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METHODOLOGICAL COMPARISON OF LANE DESIGN APPROACHES UNDER TERMINAL TRAFFIC CONDITIONS IN ŚWINOUJŚCIE

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Purpose: The aim of the study was to look at the challenges posed by the construction of a new container terminal in Świnoujście - both from a technical, operational, environmental and socio-economic perspective. The authors focused on how shipping infrastructure can be designed in a modern, safe and sustainable way. A comparison of several methods for determining the width of the fairway was made to assess which one would work best. This will enable an understanding of how to make better decisions when planning such large investments.

Design/methodology/approach: For the study, fairway width calculations were made using three methods - Canadian, PIANC and USACE - and the resulting data were collated to better understand the discrepancies. The study also made references to current research about risk in ports and the need for responsible and sustainable investment.

Findings: The results of the analysis suggest that the discrepancies between the results of the different methods highlight the importance of an informed choice of tools and design components. It was emphasised that a flexible approach to design is needed to take into account changing climatic, technical and social conditions. The importance of implementing infrastructure monitoring systems was emphasised.

Research limitations/implications: The scope of the analysis was partly limited by the availability of up-to-date technical and environmental data, which necessitated the use of simplifications that could affect the precision of the results. In the future, it would be worth extending the study to include computer simulations based on real hydrodynamic and meteorological data and comparing the results with similar investments in other ports to better adapt solutions to local conditions.

Practical implications: The results presented can be a valuable resource for practitioners - from port managers to planning and investment professionals. They highlight the importance of a holistic approach - combining technical issues with analysis of risk, environment and social considerations. This can help avoid costly design mistakes and better prepare for future operational challenges.

Social implications: The study highlights the impact of such investments on local communities and the environment. They can contribute to more open community dialogue and better policy decisions. Sustainable port planning affects not only the economy, but also the quality of life of residents and the state of the environment.

Originality/value: The publication has a practical aspect, being based on a real case study of the planned construction of a container terminal in Świnoujscie. It compares fairway design methods in relation to local conditions. It provides a tool for those involved in port infrastructure development.
Keywords: risk management, container terminal, port infrastructure, sustainability, maritime transport, sustainable maritime.
Category of the paper: Viewpoint.

1. Introduction

The importance of the development of port infrastructure in Świnoujście in the context of maritime traffic in the Baltic Sea is a key element of the strategy to strengthen the position of seaports in the area. The increase in transhipment operations and the growing demand for efficient logistics solutions require modern investments in port infrastructure. As one of the most important ports in Poland, Świnoujście plays a key role in ensuring the competitiveness of the national maritime economy and its integration into global supply chains. The planned container terminal investment - its scale and challenges represent one of the largest infrastructure investments in the region. The scope of the project includes the expansion of existing quays, the modernisation of the handling infrastructure and the implementation of advanced maritime traffic management systems. Challenges related to the implementation of the investment include technical, economic, environmental and social issues that must be taken into account in the planning and risk management process.

The safety and efficiency of container terminals depend on optimum maritime traffic management, including the proper designation of lane widths for vessels. In Świnoujście, where maritime traffic intensity is steadily increasing, it is necessary to apply appropriate methods for determining the widths of shipping lanes, taking into account both hydrotechnical parameters and operational requirements of port users. The aim of this research study is to compare methods for determining lane widths in the context of the container terminal in Świnoujście, taking into account current maritime traffic intensity. The analysis includes both theoretical models and practical solutions implemented in international ports. In order to achieve this objective, the following research hypothesis was put forward, according to which the use of computational methods based on precision navigation systems - such as approaches like USACE and PIANC - makes it possible to significantly reduce the required fairway width without compromising the level of safety, provided that the speed of vessels is properly managed.

In this paper, the research hypothesis is proven on the basis of a comparative computational analysis of three methods of determining fairway widths (PIANC, Canadian method and USACE), for two types of vessels (MSC GULSUN and BALTIMAX), and in the context of sea traffic density in Świnoujście, a collision risk analysis for the PIANC and USACE methods was also carried out.

Various approaches to risk management in container terminals have been presented in the literature. Khorram (2020) proposed a novel risk assessment method combining formal safety assessment (FSA) with FAHP methods, entropy measure and the VIKOR model to optimise risk management at container terminals (Khorram, 2020). In contrast, a study by Orymowska et al. (2022) used the MICMAC structural analysis method for risk prioritisation at marine terminals. An empirical study at the port of Sfax in Tunisia identified key risk variables requiring immediate intervention and analysed the interdependencies between them (Orymowska, et al. 2022). Pallis (2017) presented a conceptual methodology for risk management in container terminals, based on the adaptation of formal security assessment (FSA) to the specificities of ports. This methodology takes into account a variety of risk factors and their interactions, offering a decision-making framework for assessing and improving security levels at terminals (Pallis, 2017).

These various approaches highlight the importance of comprehensive and port-specific risk management in container terminals. In this paper we will focus on the application of the PIANC guidelines, which offer proven methods and recommendations for the design and management of port infrastructure, adapted to the specific operational conditions of the container terminal in Świnoujście.

The originality of this paper lies in the comprehensive comparison of three recognised methods for determining fairway widths (PIANC, Canadian method, USACE) in the context of the planned container terminal investment in Świnoujście.

The approach allows the spatial and operational effectiveness of the individual methods to be assessed and provides a basis for making practical design recommendations to support safe and sustainable port infrastructure planning.

1.1. Modern methods for determining the width of waterways and analysis of previous studies

Modern research on the width of waterways in container terminals focuses on optimising port infrastructure, taking into account traffic intensity, navigational safety and the impact of environmental factors. In recent years, simulation and numerical methods have developed significantly, allowing for more precise modelling of fairway parameters and their adaptation to dynamically changing navigation conditions.

The Permanent International Association of Navigation Congresses provides key guidelines for fairway design, taking into account hydrodynamic and operational factors (Baric et al., 2019). Computer simulations play a key role in predicting the dynamics of ships in confined port spaces (Chen et al., 2023). The US Army Corps of Engineers indicates that an approach based on real hydrodynamic conditions and the analysis of historical vessel traffic data allows for better adaptation of fairway infrastructure to local navigation conditions (He et al., 2022).

In a similar vein, dynamic berth allocation in automated container terminals influences the design of the manoeuvring space, which is reflected in model analyses (Kastner et al., 2023).

The integration of GIS and artificial intelligence systems is one of the key directions in the development of fairway width optimisation (Liu et al., 2024). Numerical modelling indicates that the appropriate layout of container terminal yards can significantly affect their operational efficiency (PIANC, 2014). The diversity of container terminal layouts and their impact on port operations remain a significant issue in maritime logistics research (Przywarty et al., 2020), emphasising that despite efforts to standardise, local conditions continue to play a key role in the design of port infrastructure.

The analysis of fairway widths is also based on field methods and analytical models. The use of kinematic methods to determine the safe width of bends in fairways allows for more precise design of navigation routes, taking into account the trajectories of vessels in real conditions (Rodrigue, 2025). Deterministic models that take into account the effect of the shore for slim-shaped vessels provide important data for designing fairways in confined spaces (USACE, 2006).

From the perspective of port efficiency and sustainable development, the analysis of container flows allows for more accurate planning of yard capacity in container terminals, which translates into more effective management of container traffic and optimisation of terminal layout (Wang et al., 2019).

