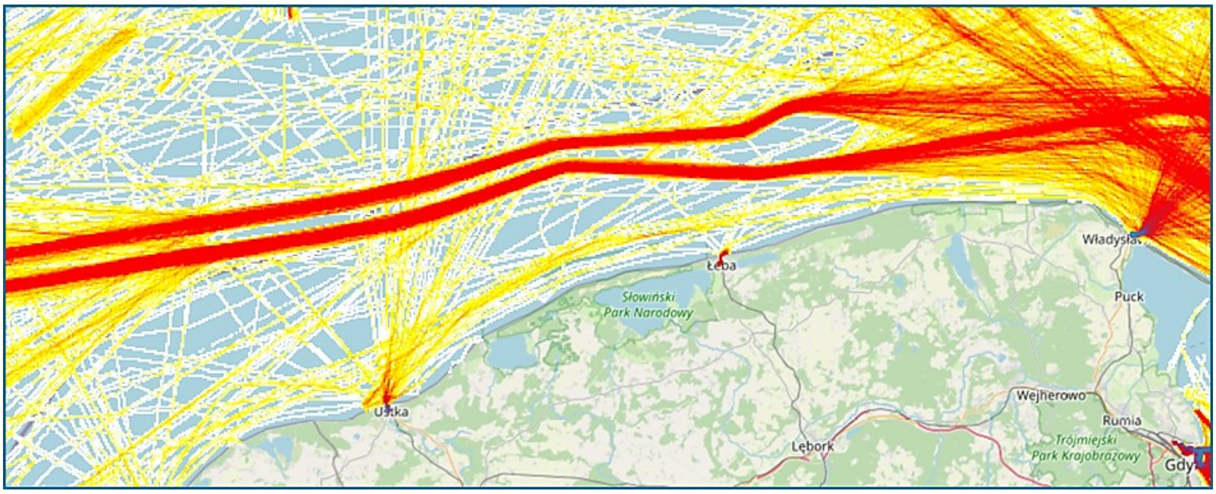

Figure 2. Characteristics of maritime traffic in the southern Baltic Sea in the Lubiatowo–Kopalino area, based on measurement points, showing vessel trajectories and the predominant directions of ship movement.

Source: own compilation based on AIS data in the IWRAP programme.

An analysis of the distribution of vessel tracks indicates that the main shipping lanes run parallel to the coastline, at a distance of several to over a dozen nautical miles from the shore. The highest concentration of vessel tracks is observed in this zone, indicating heavy transit traffic along the coast. In the immediate coastal zone, traffic intensity is significantly lower and is of a local nature. Fishing vessels, recreational craft and small ships operating in connection with local ports, including the port of Łeba, predominate here. This traffic is characterised by greater variability in direction and less regularity compared to deep-sea shipping.

The measurement sections used enable the identification of the dominant directions of vessel traffic. In the analysed area, east–west traffic predominates, which corresponds to the main shipping routes of the Baltic Sea. At the same time, local deviations in traffic routes are noticeable, linked to hydrometeorological conditions and the need to avoid restricted areas. Furthermore, the analysis of movement vectors indicates variations in vessel speeds depending on their type and function. Vessels moving within the main transport corridors exhibit greater stability in course and speed, whereas greater variability in movement parameters is observed in the coastal zone.

From the perspective of the planned location of the nuclear power plant, it is significant that this area is not situated directly on a main shipping route, which reduces the potential risk of collisions and spatial conflicts with heavy maritime traffic. Nevertheless, the presence of local shipping routes and fishing activity must be taken into account in the planning of maritime infrastructure and the organisation of future traffic of vessels serving the project.

3. Materials and Methods

3.1. Data sources

The primary data source used in this study was data from the AIS (Automatic Identification System), which is currently one of the most important tools in the analysis of maritime traffic and the assessment of navigational safety. This system enables the recording of both dynamic vessel parameters, such as position, course or speed, as well as static data, including the vessel type, its dimensions and MMSI identifier. Thanks to their high temporal and spatial resolution, AIS data enable a detailed reconstruction of vessel trajectories and an analysis of their behaviour in the maritime environment (Lei, 2020).

The literature emphasises that AIS data form the basis of modern maritime traffic analysis, enabling the identification of navigation patterns, the determination of transport routes and the assessment of interactions between vessels (Chen et al., 2022). The use of this data enables the identification of major shipping routes and the analysis of interactions between vessels.

This system also allows for the recording of vessels' dynamic parameters, such as position, course and speed, enabling the accurate reconstruction of vessel trajectories and the analysis of their behaviour in maritime space.

Furthermore, the integration of AIS data with analytical methods allows for a quantitative assessment of traffic safety and the identification of areas with an elevated risk level (Ma et al., 2024). Ship trajectory analysis also forms the basis for traffic modelling and the prediction of vessel behaviour in complex navigational conditions (Li et al., 2023).

3.2. Methods of ship traffic analysis

The analysis of ship traffic was carried out based on the reconstruction of vessel trajectories using AIS data and their analysis in a spatio-temporal context. This approach is commonly used in maritime traffic studies as it enables the identification of main navigation routes, areas of traffic concentration and changes in vessel behaviour (Ding, Weng, 2024).

In the first stage of the analysis, the distribution of vessel trajectories was visualised and assessed, which enabled the identification of the main transport corridors in the analysed area of the southern Baltic Sea. Based on the density of AIS tracks, zones of intensive traffic and areas of a local nature, mainly associated with coastal activities, were identified. This analysis was supplemented by the use of measurement sections designated as LEG 1-LEG 7, positioned in such a way as to capture both transit and coastal traffic (Fig. 3). Each section served as a reference line for which the flow of vessels crossing the given cross-section was analysed.

