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Vessel route optimization to avoid risk of collision between carriers of dangerous goods and passenger vessels

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Abstract

This article presents the underlying concepts of a mathematical model optimizing the routes of vessels carrying dangerous goods proceeding in the vicinity of passenger ferries. The method is based on the estimated risk of collision between a chemical tanker and a passenger vessel. Risk assessment was performed using three models. The first model determines the distance of the passing ships on the selected area on the basis of the AIS data. The second one is a stochastic model of navigational safety assessment, which provides statistical data on the probability of collision between the two chosen types of vessels. The third model determines the consequences of collisions between passenger ships and chemical tankers. The study defines the scope of the parameters affecting the objective function of vessel route optimization and their importance in the optimization problem.

Introduction

Maritime transport fulfills a particularly important function in the transport of cargo over long distances. A large amount of carried goods are hazardous substances, which could cause serious ecological disaster if they were dispersed in the ecosystem. The transportation of chemical cargo, even though quantitatively small relatively to crude oil and petroleum products transportation, is subject to the risk of leakage and the related consequences may be much larger than those of an oil spill (Sormunen et al., 2015). Chemical tankers can often carry more than one dangerous and harmful substance, which is an additional complication in case of failure due to possible formation of dangerous mixtures. Even small amounts of chemicals may pose a risk, for example aluminum phosphide in contact with water forms phosphine (PH3) – a toxic gas (Boć & Gucma, 2015).

Transport statistics for the Baltic Sea confirm that the carriage of goods has grown rapidly in recent years. Considering only the most dangerous liquid chemicals, their freight reached 11 million tons in 2010, compared to only 4.9 million tons in 2002 (Posti & Häkkinen, 2012). The increasing amount of sea freight results in more frequent meetings of ships at sea and thus increases the likelihood of collisions. The specificity of maritime transport makes it difficult to compare the consequences of ship collisions to similar accidents on land. Loss recovery of a disaster at sea is much more difficult and the consequences are higher. Thus, even a seemingly low probability of a collision at sea should be treated with greater precaution than in the case of a similarly low probability of land collision between cars. Competition among specialized freight forwarders in minimizing transport costs and reducing the time of transport do not go hand in hand with maximizing the transport safety. In the eyes of ship owners, the conventions and regulations aimed at improving safety at sea are too numerous and too restrictive. Therefore, the introduction of additional directives aiming to improve maritime safety should be made in a very cautious way. In land traffic it is possible to plan routes in such a way that the carriage of dangerous goods avoids potential collision areas, such as large agglomerations or crowded routes. In maritime transport, there is no such possibility. Traffic routes of chemical tankers cross other ships routes. For instance, ships navigating from ports of the Eastern Baltic Sea and proceeding to the North Sea have to cross the route of ferries proceeding from Świnoujście to Ystad.

Optimal route planning for ships with HazMat (Hazardous Materials) aims at minimizing the risks and costs incurred in the event of a collision or an accident, and should also be an important tool to support decisions in planning transportation routes. The priority will be objective economic criteria, such as minimum travel time, fuel consumption, damage to the ship and punctual arrival at the port (Jurdziński, 2014). On the other hand, the safety of shipping is mainly influenced by objective parameters like meteorological data, vessel specifications and risks of collision. Decision making, both during the planning phase of a trip and during en-route implementation of adjustments, should give the priority to objective factors at a fixed acceptable level of risk.

Assumptions for building a model of route optimization of ships carrying dangerous goods

In the planning of transport routes economic factors are primarily taken into consideration. In most cases, any course alteration made to increase the safety affects the competitiveness of freight. Therefore, it is reasonable to define the areas in which such action is necessary. Optimization based on the probability of collisions must be undertaken primarily for areas with high levels of risk, which are mainly represented by traffic intersections.

The ultimate goal of this optimization is the determination of routes for vessels carrying HazMat in order to minimize the probability of collision with passenger vessels, taking into account the acceptable level of risk of collision, objective criteria affecting the organization of maritime transport, the degree of danger posed to the carried cargo. At the same time, the negative impact of such optimization on the economic parameters of transport should be minimized.

The vector of defined objective functions includes parameters defining the criteria for assessing the risk associated with the dangerous cargo, the risk of collision, objective parameters and economic parameters.

$$F(x) = (f_{\text{cargo}}, f_{\text{risk}}, f_{\text{corr}}, f_{\text{ob}}, f_{\text{econ}}) \tag{1}$$

where:

f_{cargo} – class of danger of the transported cargo;
f_{risk} – class of risk of collision for intersecting routes;
f_{corr} – number of areas where a correction is needed;
f_{ob} – objective criteria;
f_{econ} – economic criteria.