In conclusion, the literature points to the growing role of numerical modelling, artificial intelligence integration and historical data analysis in fairway width optimisation. Future research should focus on adaptive traffic management systems and dynamic modelling of hydrological conditions, which will allow for better adaptation of port infrastructure to changing environmental and operational conditions.

2. Methodology

The paper uses a comparative-computational approach, based on two recognised methodologies: PIANC and USACE. Both methods use quantitative technical parameters to determine fairway widths and to assess the safety of navigation under intensive maritime traffic conditions. The analysis aimed to identify the differences resulting from the application of different design and technological assumptions and their impact on the efficiency and safety of the planned investment in Świnoujście. The methodology adopted includes both engineering calculations related to the dimensioning of the fairway and risk analysis in port operations.

As a first step, calculations of the fairway width were carried out using the Canadian method, which is based on empirical relationships and actual operating conditions. In order to compare the results, the fairway was also dimensioned using the PIANC (Permanent

International Association of Navigation Congresses) method, which is recognised as the standard for international navigation infrastructure design. In addition, values obtained using the USACE (United States Army Corps of Engineers) method, which takes into account the influence of modern navigation systems on the width of the required waterway, were analysed.

In the next stage of the study, a risk analysis was applied, involving the identification of potential risks associated with the operation of the fairway and the container terminal. A multi-criteria analysis was used for this purpose, taking into account technical, operational and environmental aspects. A Monte Carlo method was also used as part of the analysis, allowing a probabilistic estimation of the risk of collision on the fairway.

The study was based on literature data, analyses of historical maritime incidents and simulations of navigational conditions. The results of the calculations and analyses made it possible to assess the effectiveness of various fairway dimensioning methods and to identify optimal solutions to increase the safety and operational efficiency of the port infrastructure.

2.1. Characteristics of the area and traffic intensity

The port in Świnoujście is a key transport hub in the Baltic Sea area, playing a strategic role in Poland's maritime economy. Its infrastructure includes advanced transhipment terminals, and planned investments include the construction of a modern container terminal, which will significantly increase the port's capacity to handle large tonnage vessels. In addition, extensive navigation systems ensure a high level of navigational safety and efficient operation of the entire port complex (Ministry of Infrastructure, 2023).

The importance of the fairway leading to the port of Świnoujście is an indispensable element in ensuring the efficient handling of shipping and is a strategic component of the transport infrastructure. Its appropriate navigational parameters, such as depth, width and marking system, determine the port's ability to handle vessels with greater draught, including ocean-going vessels and smaller transport vessels. The importance of the fairway stems not only from its logistical function, but also from its impact on the handling efficiency and competitiveness of the port as a transport hub. According to the literature, the upgrading of the waterway is an important factor in increasing the capacity of ports and their ability to handle larger vessels. Studies indicate that the expansion of hydrotechnical infrastructure in ports increases their attractiveness for international shipping operators. In the context of Świnoujście, dredging and maintaining the waterway at appropriate technical parameters allows the port to be effectively integrated into global supply chains, as confirmed by analyses of maritime traffic and transshipment dynamics. The literature also emphasises the importance of the fairway in terms of navigational safety and protection of the marine environment (Gucma, Ślączka, 2017). Maintaining the fairway in an appropriate technical condition minimises the risk of collisions, facilitates the manoeuvring of vessels and ensures compliance with international maritime transport regulations. The fairway leading to the port of Świnoujście plays a fundamental role in the functioning of the maritime transport system. Its development and modernisation are a prerequisite for increasing the competitiveness of the port and its effective integration into global shipping routes. This enables ocean-going vessels and smaller transport ships to enter the port. It is a key piece of infrastructure as it provides with efficient access to the transhipment terminals, which directly affects the efficiency and competitiveness of the port.

2.2. Modernisation of the fairway

Modernisation of the Świnoujście-Szczecin fairway includes deepening and widening the track, reinforcing the bottom and slopes to prevent erosion, installing modern navigation systems and signage, as well as building and modernising breakwaters and quays. These measures significantly improve the capacity of the fairway and navigational safety, which translates into an increase in the port's handling potential. As part of this project, the waterway, with an original depth of 12.5 metres, was deepened to 14.5 metres, allowing vessels of up to 50,000 DWT (Deadweight Tonnage) to call at the port. The deepening of the fairway made it possible to adapt the port to handle Panamax-class ships, which significantly increased its competitiveness compared to other Baltic ports. The increased depth and width of the fairway has allowed the port to be better integrated into global supply chains, making it an attractive destination for international shipowners and logistics operators.

2.3. Hydrometeorological conditions

The Świnoujście area is characterised by variable hydrometeorological conditions that affect port operations and shipping safety. Strong north-westerly winds and dynamic changes in atmospheric pressure can cause manoeuvring difficulties, particularly during stormy periods. According to data available on WeatherOnline, the average wind speed in the Świnoujście area is between 2 and 4 on the Beaufort scale. During storm periods, wind speeds can increase significantly. For example, in December 2024, the Institute of Meteorology and Water Management (IMGW) issued a warning of winds reaching an average speed of up to 85 km/h (about 23.6 m/s), with gusts as high as 115 km/h (about 31.9 m/s). Such conditions may cause manoeuvring difficulties in the area of the planned development, especially during storms.

Sea currents are also an important factor affecting navigational safety, with average speeds in the fairway area ranging from 0.5 to 1.2 m/s (Gucma et al., 2021). The variability of these conditions requires the use of precise navigation aids, including Vessel Traffic Service (VTS) systems. Limited visibility is one of the main operational challenges in the Świnoujście area, especially during the autumn and winter months. Fog phenomena can reduce visibility to below 200 metres, requiring the use of advanced nautical support systems. In and around the port, there is an extensive radar system as well as an Automatic Identification System (AIS), which makes it possible to precisely track the position of ships. In addition, the use of state-of-the-art hydrometeorological monitoring systems allows for real-time forecasting of atmospheric conditions, which significantly increases the safety of port operations. A remote control system for vessel traffic in the approach area was also implemented in 2022, allowing for more efficient traffic management in conditions of limited visibility.

Overview of methods for determining lane widths

The design of lane widths in navigable water bodies requires the use of various methods that take into account both international standards and the specifics of local navigational conditions. Three main approaches are distinguished in the literature: analytical, simulation and empirical methods.

The analytical methods are based on standardised standards developed by international organisations such as PIANC (Permanent International Association of Navigation Congresses) and IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities). These guidelines set minimum values for lane widths depending on vessel size, hydrometeorological conditions and the degree of manoeuvring space limitation. Gucma et al. (2022) presented a generalised analytical method based on the analysis of hydrodynamic conditions and vessel trajectories, taking into account the width of the safe basin for bulk carriers at fairway bends. These studies showed that classical analytical models often need to be adapted to real navigational conditions, especially for bodies of water with limited manoeuvring space (Gucma et al., 2022).