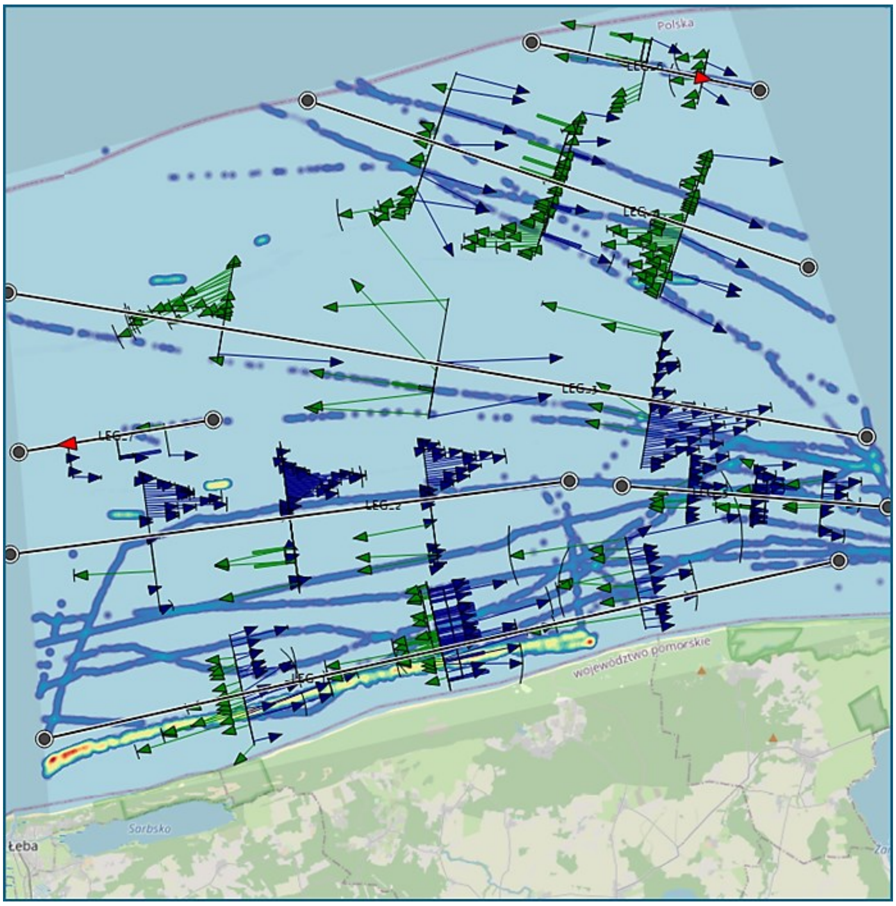

Figure 3. Distribution of ship trajectories with designated measurement sections (LEG 1-LEG7) in the southern Baltic Sea region.

Source: own compilation based on AIS data.

The use of LEG sections enabled a quantitative assessment of traffic by determining the number of vessels travelling in both directions (east–west and west–east), as well as an analysis of the fleet structure. Additional parameters were also determined for individual cross-sections, such as the maximum draught of vessels, the width of the traffic corridor and the proportion of different vessel types.

The analysis revealed a clear variation in traffic intensity between the individual sections. Section LEG 1, located closest to the coastal zone, mainly reflects local traffic, including recreational and auxiliary vessels. Section LEG 2 covers a transitional area between coastal traffic and more organised transit traffic. Sections LEG 3 and LEG 4 intersect the main shipping corridors, characterised by the highest concentration of vessel trajectories and the dominance of commercial vessel traffic. Section LEG 5 covers an area with a more diverse traffic structure, where both commercial and specialised vessels are observed. Sections LEG 6 and LEG 7, situated closer to the shore, primarily represent local traffic with lower intensity and greater variability in directions.

Additionally, vessels were classified by type, enabling an assessment of the contribution of individual vessel categories to maritime traffic. Distinguishing between commercial, fishing and specialised vessels is of significant importance from the perspective of navigational safety, as different vessel types are characterised by distinct traffic parameters and manoeuvrability.

The method employed, combining AIS trajectory analysis with the use of measurement cross-sections, allowed for a comprehensive assessment of the structure of maritime traffic and the identification of areas potentially significant from the perspective of navigational risk.

3.3. Risk identification and assessment

The identification and assessment of navigational risks was carried out on the basis of an analysis of actual vessel movements, reconstructed from AIS data. The AIS dataset used in this study covers the period from 1 January 2024 to 31 December 2024. The data were collected continuously during this time frame, which allows them to be considered representative of the area under analysis. The initial focus was on the spatial relationships between vessels and the course of their trajectories, which made it possible to identify the locations where potentially dangerous situations occur most frequently. The analysis took into account typical scenarios of vessel encounters, such as crossing courses, overtaking and head-on encounters. For each of these situations, basic movement parameters were analysed, including course, speed and their variation over time. Particular attention was paid to the distances between vessels, including the CPA (Closest Point of Approach) parameter, which allows one to determine how close vessels can come to each other whilst maintaining their current movement parameters. This analysis enabled the identification of areas with increased interaction between vessels, which can be treated as zones of heightened navigational risk. These areas are of particular significance in the context of maritime infrastructure planning, as they potentially increase the likelihood of hazardous incidents occurring.

In the next stage, modelling was carried out using the IALA IWRAP Mk2 software, which enables a quantitative risk assessment. Unlike trajectory analysis alone, IWRAP not only identifies potential conflict points but also converts them into probabilistic values. This means that, based on traffic density, route geometry and fleet structure, the programme determines the probability of a collision occurring.

The model takes into account so-called causal factors, which reflect the probability that a vessel will fail to perform an effective evasive manoeuvre. This makes it possible to move from a qualitative assessment of hazardous situations to a quantitative determination of the risk level. The results obtained in IWRAP made it possible to identify the most vulnerable areas of the water body and to determine the risk level on an annual basis. It should be emphasised, however, that this analysis concerns only the probability of events occurring, whilst the assessment of their consequences requires a separate approach.