The essential parameters and criteria considered when defining the objective function are discussed in detail later in this work.

Optimization restrictions

The theoretical model puts very strict standards on optimization. The restrictions that must be imposed on the adopted theoretical model parameters should take into account the actual conditions of carriage and, above all, minimize the cost of implementing the optimization results with the following limitations:

- Route optimization is carried out on the basis of economic criteria, with the exception of high-risk areas.
- The imposition of course alteration to prevent excessive proximity between passing vessels takes place only in areas with a high level of risk of collision.
- It is necessary to designate the areas with a high level of risk of collision and take into account the given objective parameters to determine whether a vessel with HazMat should procced through a relatively narrow traffic lane set within the recommended zone.

To determine the effect of various parameters on the objective function, it is significant to characterize parameters which are important when deciding on the route of the ship. Assessment of the danger consists in assigning to each function parameter. Another important task is to separate, on the basis of empirical data derived from AIS, the areas with increased risk of collision.

Description of parameters affecting the optimal route of ships carrying dangerous cargo

Economic parameters of route planning

These parameters are not specific to the transport of dangerous goods, but rather are taking a significant share of optimization procedure for all transport. For economic reasons, the goal of each company is to save time and fuel. Both of these factors allow to save money, and therefore to increase the profits. Owners seek to minimize costs through efficient economic operation of ships. The impact on the decisions taken by the ships' captains is difficult to estimate.

Hazard class of substances transported by vessels

The International Maritime Organization (IMO) has unified rules on the transport of dangerous goods by sea by releasing the IMDG code (International Maritime Dangerous Goods). In this code, dangerous goods are divided into nine classes according to their threat. The IMDG code also includes guidelines for transport, labeling and securing of dangerous goods. First of all, for further optimization measures it is necessary to build an additional classification of hazardous cargo that is based on the IMDG code but also takes into account the volume of transport, composition and other factors. This would be the first criterion influencing the optimization of transport routes.

According to the report presenting transportation of cargo in the Baltic Sea (Posti & Häkkinen, 2012) almost 730 million tons of international cargo was handled in the Baltic Sea Ports. Around 42% of this was liquid bulk. Oil and oil products are the most common type of liquid bulk cargo (with a 95% share), the liquid chemicals share is 3.5% and the rest is other liquid bulk cargo. Courtiers with the biggest share of liquid chemicals handling are: Finland (57%), Estonia (11%), Sweden (8%) and Poland (7%). The report (Posti & Häkkinen, 2012) states that in case of Swedish ports, the real volume of liquid chemicals is higher than reported and the estimated volume of handled chemicals is supposedly over 2 million tons. It also states that German ports situated in the Baltic Sea handle liquid chemicals in large quantities, but exact amounts are unknown. According to Posti & Häkkinen (Posti & Häkkinen, 2012), the most abundant chemicals handled in the Baltic Sea area are methanol, sodium hydroxide solution, ammonia, sulfuric and phosphoric acid, pentanes, aromatic free solvents, xylenes, methyl ter-butyl ether (MTBE), and ethanol and ethanol solutions.

A method of determining and classifying particularly dangerous intersections of cargo and passenger ship routes on the basis of a simulation

Areas where routes running from north to south intersect routes running from west to east of the Baltic Sea are particularly vulnerable to collisions. Hence the need for thorough look at these zones. The specificity of maritime shipping route intersections does not allow the possibility of avoiding them; however, they can be precisely traced and treated as the areas of increased risk of collisions.

The designation of suggested shipping lanes and traffic separation schemes (late nineteenth century) replaced the so-called "freedom of navigation" and forced to proceed along specified routes. This helped significantly reduce the number of collisions in those areas where such restrictions were applied (e.g. English Channel 1967 years).

Ordering the traffic of vessels in the Baltic Sea is systematically implemented and there is no turning back from these decisions if one thinks of maintaining the safety in the maritime transport while increasing the volume of goods being transported.

Planning the route between the port of departure and the destination port is one of the tasks of the vessel's crew. The concept of route optimization taking into account safety aspects should be based on obligatory course alterations only in areas of heightened risk of collision. In these areas, HazMat vessels would proceed into a separated narrow route, which would be represented as a zone where increased precautions must be taken. The ship approaching such an area should optimize its navigational decisions depending on navigation conditions and knowledge about potential threats.

Initially, the location of particularly sensitive areas should prevent from close quarters situations between chemical tankers and passenger vessels. In addition, it should then prevent vessels from approaching areas of high traffic density intersections. The optimization should be made on the basis of AIS data and also on historical statistical data.