With the development of computer technology, navigation simulators are increasingly being used to determine optimal lane width parameters. Simulation methods allow real navigation scenarios to be modelled and the influence of various factors such as wind, currents or the movement of other vessels to be analysed. A study by Artyszuk et al. (2016) shows that the use of simulation models in the fairway design process allows lane widths to be adapted to actual operating conditions (Artyszuk et al., 2016). The simulation results allow precise definition of safety zones, minimising the risk of collisions and improving the capacity of the shipping infrastructure. Taking into account the specific characteristics of large container ships (e.g. ULCS - Ultra Large Container Ships) In the context of the increasing size of vessels such as Ultra Large Container Ships (ULCS), it is necessary to adapt lane widths to the specific manoeuvring requirements of these vessels. Gucma & Przywarty (2020) conducted simulation tests on fairways, analysing the minimum lane widths required for the safe navigation of large vessels. The results showed that the lane widths need to take into account a larger passing distance and adapt the fairway parameters to the specific hydrodynamic characteristics of the ULCS (Gucma, Przywarty, 2020).

Empirical methods are based on the analysis of historical data from actual navigation operations. This approach allows conclusions to be drawn based on the actual behaviour of ships under specific conditions. Montewka & Przywarty (2005) used historical data from port operations to determine the actual distribution of ship trajectories and to determine the optimal lane widths (Montewka, Przywarty, 2005). The results of the study showed that taking into account the actual traffic trajectories allows the width of the fairways to be adapted to the actual operating conditions and not only to normative guidelines.

Each of the methods used in the process of determining lane widths has its advantages and limitations. Analytical methods provide a standardised approach, but may require adaptation to local conditions. Simulation methods enable accurate modelling of different traffic scenarios, while empirical methods are based on real data, which increases their reliability. Optimal solutions often combine these approaches to achieve the best results in water traffic planning and management.

When designing the new container terminal in Świnoujście and the deepening of the waterway, it is crucial to take into account the parameters of the largest vessels that the new quays will be able to handle. In this case two classes of vessels have been adopted as reference (Table 1):

- MSC Gulsun (Megamax-24 class) - the largest container ship to call at the port of Gdansk.
- Baltimax - a class of vessel optimised for Baltic navigation.

Table 1.
Summary of operational and technical parameters of selected vessels

Parameter	MSC Gulsun (Megamax24)	Baltimax
Overall length (LOA)	399,9 m	330 m
Width (BOA)	61,5 m	48-50 m
Maximum draught	16,5 m	15 m
Capacity (TEU)	23,756 TEU	12 000-15 000 TEU
Operating speed	22.5 knots	20-22 knots
Drive	MAN Diesel & Turbo engine	MAN B&W engine

Source: Own compilation based on data from MarineTraffic.

The modernisation of the approach track in Świnoujście is a key element in adapting the port to handle the largest container ships. The MSC Gulsun, representing the Megamax-24 class, has a draught of 16.5 m, a width of 61.5m and a length of 400m, which requires a fairway depth of at least 19.5 m and a width of 200-250 m. For Baltimax class vessels, with a maximum draught of 15.0 m, the existing fairway (depth 14.5 m, width 180-200 m) is insufficient. Increasing the bend radius of the track to 3,000m will ensure safe manoeuvring, eliminating the risk of collisions and optimising the approach time to the port. The new approach track parameters will allow for an increase in container handling and attract global operators. Table 2 shows a comparison of the approach track parameters in Świnoujście - before and after modernisation.

Table 2.
Parameters of the approach fairway in Świnoujście - before and after modernisation

Parameter	Before modernisation	After modernisation
Track depth	14,5 m	19,5 m
Track width	180-200 m	200-250 m
Corner radius	~2 000 m	3000 m
Track length	32 nautical miles	No change
Supported vessels	Up to 13,500 TEU	Up to 24,000 TEU
Max. draught	13,5 m	16,5 m
Max. vessel width	48 m (Baltimax)	61.5 m (Megamax-24)

Source: Own compilation based on data from Szczecin-Świnoujście Port Authority.

The current infrastructure allows the handling of large vessels, but not the largest container vessels of the Megamax-24 class. The approach track after the upgrade will be adapted to the largest container vessels.

Figure 1 shows a diagram of the planned container terminal (shown in red and yellow).

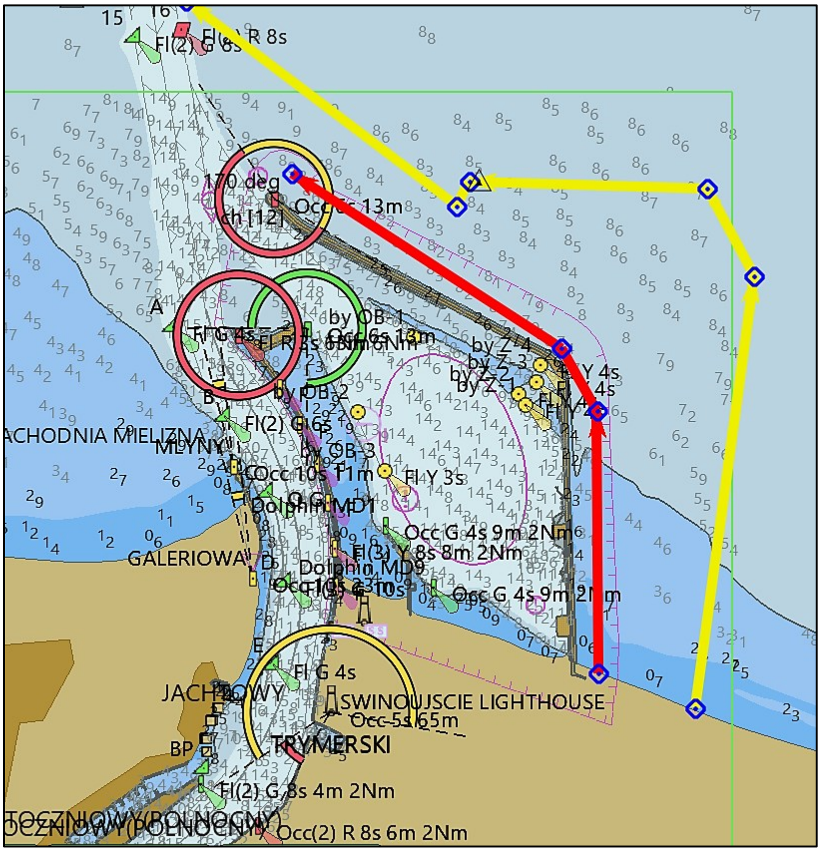

Figure 1. Diagram of the planned container terminal.

Source: The study was independently prepared using the tools available in OpenCNP.

2.4. Criteria for assessing fairway dimensioning methods

Criteria for evaluating methods to design fairways focus on navigational safety, operational efficiency and flexibility in traffic management, which is important for ports with high maritime traffic (PIANC, 2014; USACE, 2018). Shipping safety ensures that the risk of collision is minimised through appropriate track widths, taking into account parameters such as ship manoeuvrability and hydrometeorological conditions (PIANC, 2014). Infrastructure capacity refers to the capacity of the terminal and fairway, which affects the number of vessels to be handled, as well as the timing of port manoeuvres (USACE, 2018). The ability to regulate the movement of vessels relates primarily to the ability to adapt the navigation infrastructure to increasing vessel sizes and changes in global maritime transport (PIANC, 2020). The PIANC and USACE methods differ in their approach - PIANC focuses on navigational standards, while USACE considers dynamic traffic modelling and the influence of environmental factors (USACE, 2018). Dimensioning tracks according to these criteria enables optimisation of port infrastructure and increased operational efficiency.