3.4. Analytical tools and modelling (IALA IWRAP Mk2)

In this study, the IALA IWRAP Mk2 (IALA Waterway Risk Assessment Program) software was used to assess navigational risk; this software belongs to a group of tools used in the quantitative analysis of maritime safety. This programme enables the determination of the probability of adverse events occurring, in particular collisions between vessels and vessels running aground. IWRAP is part of the broader IALA Risk Management Toolbox, in accordance with the recommendations contained in the IALA G1018 guidelines on risk management. This tool does not function as a standalone solution, but serves as a supporting element for a comprehensive safety analysis, which should be supplemented by impact assessment and other analytical methods. The programme operates by creating a model of the analysed waterway that replicates actual navigational conditions. This model includes the geometry of fairways, vessel routes, traffic intensity, fleet structure and bathymetric conditions. In the study conducted, the model was developed on the basis of AIS data, which enabled the reconstruction of actual vessel trajectories and the nature of traffic in the analysed area. Based on the model prepared in this way, the programme performs statistical calculations, the result of which is an estimate of the average annual number of dangerous incidents. The calculations take into account so-called causal factors, interpreted as the probability that a vessel will fail to take effective manoeuvring actions to avoid a collision or running aground. It is worth noting that the scope of the analysis carried out in IWRAP is limited to determining the probability of events occurring, without taking their consequences into account. The assessment of potential consequences, such as environmental damage or threats to infrastructure, requires the use of additional methods and constitutes a separate stage of risk analysis.

The results of the modelling provide values describing the level of risk, including the predicted annual number of incidents and summaries enabling the identification of areas particularly vulnerable to hazardous situations. These results form an important basis for further interpretation and the formulation of conclusions regarding navigational safety, particularly in the context of the planned location of the nuclear power plant.

4. Results

4.1. Structure and intensity of maritime traffic

Analysis of AIS data revealed clear variations in both the intensity of maritime traffic and its structure across the individual measurement sections (LEG 1-LEG 7). Vessel traffic in the analysed area is asymmetrical, with one direction dominating in selected sections and a varied proportion of vessel types depending on the direction of travel. The summary of results is presented in the graph (Fig. 4), which illustrates both the total traffic volume and the proportion of individual vessel types in the analysed measurement sections. There is a clear dominance of section LEG 2, which stands out with by far the highest number of vessels and the largest proportion of commercial vessels.

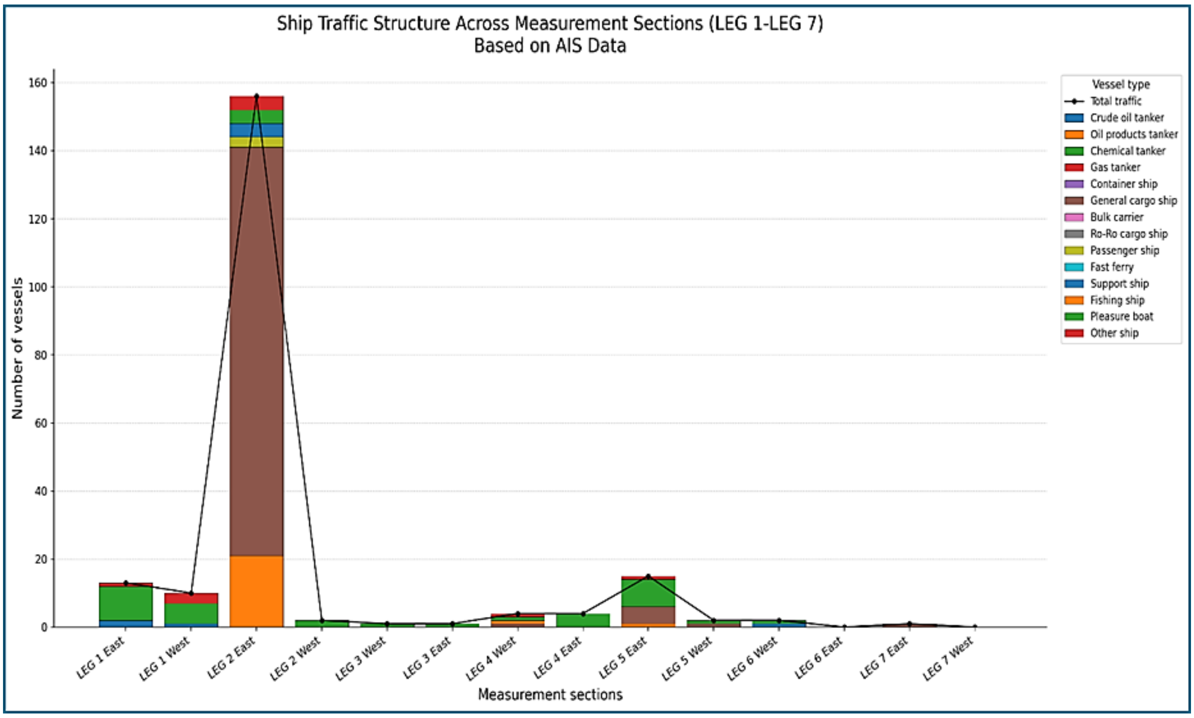

Figure 4. Ship Traffic Structure diagram.

Source: own compilation based on AIS data.

The heaviest traffic was recorded on the LEG 2 section, where 156 vessels were recorded heading east and only 2 heading west. As shown in the graph, the dominant group consists of general cargo ships, accompanied by oil product tankers. Passenger ships, as well as auxiliary and recreational vessels, are present to a lesser extent. Such a clear concentration of traffic and its one-way nature indicate the existence of a major transport corridor of regional significance. On the LEG 1 section, traffic volume is significantly lower and more balanced (13 vessels eastbound, 10 westbound). The graph shows that recreational and auxiliary vessels dominate here, which clearly indicates the local nature of the traffic.

Sections LEG 3 and LEG 4 are characterised by very low activity. The graph shows a marginal share of all vessel types, confirming their negligible significance in the traffic structure. Only isolated vessels are present here, mainly recreational and occasionally commercial.

Moderate traffic intensity is observed on section LEG 5 (15 vessels heading east and 2 heading west). As is also clearly visible in the chart, the fleet structure is dominated by recreational vessels and general cargo ships, indicating the mixed nature of the traffic – partly local, partly transit. Section LEG 6 shows very low activity, limited to isolated vessels heading west, mainly of an auxiliary and recreational nature. The chart shows an almost complete reduction in traffic in this area. The lowest traffic intensity was recorded on section LEG 7, where only a single vessel appears. Graphically, this section plays virtually no significant role in the maritime traffic system.

This spatial distribution is of significant importance from the point of view of navigational safety, as areas with the highest traffic density and a high proportion of merchant ships and tankers may constitute potential zones of increased collision risk, which will be analysed in detail in the next stage of the work.