The AIS data is increasingly being used in research on maritime safety as a valuable source of information about the movement of ships. AIS identifies each vessel fitted with an AIS transmitter and transmits static data (IMO number, destination, cargo, etc.) and information about the ship's position, speed and course. AIS information databases are used, for example to create advanced methods for detecting possible near miss collisions (Zhang, 2013).

It was assumed that a model of navigational safety assessment could be used to evaluate the risk of collision while planning the optimal routes for vessels carrying dangerous goods. In the present study, the model developed by the Institute of Marine Traffic Engineering in Maritime University of Szczecin

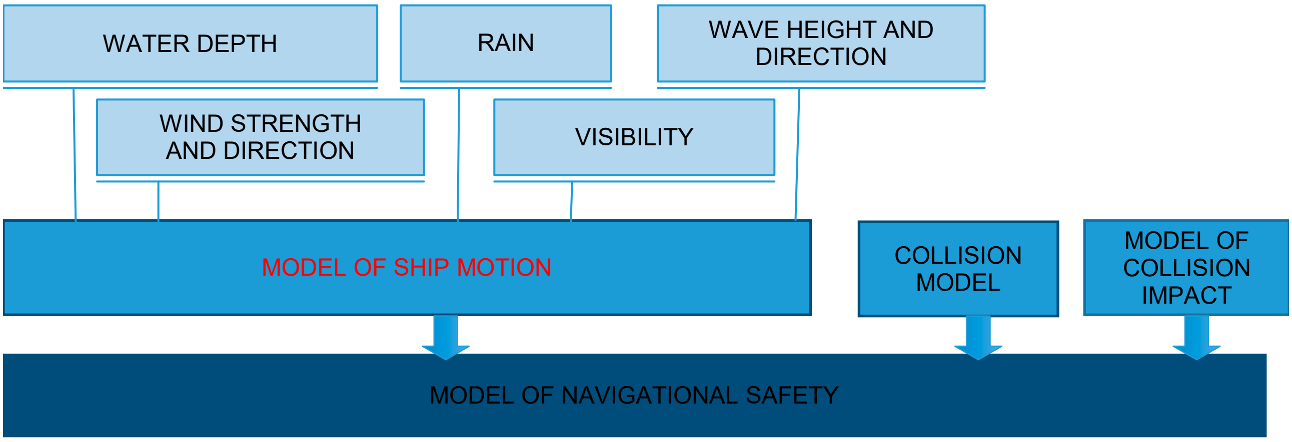

Figure 1. Scheme of navigational safety assessment model

was used. Construction of this model uses sub-models developed mainly on the basis of statistical data. The ship traffic model is developed on the basis of AIS data and navigational charts; the model of external conditions is based on data from hydro-meteorological stations and navigational publications. Detailed specification of this model can be found in (Przywarty, 2012) and conference papers (Przywarty et al., 2015). The scheme of the navigational safety assessment model is shown in Figure 1.

Computer simulations developed on the basis of this model and on collected statistical data allow to carry out simulation experiments for chemicals tankers. The simulation identifies and classifies the intersections of merchant vessel routes with routes of passenger ferries.

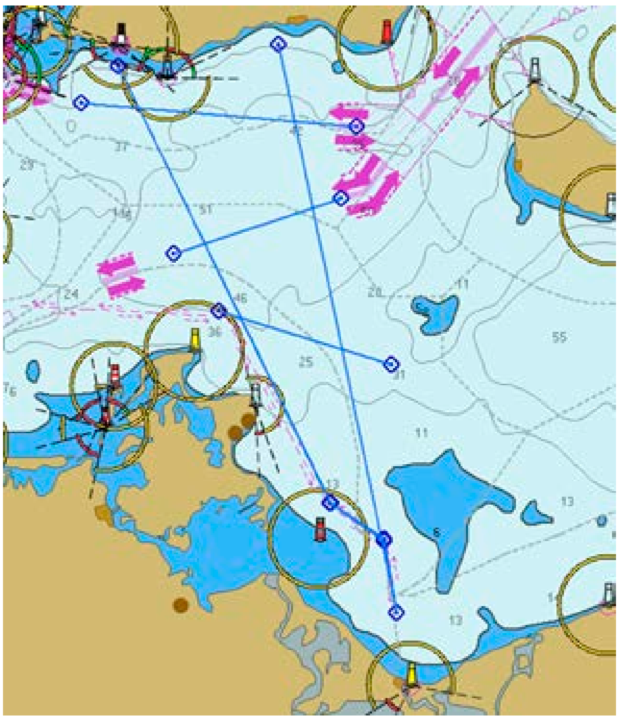

Figure 2. Shipping routes designated on the basis of AIS data

The model works in accelerated time, enabling the analysis of a large number of scenarios and providing stable statistical results. To pre-determine the critical zone for navigation in the study area of the Baltic Sea, the AIS data of highest vessel traffic density in the two summer months (June and July) of 2011 was used. Analysis of the data from this system also allows to determine the parameters of shipping routes that are presented in Figure 2, marked with blue lines.