Figure 2 shows the key navigational parameters, including the course change of vessels, relevant to determining the required lane width at the bend in the waterway, which has a direct impact on the safety and smoothness of navigation in the area of the container terminal in Świnoujście.

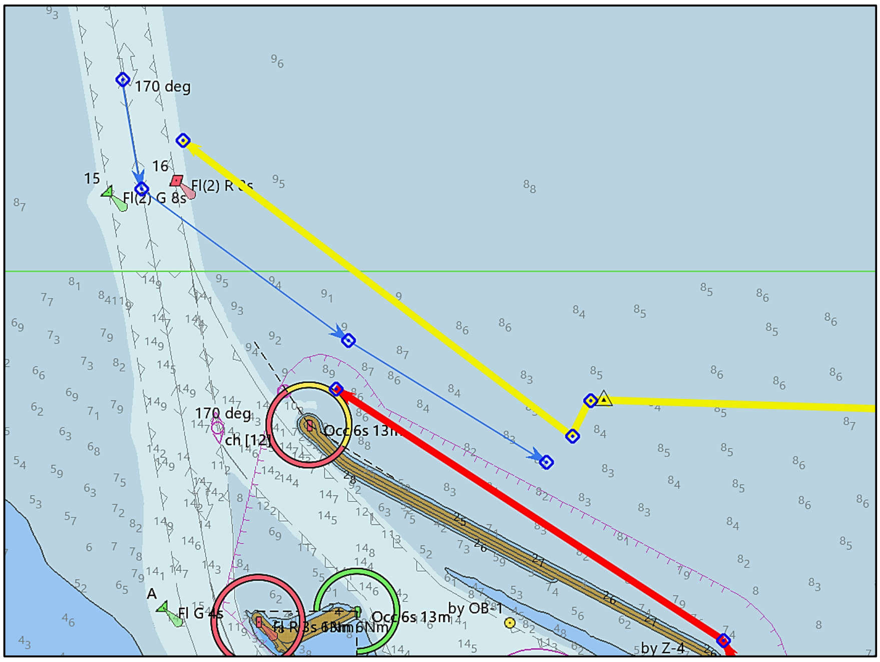

Figure 2. Navigational parameters relevant for determining the required lane width at the waterway bend.

Source: The study was independently prepared using the tools available in OpenCNP.

2.5. Dimensioning of the two-way fairway using the PIANC method

PIANC (Permanent International Association of Navigation Congresses) is an international organisation dealing with standards for the design of water infrastructure, including fairways, locks and ports. The dimensioning of fairways according to PIANC recommendations takes into account factors such as vessel width, hydrometeorological conditions, manoeuvrability of vessels and safety rules. The PIANC method is based on the determination of the minimum width of the fairway based on the width of the vessels (the largest vessel operating in the fairway), the safety margins - determined by the influence of currents, waves and navigational conditions and additional requirements - resulting from the characteristics of the port and vessel traffic. In the case of a bi-directional fairway, a key aspect of dimensioning is to ensure the safe passing of vessels in counter-rotating traffic, which requires consideration of the minimum track width.

Table 3 and Table 4 show the components that were used for the PIANC calculations. For the selected vessels these include parameters such as the fairway width and the depth required for safe navigation. For a container ship, the parameters analysed are the manoeuvring width depending on the hydrodynamic conditions and the minimum depth adapted to its draught and wave motion, while for an oil tanker, larger bend radii and additional safety reserves in the track depth due to its weight and limited manoeuvrability were taken into account.

Table 3.
Components used in the calculation for MSC GULSUN

PIANC components	Type of amendment	Symbol	Amendment value
Additional amendment			
Vessel speed	V > 12 w	di1	0,1 B
Prevailing wind	15-33 w	di2	0,3 B
Cross current	0,2-0,5 w	di3	0,2 B
Longitudinal current	V < 1.5 w	di4	0,0 B
Height and wave length	3 m >hf > 1 m	di5	2,0 B
Navigational markings	good	di6	0,1 B
Bottom type	soft bottom	di7	0,0 B
Depth to draft	h/T > 1.5	di8	0,2 B
Type of cargo	all others	di9	0,0 B
Reserve left (open track)	V > 12 in	drc	0,7 B
Reserve right (open track)	V > 12 in	drz	0,7 B
Width of manoeuvre		dm	
Manoeuverability of the vessel	very good handling	dm	1,3 B
Two-way traffic			
Delimitation lane components (vessel speed)	V = 8-12 in	dpj1	1,6 B
Delimitation lane components (traffic intensity)	Large (> 3.0 vessels/h)	dpj2	0,5 B
Components used to calculate the lane on the bend			
Return angle [^{0}]		ΔΨ	
Vessel speed [m/s]		V	
One-way traffic factor		F	
Curve radius at the bend [m]		Ro	
Minimum required visibility from the bridge of the vessel [m]		s	
Vessel steering ratio		kz	

Table 4.
Components used in the calculation for the BALTIMAX vessel

PIANC components	Type of amendment	Symbol	Amendment value
Additional amendment			
Vessel speed	V > 12 w	di1	0,1 B
Prevailing wind	15-33 w	di2	0,3 B
Cross current	0,2-0,5 w	di3	0,2 B
Longitudinal current	V < 1.5 w	di4	0,0 B
Height and wavelength	3 m >hf > 1 m	di5	1,0 B
Navigational markings	good	di6	0,1 B
Bottom type	soft bottom	di7	0,0 B
Depth to draft	1,25-1,5	di8	0,1 B
Type of cargo	all others	di9	0,0 B
Reserve left (open track)	V > 12 in	drc	0,7 B
Reserve right (open track)	V > 12 in	drz	0,7 B
Width of manoeuvre			
Manoeuverability of the vessel	very good handling	dm	1,3 B
Two-way traffic			
Delimitation lane components (vessel speed)	V = 8-12 in	dpj1	1,6 B
Delimitation lane components (traffic intensity)	Large (> 3.0 vessels/h)	dpj2	0,5 B
Components used to calculate the lane on the bend			
Return angle [^{0}]		ΔΨ	
Vessel speed [m/s]		V	
One-way traffic factor		F	
Radius of curve on bend [m]		Ro	
Minimum required visibility from the bridge of the vessel [m]		s	
Vessel steering ratio		kz	

2.6. Dimensioning of the fairway using the Canadian method

Designing fairways requires a precise approach based on proven engineering methods that take into account both the safety and efficiency of navigation. One popular technique used in fairway dimensioning is the Canadian method, based on empirical relationships derived from real-world studies. In practice, it is often combined with the PIANC guidelines to form a hybrid approach to determining key fairway parameters. The method takes into account important factors such as the width of the track, its depth, curve radii and navigational conditions, ensuring optimal conditions for vessel traffic. Its application allows the parameters of the water infrastructure to be determined in a way that is adapted to the specific hydrodynamic conditions and operational requirements. In practice, algorithms based on this method integrate empirical relationships from the PIANC and Canadian methods, enabling efficient design of fairways under different navigational conditions (Zalewski, 2012). The components used in the calculations can be found in Table 5.