4.2. Hazard scenarios – results of IALA IWRAP Mk2 modelling

The navigational risk analysis carried out using the IALA IWRAP Mk2 programme enabled a quantitative assessment of the probability of hazardous events occurring in the analysed area. The study considered two basic collision scenarios: overtaking and head-on encounters. The results for the overtaking scenario are presented in the graph (Fig. 5 and Fig. 6).

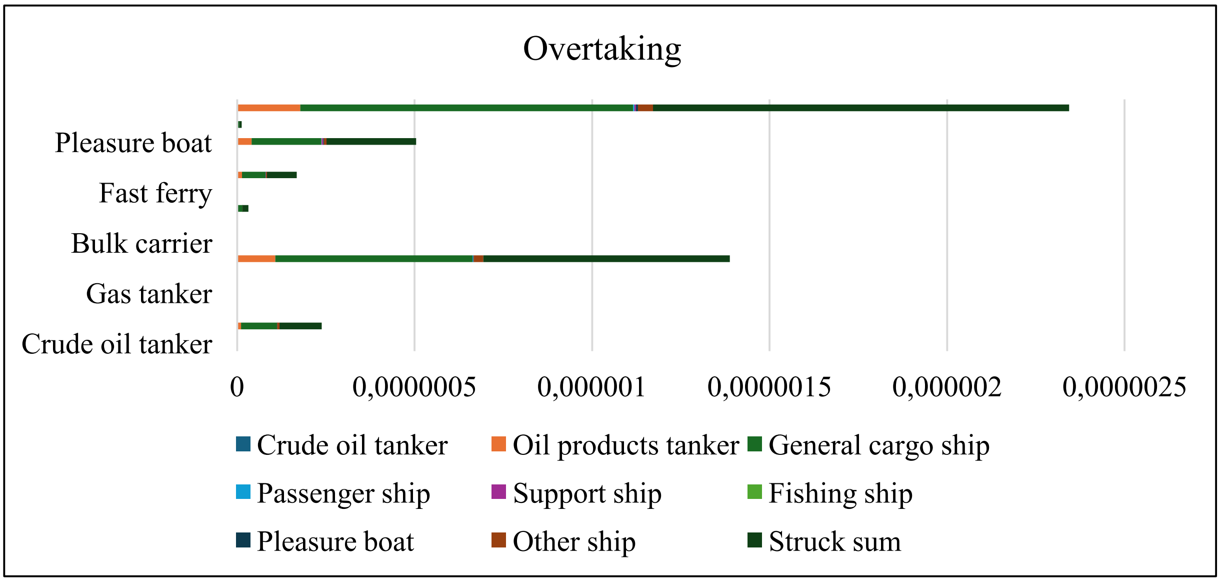

Figure 5. Summary of AIS data regarding overtaking situations.

Source: own compilation based on AIS data.

In the overtaking scenario, interactions involving commercial vessels are clearly predominant, particularly general cargo ships, which account for the largest share of the total risk. Product tankers also make a significant contribution, whilst the share of other vessel types, such as passenger ships or auxiliary vessels, remains relatively small. The total risk value for this scenario is the highest among the cases analysed, indicating that overtaking is the main mechanism for potential collisions in the area under study.

In turn, the results for the head-on encounter scenario are presented in the graph (Fig. 6).

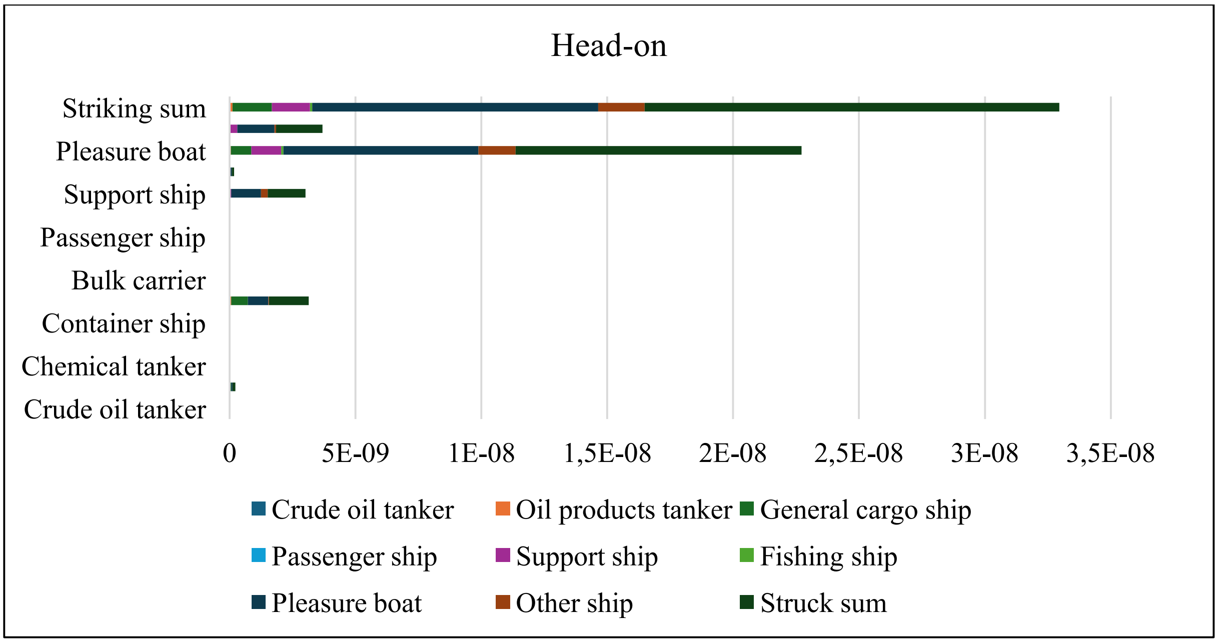

Figure 6. Summary of AIS data regarding head-on situations. Source: own compilation based on AIS data.