Table 5.
Components used in the Canadian Method

Components of the Canadian Method	**Type of amendment**	**Symbol**	**Amendment value**
Additional amendment			
Prevailing wind	15-33 w	dd3	0,3 B
Cross current	0,2-0,5 w	dd4	0,2 B
Controllability of the vessel	0,75-1,25 B	dd5	1,0 B
Navigational markings	good	dd6	0,1 B
Bottom type	soft bottom	da3	0,0 B
Type of cargo	all others	da1	0,0 B
Depth/depth ratio	1.15 < h/T < 1.5	da2	0,2 B
Correction for visibility and time of day		da4	0,0 B
Correction for high ship speeds		da5	0,1 B
Width of manoeuvre		dd1	
Controllability of the vessel	very good handling	dd1	1,3 B
Two-way traffic			
Delimitation lane components (traffic intensity)	Large (>3.0 vessels/h)	dd2	0,5 B
Components used to calculate the lane on the bend			
Return angle [^{0}]		$\Delta\Psi$	
Vessel speed [m/s]		V	
One-way traffic factor		F	
Radius of curve on bend [m]		Ro	
Minimum required visibility from the bridge of the vessel [m]		s	
Ship steering ratio		kz	

3. Results

The United States Army Corps of Engineers (USACE) method takes a comprehensive approach to fairway design, based on an analysis of dynamic navigation conditions, taking into account the width of vessels, hydrodynamic effects, safety margins and the influence of hydrometeorological conditions (Emery, 2024).

The American method for determining track gauge, is particularly useful in the analysis of fairways with variable navigational conditions, where it is necessary to model ship traffic based on empirical data and hydrodynamic simulations. It makes it possible to adapt the track width to extreme conditions, such as strong currents, large tidal amplitude or wave influence (Emery, 2024). In this way, the USACE method ensures a high level of safety and efficient management of maritime traffic, which is crucial for ports with heavy traffic.

In order to correctly calculate and dimension the fairway for the Świnoujście terminal, the following data must be collected:

- Parameters of the largest vessels served (MSC Gulsun - Megamax24 class);
- Hydrographic parameters of the fairway- atmospheric and hydrological conditions;
- Traffic volume and operational analysis- shipping intensity data;

The components used in the United States Army Corps of Engineers (USACE) calculations include key hydrodynamic, navigational and operational parameters that determine the dimensioning of the fairway. The following table shows the key factors considered in the analysis (Table 6).

Table 6.
Components used in the USACE calculations

Fixed waterway cross-section, very good navigational aids - one-way traffic	
Cross-section of the waterway:	Dredged fairway
Current speed:	0,5-1,5 w
Component value:	3,25 B
Fixed waterway cross-section, very good navigational aids - two-way traffic	
Cross-section of the waterway:	Dredged fairway
Current speed:	0,5-1,5 w
Component value:	5,5 B

The design of fairways requires the consideration of many factors, such as the size of vessels, their manoeuvrability, hydrographic conditions or the availability of navigation systems. Each calculation method makes different assumptions about the safety and efficiency of navigation, which affects the resulting values for fairway widths. Table 7 shows the calculation of waterway widths based on the selected methods in the study.

Table 7.
Calculation of waterway widths based on selected calculation methods

MSC GULSUN	BALTIMAX
Straight section of waterway calculated using the PIANC method	
One-way	
282,90 m	225,00 m
Two-way	
695,95 m	555,00 m
Section at the bend of the waterway calculated using the PIANC method and the Canadian method	
One-way	
288,98 m	241,72 m
Two-way	
707,11 m	571,72 m
Canadian method on a straight stretch of road	
Two-way	
227.55 m	185,00 m
A rectilinear section of the waterway calculated using the USACE method - a fixed section of the waterway with very good navigational aids	
One-way	
199,87 m	162,50 m
Two-way	
338,25 m	275,00 m

The analysis of the results obtained based on the comparison of the methods on the straight section predicts the greatest widths with the PIANC method. For one-way traffic, it is 282.90 m for MSC GULSUN and 225.00 m for BALTIMAX, a difference of 57.90 m. For two-way traffic, these values increase to 695.95 m and 555.00 m respectively, giving an even greater difference of 140.95 m. The Canadian method, which is used for straight sections of track, shows a smaller width requirement than PIANC. For MSC GULSUN, the width obtained is 227.55 m, while for BALTIMAX it is 185.00 m, a difference of 42.55 m in favour of the smaller vessel. It is worth noting that, compared to the PIANC method, these differences are significant - the waterway width is 55.35 m less for MSC GULSUN and 40.00 m less for BALTIMAX. The most compact waterway width values result from calculations using the USACE method, which assumes the use of modern navigation systems that allow safe manoeuvring in a narrower body of water. For MSC GULSUN, 199.87 m (one-way) and 338.25 m (two-way) were obtained, and for BALTIMAX 162.50 m and 275.00 m respectively. This means that, compared to PIANC, the USACE method allows a track width reduction of 83.03 m (MSC GULSUN) and 62.50 m (BALTIMAX) for one-way traffic and 357.70 m and 280.00 m for two-way traffic. In contrast, additional manoeuvring space is required at the bends. The fairway width values increase compared to the straight sections. For one-way traffic, MSC GULSUN requires 288.98 m and BALTIMAX 241.72 m, a difference of 47.26 m. For two-way traffic, the values are 707.11 m and 571.72 m respectively, where the difference increases to 135.39 m.

Figure 3 shows a comparison of the fairway limits determined by the PIANC method for the MSC GULSUN in one-way traffic with the currently existing fairway. This comparison helps to illustrate the differences in required track width and the potential upgrade needs resulting from the operation of larger vessels. Figure 4 shows the one-way and two-way track (red) calculated using the PIANC method. The width of the two-way track is much wider, almost 2.5 times wider than the one-way track.

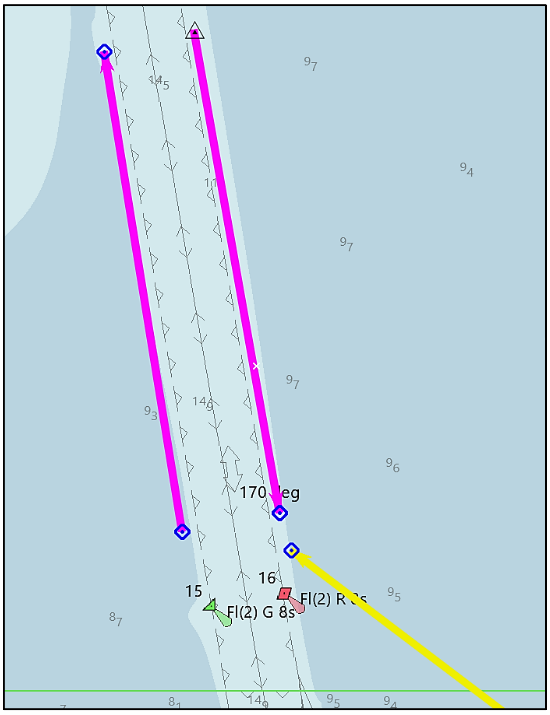

Figure 3. Boundaries of the fairway calculated using the PIANC method for the MSC GULSUN ship, unidirectional, compared to the existing fairway.

Source: The study was independently prepared using the tools available in OpenCNP.

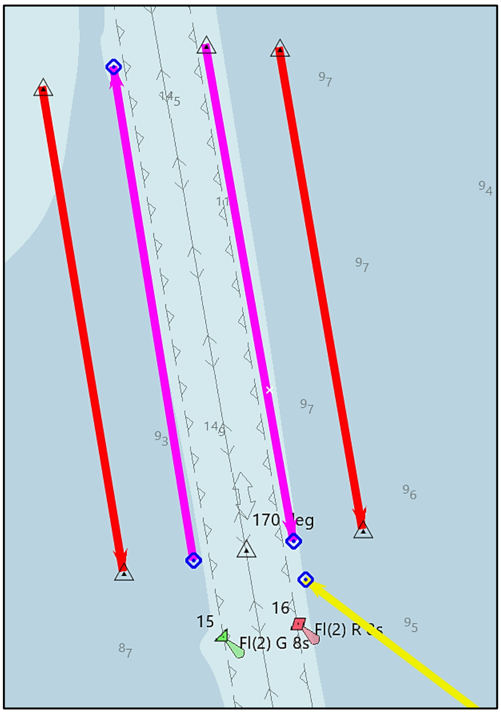

Figure 4. One-way and two-way track calculated using the PIANC method.

Source: The study was independently prepared using the tools available in OpenCNP.

Figure 5 illustrates the widening of the fairway at the curve of the road, taking into account the optimisation of the track width for Baltimax vessels. An analysis based on the PIANC method allows the required navigational space to be determined precisely, minimising the risk of collision and ensuring safe navigation conditions.

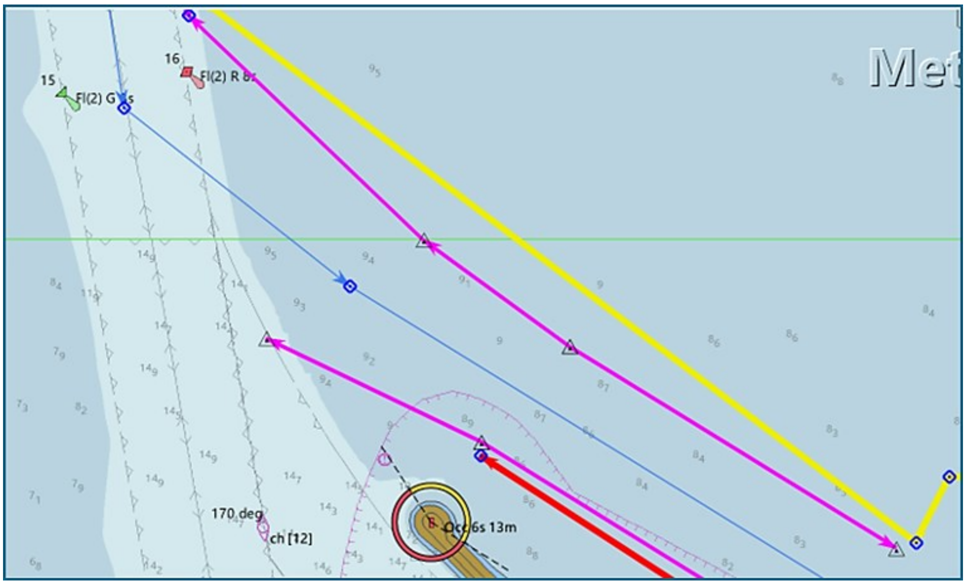

Figure 5. Widening of the fairway at the curve of the road, taking into account the optimisation of the track width for Baltimax vessels.

Source: The study was independently prepared using the tools available in OpenCNP.

Figure 6 shows the designated section of the fairway for the Baltimax vessel, taking into account the width constraints due to the limited area of the planned port infrastructure. This analysis assesses the impact of the infrastructure on the availability and manoeuvrability of the vessels in the port basin, indicating potential upgrade needs.

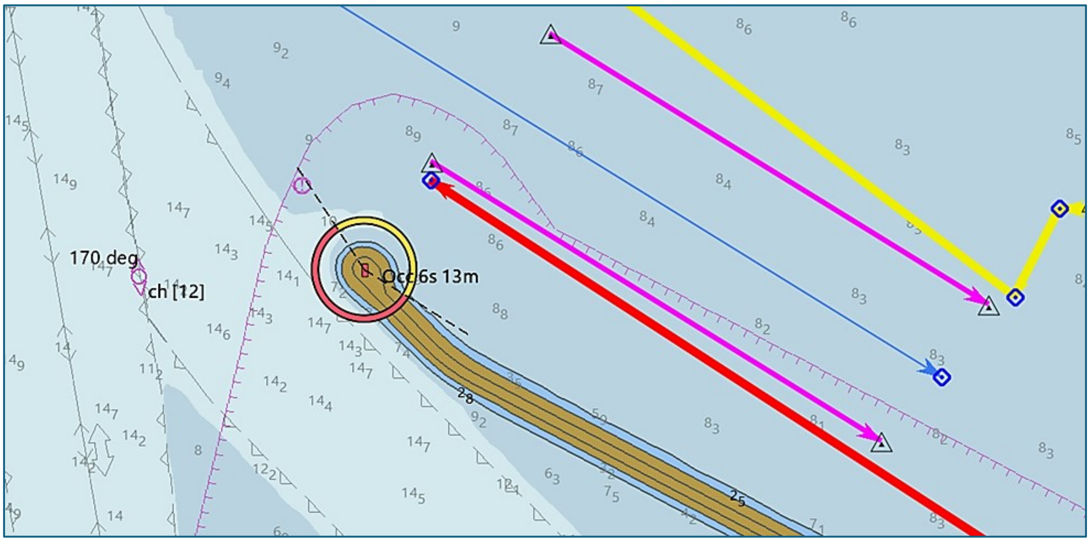

Figure 6. Designated fairway section for the Baltimax vessel.

Source: The study was independently prepared using the tools available in OpenCNP.

Figure 7 shows a comparison of the fairway widths calculated by the different methods, allowing an assessment of their impact on the safety and efficiency of navigation. This analysis takes into account the variants of fairway dimensioning, indicating the differences due to the calculation assumptions made and the specificities of each method.