In the head-on scenario, the risk values are significantly lower and are marginal in comparison to overtaking. The largest contribution in this scenario comes from commercial vessels as well, and to some extent auxiliary and recreational craft; however, their impact on the overall risk remains limited. The low figures are primarily due to the orderly nature of vessel traffic, which takes place along parallel shipping lanes, significantly reducing the number of direct head-on encounters. A comparison of the two scenarios clearly indicates that the dominant source of risk in the analysed area is overtaking manoeuvres, associated mainly with the high volume of commercial vessel traffic in the main transport corridors. The head-on encounter scenario, however, is of secondary importance and does not constitute a significant risk factor in the studied area. From the point of view of navigational safety and the planned location of the nuclear power plant, this means that particular attention should be paid to areas of intensive transit traffic, where the highest number of interactions between vessels occurs.

4.3. Identification of high-risk zones based on AIS data and IWRAP Mk2 modelling

The identification of high-risk navigation zones was carried out based on the integration of AIS data and modelling results obtained using the IALA IWRAP Mk2 programme. This approach allows the actual distribution of vessel traffic to be linked to a quantitative assessment of the probability of hazardous incidents, such as collisions or groundings.

In the first stage of the analysis, AIS data were used to identify areas of traffic concentration, referred to as 'hotspots'. An analysis of vessel trajectory density revealed that maritime traffic in the analysed region of the southern Baltic Sea is highly organised and concentrated in several clearly defined shipping corridors running parallel to the coastline. Of particular significance is the area corresponding to the LEG 2 cross-section, where the highest traffic density and a predominance of large commercial vessels were recorded.

In the next stage, the results of the trajectory analysis were combined with the results of IWRAP Mk2 modelling, which enabled the identification of the spatial distribution of collision risk. The values obtained indicate that the highest probability of hazardous incidents occurs in areas with the highest traffic intensity and where the trajectories of vessels travelling at different speeds overlap.

The most significant high-risk zones were identified:

- along the main transport corridors (particularly in the area corresponding to LEG 2),
- in areas where local and transit routes intersect,
- in the coastal zone, where commercial, recreational and auxiliary vessels mix.

The analysis showed that the dominant mechanism generating risk is overtaking, which results from the large number of vessels travelling in the same direction but at different speeds. In contrast, the risk associated with head-on collisions is marginal and occurs mainly locally. The fleet structure is also a significant factor influencing the level of risk. General cargo ships and tankers contribute most to the generation of risks; due to their size, limited manoeuvrability and economic importance, they constitute a key element of the transport system, but at the same time increase the potential consequences of incidents. From the perspective of the planned location of the nuclear power plant in the Lubiatowo–Kopalino area, the high-traffic zones running parallel to the coast are of particular significance. Although the site itself lies outside the main shipping route, its proximity to areas of increased traffic volume necessitates the consideration of potential collision scenarios in the maritime infrastructure planning process.

It should be emphasised that the identification of high-risk areas in this study is qualitative in nature and is based on an analysis of vessel traffic density and the results of IWRAP probabilistic modelling. This programme provides probability values for events, but does not define clear-cut thresholds for classifying risk levels. Consequently, the identification of high-risk areas was based on a relative comparison of traffic intensity and the risk values obtained within the analysed water body. Due to the methodology adopted, detailed risk maps were not produced; however, the results allow for the identification of zones with an elevated level of risk.

4.4. Impact of maritime traffic on plant safety

An analysis of maritime traffic and the results of navigational risk modelling indicates that the presence of heavy ship traffic in the southern Baltic Sea region is a significant factor that must be taken into account in the context of the safety of the planned nuclear power plant at the Lubiatowo–Kopalino site. The results obtained clearly show that maritime traffic in the analysed area is highly concentrated and takes place along clearly defined transport corridors, dominated by commercial vessels, in particular general cargo ships and oil product tankers. Due to their operational parameters, such as deep draught, limited manoeuvrability and longer reaction times, these vessels constitute a potential source of risk in the event of an emergency. Although the power plant is located directly outside the main shipping route, its proximity to areas of increased traffic, particularly in the region corresponding to the LEG 2 cross-section, means that the impact of maritime traffic on the safety of the investment cannot be ruled out. This applies in particular to extreme situations, such as loss of vessel control, navigational errors or adverse hydrometeorological conditions.

The results of IWRAP Mk2 modelling indicate that the dominant scenario for potential hazardous events is overtaking, which stems from the one-way nature of the traffic and speed differences between vessels. Such situations increase the likelihood of collisions within the main transport corridors and, consequently, may lead to secondary hazards, such as a damaged vessel drifting towards the coastal zone.

From the point of view of power plant safety, the following potential scenarios are particularly significant:

- ship collisions near the coast, which may lead to loss of control of the vessel,
- vessels drifting towards coastal infrastructure, including cooling installations,
- accidents involving vessels transporting hazardous substances, in particular tankers,
- the impact of increased traffic on the organisation of maritime space, including the need to designate safety zones.

Additionally, account must be taken of the fact that the coastal area is characterised by mixed traffic, where large commercial vessels coexist with recreational and auxiliary vessels. This diversity may lead to an increase in the number of interactions between vessels with different manoeuvring capabilities, which further affects the level of risk.

In the context of the planning and operation of a nuclear power plant, it is therefore essential to implement appropriate risk-mitigation measures, such as:

- the designation of restricted traffic zones (safety/exclusion zones) around the infrastructure,
- adjusting the organisation of maritime traffic in the project area,
- the use of vessel traffic monitoring systems (VTS/AIS),
- the development of emergency response procedures.

Maritime traffic in the analysed area does not pose a direct threat to the power plant site; however, its nature and intensity mean that it is a significant indirect risk factor. This applies in particular to emergency situations and secondary impacts that may affect the safety of coastal infrastructure. Taking these conditions into account in the design and safety management of the power plant is crucial to ensuring its safe operation.