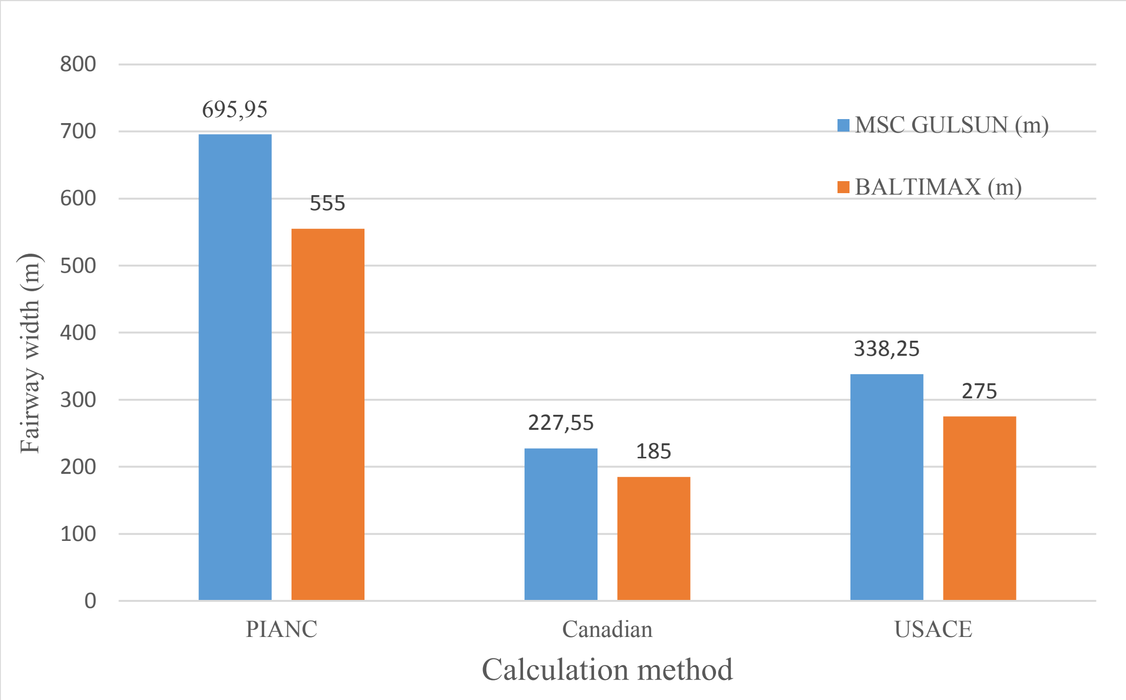

Figure 7. Comparison of fairway widths by PIANC, USACE and Canadian methods.

Comparing the fairway widths for the different calculation methods (PIANC, Canadian, USACE) for the two selected vessels, it can be seen that the PIANC method requires the largest fairway widths, especially for the MSC GULSUN, while the USACE method allows for significant width reductions due to advanced navigation systems. The PIANC method also requires larger fairway widths for two-way traffic as well. The Canadian method reduces the width of the fairways by about 15-20% compared to PIANC. In contrast, the USACE method, through the use of precision navigation systems, reduces track widths by up to 40-50% compared to PIANC. The bends require wider tracks than the straight sections, with differences between the two averaging 5-10%.

In order to analyse the impact of the new approach fairway on the capacity of Świnoujście port, the following parameters were compared:

- Changing the vessels served - how the new track parameters affect vessel types.
- Increasing the number of ship calls - how the increased depth and width of the track will affect ship traffic.
- Change in the timing of manoeuvres and port operations - impact of larger vessels on operational efficiency.
- Economic implications for the port - potential increase in trade and revenue for the port.

Data based on official port reports, engineering standards (PIANC, USACE), and a comparative analysis of similar upgrades in other ports were used to calculate the impact of the Świnoujście approach fairway upgrade on port throughput. Table 8 shows a comparison before and after the approach fairway upgrade taking into account the nominal requirements of the PIANC and USACE methodologies.

Table 8.
Comparison of the Approach Fairway Before and After the Upgrade Considering the Nominal Requirements of the PIANC and USACE Methodologies

Parameter	Before modernisation	After modernisation	Growth
Supported vessels	Up to 13,500 TEU	Up to 24,000 TEU	+80%
Fairway length	32 nautical miles	32 nautical miles	-
Track width	180-200 m	200-250 m	+25%
Track depth	14,5 m	19,5 m	+35%
Number of arrivals per year	~1000	~1400-1500	+40%
Transshipments per year	~1.2 million TEU	~2.5 million TEU	+100%

Source: own compilation based on data from MarineTraffic, VesselFinder, Maritime Authority hydrographic reports, AIS data, Szczecin-Świnoujście Port Authority reports & Forecasts of the Szczecin-Świnoujście Port Authority.

The expansion of the deep-water track in Świnoujście will have a significant impact on port capacity, shipping safety and operational efficiency. The widening and deepening of the track will enable the handling of larger vessels, such as Megamax-24 class container ships, which will optimise logistics and reduce sea transport costs. In addition, it will increase the width of the track, which will improve the passing of vessels and the manoeuvrability of ships. The result is a reduction in the risk of collisions in heavy traffic. The calculated increase in approach track parameters has been calculated based on a percentage increase formula:

$$Growth = \frac{New\ Value - Old\ Value}{Old\ Value} \times 100\% \quad (1)$$

Source: (Mankiw, 2020).

This formula is commonly used in hydraulic engineering analyses, as well as in port reports to assess changes in water infrastructure. Applying the above formula to the analysis of track parameters helps to accurately determine the scale of change, which is important for strategic planning of the port and predicting its future role in the global supply chain.

Designing a fairway requires a precise determination of its width, taking into account the parameters of the vessels and the navigational conditions. This study compares three methods used in fairway dimensioning: PIANC, USACE and Canadian, focusing on two presentable container vessels - MSC GULSUN and BALTIMAX. The aim of the study was to determine the impact of selected computational methods on navigational safety and to assess the risk of collision before and after vessel speed reduction. Monte Carlo simulations were used to provide a probabilistic estimate of collision risk, taking into account variable operational parameters such as fairway width and vessel speed. The values of the input variables were selected on the basis of available literature, shipping reports and analyses of the Świnoujście-Szczecin fairway. The following assumptions were made, which are listed in Table 9.

Table 9.
Values of output variables

Vessel traffic volume	an average of 30 units per day
Speed of vessels	random variable with normal distribution N(10, 2) [nodes]
Speed of vessels	random variable with normal distribution N(7,1.5) [nodes]
Crew response time	random variable between **30-90 seconds**
Fairway width	values obtained by the methods
Hydrological conditions	sea currents from **0.5 to 1.2 knots**
Visibility conditions	in 30% of cases, reduced visibility of less than 2 km

The scope of the study is to compare the fairway width for MSC GULSUN and BALTIMAX depending on the sizing method used (PIANC, USACE, Canadian). For the Collision Probability Calculations for each method, both the standard speed *N* (10.2) [knots] and after speed reduction to *N* (7.1.5) [knots] were used. The analysis considered the effect of speed reduction on collision risk reduction for each method. The calculation results, visualisations and a detailed comparison of the fairway sizing methods are presented below.

Table 10 summarises the collision probabilities for the PIANC, USACE and Canadian methods before and after speed reduction. The calculations were performed in Python, based on a Monte Carlo simulation (100,000 iterations).

Table 10.
Comparison of collision probability before and after speed reduction

Method	Vessel	Collision probabilities for *N* (10,2) [nodes]	Collision probabilities for *N* (7.1.5) [nodes]
PIANC	MSC GULSUN	0,03	0,0
PIANC	BALTIMAX	1.859	0,001
USACE	MSC GULSUN	37.501	7.498
USACE	BALTIMAX	57.161	23.098
Canadian	MSC GULSUN	72.867	41,079
Canadian	BALTIMAX	86.500	55.897

Figure 8 shows a comparison of collision probabilities for MSC GULSUN and BALTIMAX vessels according to PIANC, USACE and Canadian methods, both before and after speed reduction, demonstrating the impact of speed reduction on navigational safety.

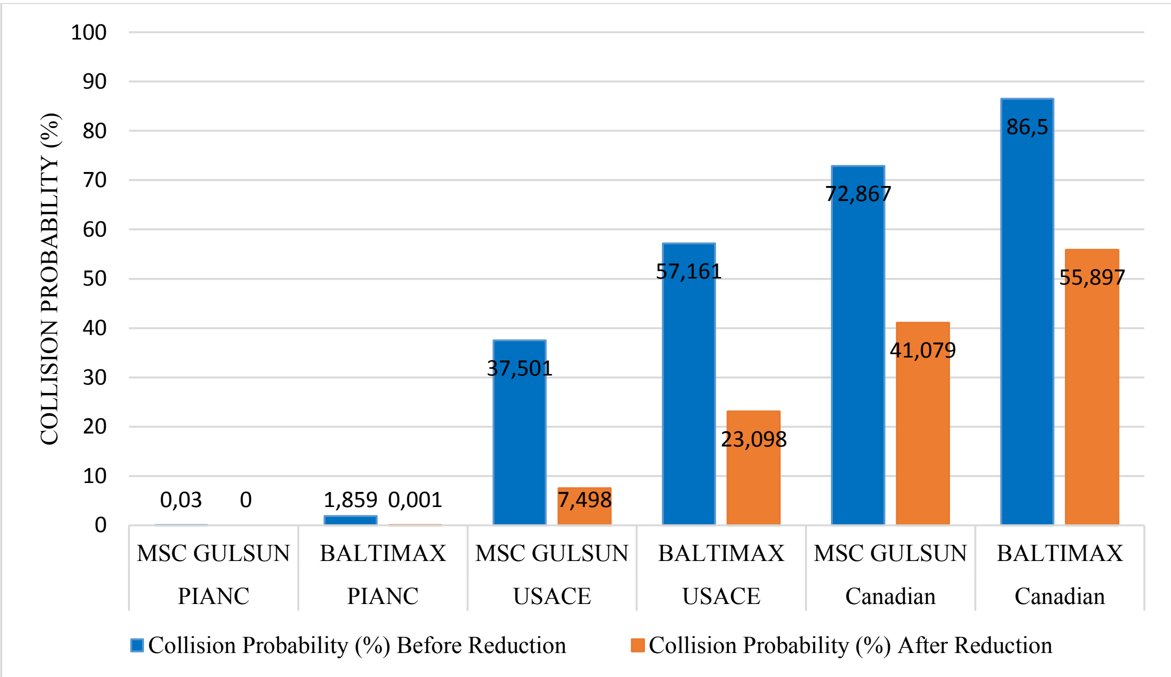

Figure 8. Comparison of Collision Probability Before and After Speed Reduction.

Based on the calculations, the PIANC method almost completely eliminates the risk of collision, especially after speed reduction - the probability is 0.000% for MSC GULSUN and 0.001% for BALTIMAX, suggesting that the predicted fairway widths are fully safe for these vessels. The USACE method shows a significant improvement after speed reduction, but the risk of collision remains at 7.5% for MSC GULSUN and 23.1% for BALTIMAX, indicating that the track widths may not be sufficient for larger vessels. The Canadian method, despite the speed reduction, still shows the highest collision risk of 41.1% for MSC GULSUN and 55.9% for BALTIMAX, suggesting that the fairway width calculated by this method is not suitable for the safe navigation of large vessels and requires additional safety measures.

4. Discussion

Based on the results of the study, a comparison of different methods for determining lane widths was carried out, taking into account both International Maritime Organisation (IMO) standard procedures and approaches used in other major container ports. The analysis showed that dynamic models, taking into account actual hydrodynamic conditions and traffic volumes, allow optimising safety and operational efficiency. The results of the study indicate that an increase in maritime traffic intensity requires a flexible approach to lane delimitation. Optimisation of shipping lane widths should take into account not only static mathematical models, but also dynamic traffic monitoring and predictive analysis based on historical and current data. The discussion of the research results points to the need to integrate modern maritime traffic monitoring technologies with navigational safety management procedures.

In the literature, studies on the planned location and functional layout of the container terminal in Świnoujście are available, such as Gucma et al. (2016). In them, the authors presented a detailed analysis of the terminal's location options, the safety zones related to the vicinity of the LNG terminal and the fairway widths determined by the CIRM method, which is based on simulation.

The implementation of traffic management systems based on artificial intelligence and predictive models will increase safety and optimise port operations.

It is worth noting that although the analysis presented here focuses on modelling and analysis of maritime traffic data, it is important to emphasise the need to include actual maritime incidents in further research details. In order to better illustrate the practical application of collision risk assessment and the implementation of flexible maritime traffic management strategies in the area of the planned container terminal.

It is recommended to implement integrated platforms such as IWRAP IALA, which allow continuous risk assessment based on actual conditions and predicted traffic scenarios. Systems of this type enable on-the-fly adaptation of operational parameters, such as fairway width, to changing maritime traffic conditions.

In addition, the contribution of artificial intelligence can support real-time vessel traffic analysis (using, for example, AIS data). It will allow the identification of potential collision risks and the optimisation of vessel entry and departure schedules from the port. This type of approach makes it possible to increase the flexibility and availability of ports in the face of dynamic developments in the structure and volume of maritime traffic.

5. Conclusions

An analysis of the modernisation of the fairway and the application of different calculation methods showed significant differences in the approach to the design of the shipping infrastructure. The modernisation carried out will significantly increase the operational capacity of the fairway. The handling of vessels will increase from a capacity of 13,500 TEU to 24,000 TEU, an increase of 80%. At the same time, the width of the track will increase by 25%, reaching a range of 200-250m, and its depth will increase from 14.5m to 19.5m, an increase of 35%. These changes will increase the number of calls per year by 40%, while the port's annual throughput will double, reaching 2.5 million TEU.

A comparison of the results obtained with the PIANC, Canadian and USACE methods showed significant differences in fairway widths. The PIANC method assumes the largest track width values, especially for two-way traffic, with a width of 695.95 m for MSC GULSUN and 555.00 m for BALTIMAX. This approach provides large safety margins to allow large vessels to manoeuvre freely. In contrast to PIANC, the Canadian method provides for smaller track widths, which is the result of a more practical approach that takes into account actual operating conditions. For the MSC GULSUN, the track width calculated by this method is 227.55 m and for the BALTIMAX 185.00 m. An even greater reduction in track width is made possible by the USACE method, which, with the use of advanced navigation systems, allows a significant optimisation of the navigable space. In this case, the track width for MSC GULSUN is 199.87 m for one-way traffic and 338.25 m for two-way traffic, while for BALTIMAX it is 162.50 m and 275.00 m respectively.

The results indicate that increasing the width of the fairway has a positive impact on safety and navigational capacity, allowing larger vessels to be handled and facilitating manoeuvring in difficult hydrographic conditions. However, the use of computational methods based on precision navigation systems, as in the case of the USACE, makes it possible to significantly reduce the width of the fairway without adversely affecting safety. The modernisation of fairways and the optimisation of dimensioning methods are key to improving the efficiency of maritime transport and increasing the competitiveness of ports. The choice of the appropriate method should take into account the specifics of the water body, the size of the vessels to be served and the availability of modern navigation systems.

It is also important to highlight the results of the risk analysis carried out, which showed that the PIANC method provides the highest level of safety, reducing the probability of collision to minimal values, especially after speed reduction. The USACE and Canadian methods, despite speed reduction, still show an increased risk of collision, indicating the need for additional safety measures such as widening the fairway or better traffic management. The results confirm that speed reduction significantly reduces collision risk, but for methods with narrower fairways it may not be sufficient, requiring further optimisation of the shipping infrastructure.

Despite the significant conclusions obtained, the studies carried out have some limitations. First of all, the empirical method used derives from a preliminary analysis of the issue, which includes environmental and operational constraints that may affect the accuracy of the estimates. In addition, dynamic variables, real-time weather conditions, which affect the dimensioning of the fairways, were not fully considered.

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