5. Discussion

5.1. Interpretation of results

The analysis of maritime traffic and navigation risk modelling indicates a clear correlation between the intensity of vessel traffic and the level of risk generated. The results clearly show that areas of traffic concentration are of key importance, particularly the main transport corridors running parallel to the coast. In these zones, the highest density of AIS tracks and a predominance of large commercial vessels are observed, which directly translates into an increased likelihood of interaction between ships. A significant finding is the predominance of the overtaking scenario as the main mechanism generating collision risk. This stems from the nature of traffic in the analysed area, which is largely unidirectional but varies in terms of vessel speed. Under such conditions, even minor differences in traffic parameters can lead to potentially dangerous situations. At the same time, the relatively low values for the head-on encounter scenario confirm that vessel traffic is well organised spatially and proceeds in an orderly manner. The role of the fleet structure deserves particular attention. General cargo ships and oil product tankers contribute most to the generation of risk, which is directly linked to their numbers and transport function in the region. Due to their manoeuvrability and operational characteristics, these vessels constitute a key element of the shipping system, but at the same time increase the potential consequences of incidents.

5.2. Comparison with other nuclear power plant locations (case studies)

The results obtained are consistent with observations regarding other coastal nuclear power plant locations, where access to water resources is one of the main location factors, but at the same time necessitates the consideration of maritime traffic as a significant element of the operational environment. In many cases, nuclear power plants are located near areas with moderate or controlled traffic volumes, and the main shipping routes run at some distance from critical infrastructure. Analyses conducted for power plants in Western Europe and Asia indicate that the greatest risk to coastal facilities does not stem from daily ship traffic, but from rare yet potentially serious incidents, such as a vessel losing steering control or collisions leading to drifting towards the shore. In this context, the results obtained for the Lubiatowo–Kopalino area fit the typical operational model of coastal sites, where the main risks are of an indirect nature and relate to the interaction between heavy transit traffic and the coastal zone.

5.3. Implications for safety management

The results of the analyses carried out are of significant importance for the planning and safety management of the planned nuclear power plant. In particular, they highlight the need to consider maritime traffic as a systemic element that may affect the safety of the infrastructure, especially in emergency situations. From a practical perspective, this means there is a need to implement solutions that mitigate the risk of interaction between vessels and coastal infrastructure. Proper management of the maritime space is of key importance, including the designation of safety zones around the power plant and the adaptation of traffic organisation in its vicinity. Monitoring of vessel traffic using AIS and VTS systems also plays a significant role, as these enable real-time monitoring of the navigational situation and a rapid response in the event of a threat. The results also indicate the need to incorporate emergency scenarios into the infrastructure design process, including the potential impact of drifting vessels and incidents involving the transport of hazardous substances. The integration of navigational analyses with power plant safety planning is therefore a key element of a systems-based approach.

5.4. Limitations of the study

Despite yielding consistent and unambiguous results, the analysis conducted has certain limitations that must be taken into account when interpreting the findings. First and foremost, the analysis is based on AIS data, which, although one of the most important sources of information on maritime traffic, may not cover all vessels, particularly smaller vessels not registered in the system. Additionally, the IWRAP Mk2 model allows for the assessment of the probability of events, but does not account for their consequences, such as environmental or infrastructural impacts. This means that the presented results relate solely to the level of risk in probabilistic terms, and a full risk assessment would require extending the analysis to include a consequence component. Another significant limitation is the use of a static traffic model, which does not fully account for the variability of hydrometeorological conditions, seasonal traffic patterns or extreme situations. In practice, these factors can significantly influence the level of risk and should be the subject of further research. Despite these limitations, the results obtained provide a reliable basis for assessing navigational safety and can be utilised in the planning and management of critical infrastructure in the coastal zone. A significant limitation of the analysis is that it does not take into account hydrometeorological factors, such as wind conditions, wave action or ocean currents, which can have a significant impact on vessel traffic and the level of navigational risk. The model used is based on a statistical analysis of vessel traffic and does not account for variations in environmental conditions over time. Consequently, the results obtained should be interpreted as an average picture of risk, not taking into account the impact of extreme conditions. Taking these factors into account represents an important direction for further research.

5.5. Safety Management System Concept

Based on the analyses conducted, an integrated safety management system has been proposed, the aim of which is to minimise navigational risk in the vicinity of the planned nuclear power plant. This system is based on a multi-layered approach, combining maritime traffic monitoring, risk analysis and operational procedures. A key principle is treating safety as a continuous process, encompassing both the planning and operational phases of the facility.

In the proposed model, the ongoing analysis of vessel traffic data and its integration with risk assessment tools plays a key role, enabling a dynamic response to changing navigational conditions. Figure 7 below illustrates the architecture of the proposed safety management system, incorporating multi-source data integration, vessel traffic analysis and risk modelling.

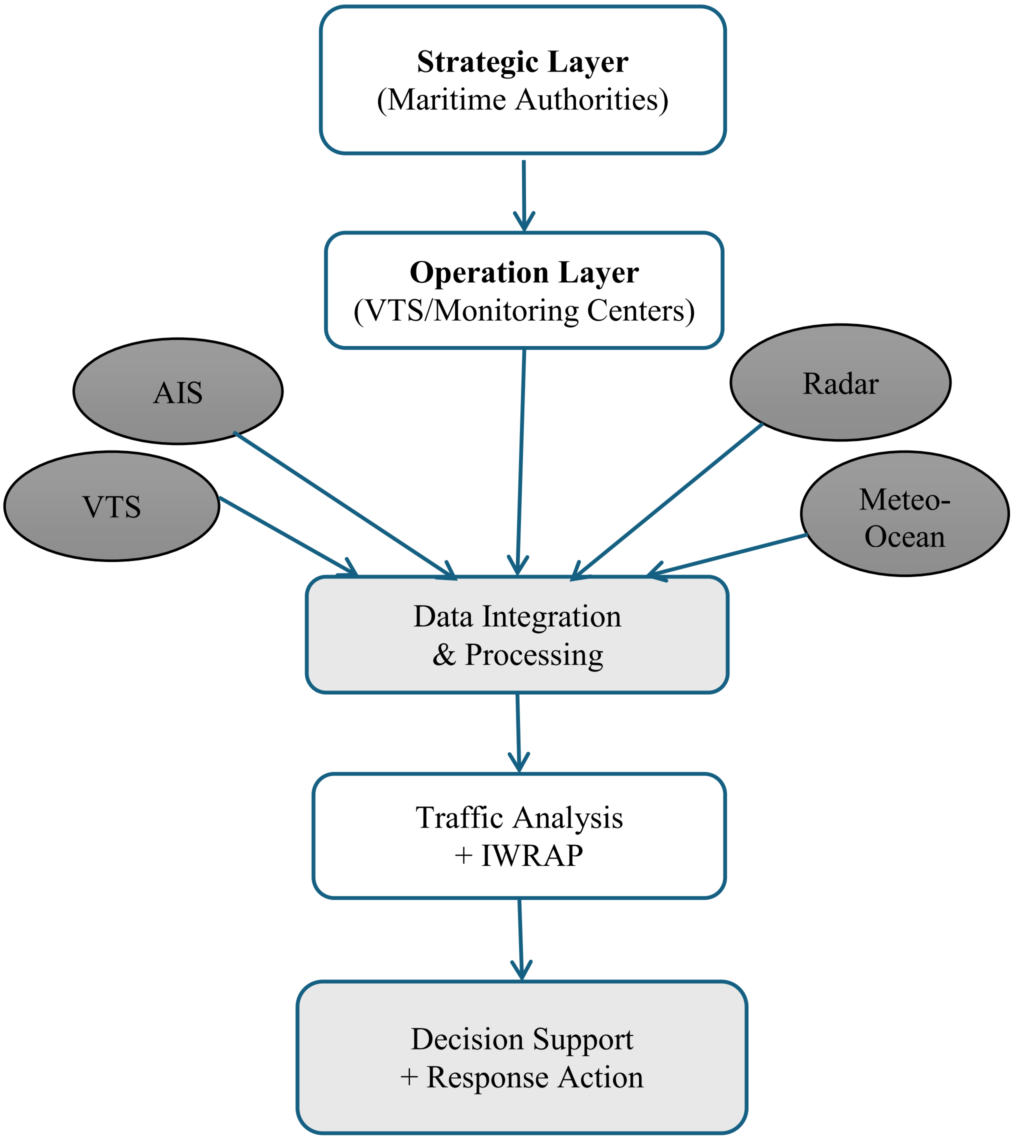

Figure 7. Architecture of an integrated maritime safety management system, combining AIS, radar, VTS and meteorological-oceanographic data with vessel traffic analysis and probabilistic risk modelling (IWRAP) to support decision-making.

Source: own compilation based on AIS data.

The proposed system is conceptual in nature, but its structure is based on the logical interconnection of three fundamental elements: input data, decision-making mechanisms and operational actions. Input data primarily comprises information from AIS, radar and VTS systems, as well as hydrometeorological data, which form the basis for the ongoing assessment of the navigational situation. Based on this, the analytical stage is carried out, involving the identification of potential hazards and risk assessment using tools such as IWRAP.

The results of this analysis form the basis for the decision-making process, within which appropriate operational actions are determined, such as warning vessels, modifying traffic organisation or activating emergency response procedures. This approach allows input data to be linked to specific management actions, creating a coherent framework for the operation of the safety system.

The system also provides for a clear separation of management levels: strategic (maritime administration), operational (VTS, monitoring services) and technical (power plant operator), whilst ensuring their mutual interoperability. The basis for the operation of the safety system is the integration of various sources of navigational data. AIS data enables the identification of vessels and the analysis of their trajectories; however, its effectiveness is limited in the case of vessels not equipped with transponders or in conditions of signal interference. It is therefore necessary to supplement AIS with radar data and vessel traffic surveillance systems (VTS), which provide a more complete picture of the navigational situation. The integration of these systems allows for:

- real-time tracking of vessel movements in the vicinity of the power plant,
- identification of potentially dangerous situations (e.g. vessel approaches),
- forecasting of trajectories and possible conflicts,
- rapid transmission of information to operators and services responsible for safety.

The integrated monitoring system forms the basis for implementing so-called situational awareness, which is crucial in the management of critical infrastructure security.

5.6. Emergency response procedures

A key element of the proposed safety management system is the development of coherent and multi-layered crisis response procedures, taking into account the specific nature of maritime traffic in the coastal zone and the nature of critical infrastructure. These procedures should cover both events with a high probability of occurrence and rare scenarios with potentially catastrophic consequences.

Analysis of vessel traffic and the results of risk modelling indicate that incidents involving loss of control of a vessel, interactions between vessels, and uncontrolled drifting towards coastal infrastructure are of key importance. Particular attention should be paid to vessels carrying dangerous cargoes, whose share – though limited – generates a disproportionately high risk in the event of an accident.

The basis for an effective response is the rapid identification of a threat, based on continuous monitoring of AIS data, radar data and information from VTS systems. The effective flow of information between traffic control services, the maritime administration and the power plant operator is also of key importance, enabling decisions to be made in near real time. In practice, this means that operational procedures based on clearly defined incident scenarios must be implemented, and responsibilities must be assigned to specific entities. Figure 8 presents a diagram of emergency response procedures, taking into account various incident scenarios as well as the decision-making process and operational actions.

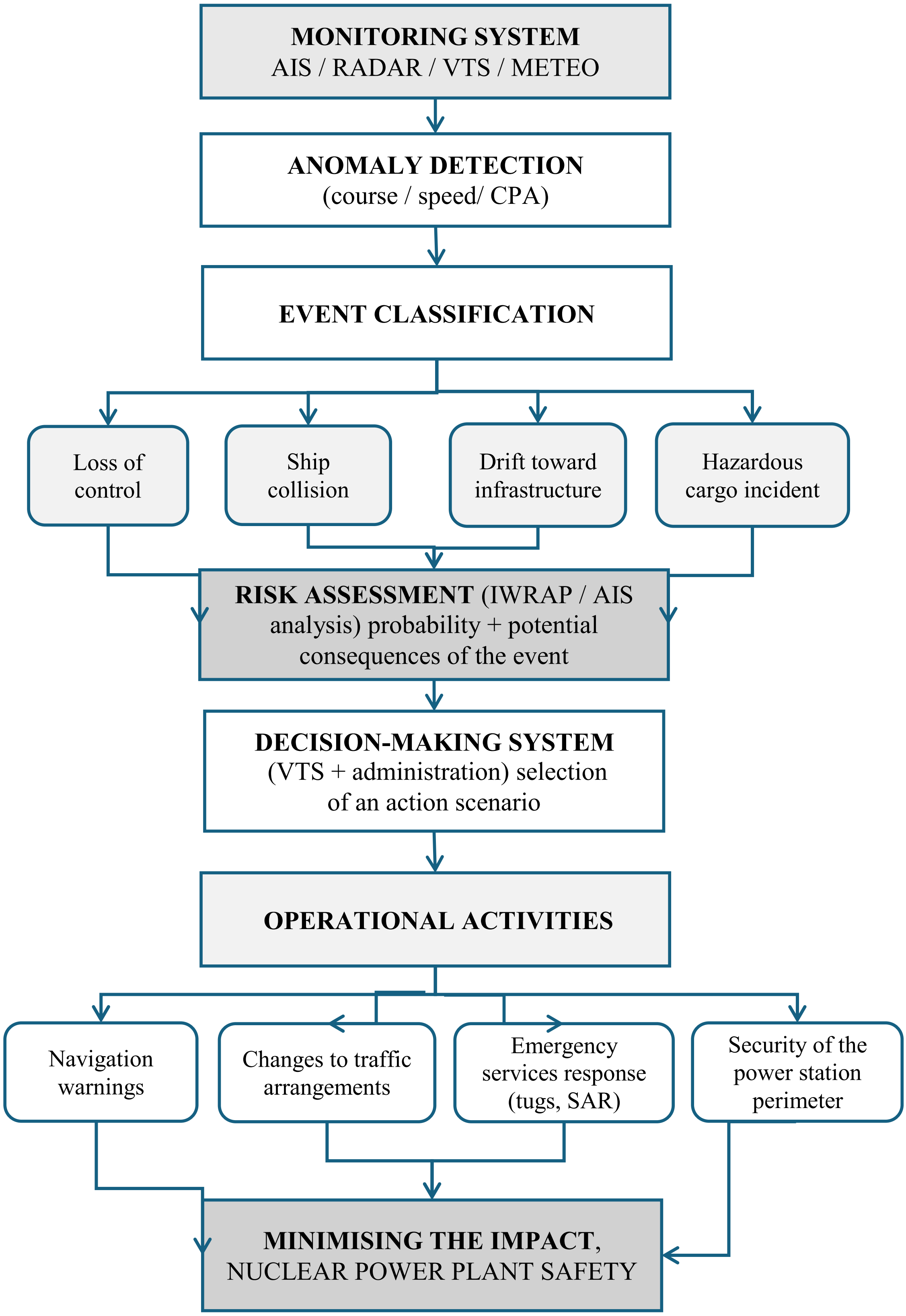

Figure 8. Diagram of emergency response procedures within an integrated safety management system, covering the identification and classification of incidents, as well as operational measures for various hazard scenarios.

Source: own compilation based on AIS data.

In the context of the planned nuclear power plant, it is particularly important to implement preventive and organisational measures, such as the designation of safety zones around the infrastructure, the adaptation of maritime traffic management and the development of monitoring systems.

The integration of AIS data with analytical tools, including probabilistic models (e.g. IWRAP), enables real-time risk assessment and the identification of potential hazardous situations. These measures should be complemented by regular updates to risk analyses and training for operational staff, thereby enhancing readiness to respond to emergencies.

The implementation of a comprehensive emergency response system not only reduces the likelihood of hazardous incidents occurring but also minimises their consequences, thereby enhancing the resilience of the entire safety system in the project area.

6. Conclusions

The analysis of maritime traffic in the southern Baltic Sea region, supplemented by navigation risk modelling using the IALA IWRAP Mk2 tool, enabled a comprehensive assessment of safety conditions in the context of the planned location of a nuclear power plant in the Lubiatowo–Kopalino area. The results obtained clearly indicate that vessel traffic in the analysed area is highly organised and concentrated in clearly defined transport corridors running parallel to the coastline. The most significant sections are those corresponding to the main transit routes, where commercial vessels dominate, in particular general cargo ships and oil product tankers.

Analysis of AIS data revealed significant variation in both traffic intensity and its spatial structure. Areas with the highest traffic intensity coincide with zones of increased risk, as confirmed by the results of probabilistic modelling. The dominant scenario for hazardous incidents was overtaking, resulting from the one-way nature of the traffic and the variation in vessel speeds. Conversely, the risk of head-on collisions remains limited, which indicates a relatively orderly shipping pattern in the analysed area.

From the perspective of the safety of the planned nuclear power plant, it is of key importance that, although the site of the project lies outside the direct route of the main shipping lanes, its proximity to areas of intense maritime traffic necessitates consideration of indirect risks. This applies primarily to emergency situations, such as loss of vessel control, collisions in the vicinity of shipping lanes, or ships drifting towards the coast. Of particular significance here are large vessels with limited manoeuvrability, whose potential impact may extend beyond the immediate traffic area. The results obtained have significant implications for the development of security policy regarding critical infrastructure located in the coastal zone. They highlight the need to integrate maritime traffic monitoring systems, such as AIS, radar and VTS, with risk analysis tools, enabling the ongoing assessment of the navigational situation and real-time decision-making. The implementation of a systemic approach, involving cooperation between maritime authorities, traffic monitoring services and power plant operators, is also of key importance. The security management model proposed in this study, based on data integration, risk analysis and operational procedures, provides the foundation for building an effective risk mitigation system.

The research findings also highlight the need for further development of risk assessment methods in the maritime environment. In particular, it is appropriate to extend the analyses to include a consequence component, covering the effects of potential incidents on the environment and infrastructure. It is also important to take into account the variability of hydrometeorological conditions and the seasonality of vessel traffic, which may influence the level of risk. In future research, it is also worth considering the use of advanced modelling methods, including dynamic simulations and artificial intelligence-based tools, which will allow for more precise hazard forecasting and support decision-making processes.

In summary, the analysis provides a coherent picture of the relationship between maritime traffic patterns and the level of navigational risk, and highlights the crucial importance of integrating data and analytical tools into the safety management process. These findings can provide significant support for both infrastructure investment planning and the development of modern safety management systems in the coastal zone.

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