After gathering and implementing all the required statistical data, a simulation trial was conducted in order to identify the number of incidents and accidents. Details allowing classification of intersections are shown in Table 1, and the simulation results show places with the largest number of encounters between passenger ships and chemical tankers Figure 3.

Table 1. Encounters between passenger vessels and chemical tankers

Intersection	Number of encounters	Number of iterations	Encounters frequency [1/month]	A mean time between encounters [months]
I	358	100	1.8	0.6
II	342	100	1.7	0.6
III	214	100	1.1	0.9
IV	549	100	2.8	0.4
V	664	100	3.3	0.3
VI	90	100	0.5	2.2
VII	122	100	0.6	1.6
VIII	74	100	0.4	2.7

The results of computer simulations allow to distinguish eight areas with different frequencies of encounters between passenger ships and chemical

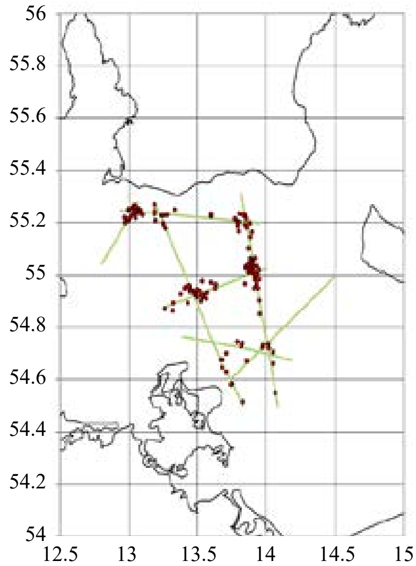

Figure 3. Positions of simulated encounters between passenger ships and chemical tankers in the study area (the two-month iterations)

tankers. The areas have different encounter densities, allowing the assignment of different weights that would affect the role of the parameter describing the risk of an encounter. In areas I, IV, V the highest priority should be assigned, whereas the lowest priority should be assigned to area VIII.

Route planning objective parameters

Unlike the other classes affecting the assessment of the risk of collision between a passenger ship and a ship carrying dangerous goods, these parameters are completely objective and have a decisive influence on the process of route optimization. These parameters include meteorological and navigational conditions as well as technical parameters of the ship. Unlike the other parameters, these can be objectively defined and measured.

When building a target function for individual subjects in this class of parameters the following should be considered:

- weather conditions – wind strength and direction, wave height and direction, occurrence of haze or rain;
- navigational conditions – water depth, shoals;
- parameters of the ship – deadweight tonnage, current % of loading, maximum speed, maneuverability.

Especially in the decision-making process of the optimal route selection, the main factor to be considered is the weather condition, since it affects the duration of the voyage. Along with the accepted risk of collision, weather conditions will be the basis of route optimization.

Determination of the effect of various parameters on the risk of collision is a major problem that must be entered as input data and that will have a decisive impact on the optimization of the route. Conducting research on the influence of parameters on the level of collision risk of a vessel carrying dangerous goods is a key issue to create a mathematical model.

An algorithm selecting a method optimizing the route of dangerous goods in maritime transportation

The next step after creating a mathematical model, whose task is to define and calculate the values of factors affecting the optimization of routes of ships carrying dangerous cargoes, is to create an algorithm of computer application to verify the obtained results. An example of this algorithm is shown in Figure 4.

After dividing the route into smaller sections, the algorithm determines the procedure for each segment based on the answers to questions. After loading new data, the algorithm checks if the cargo carried by the vessel is DG cargo type. If the answer is negative, the calculation block chooses the economic criterion and ends operations. If the vessel is carrying dangerous goods the algorithm checks whether the vessel is already in its port of destination. If the vessel is still underway, vessels rout is checked in the following steps and, if it is planned to enter an area of increased risk, vessel parameters and weather conditions are calculated. After taking into consideration these parameters, a calculation block determines whether the vessel's course is safe or whether it should be changed. Once more, the weather conditions and whether the ship had already left the area of increased risk are checked. When the vessel is already outside the area of increased risk, the algorithm is completed. For the purposes of this algorithm, objectified weight should be assigned for each parameter of the ship navigational and meteorological conditions that would lead to a final "yes" or "no" decision. The created algorithm identifies areas of increased risk, calculates the vessel's parameters and checks the weather conditions to allow correction of the vessel's course and safe way of leaving the increased risk area. The algorithm is an introduction to create a model for the route optimization of ships carrying dangerous.

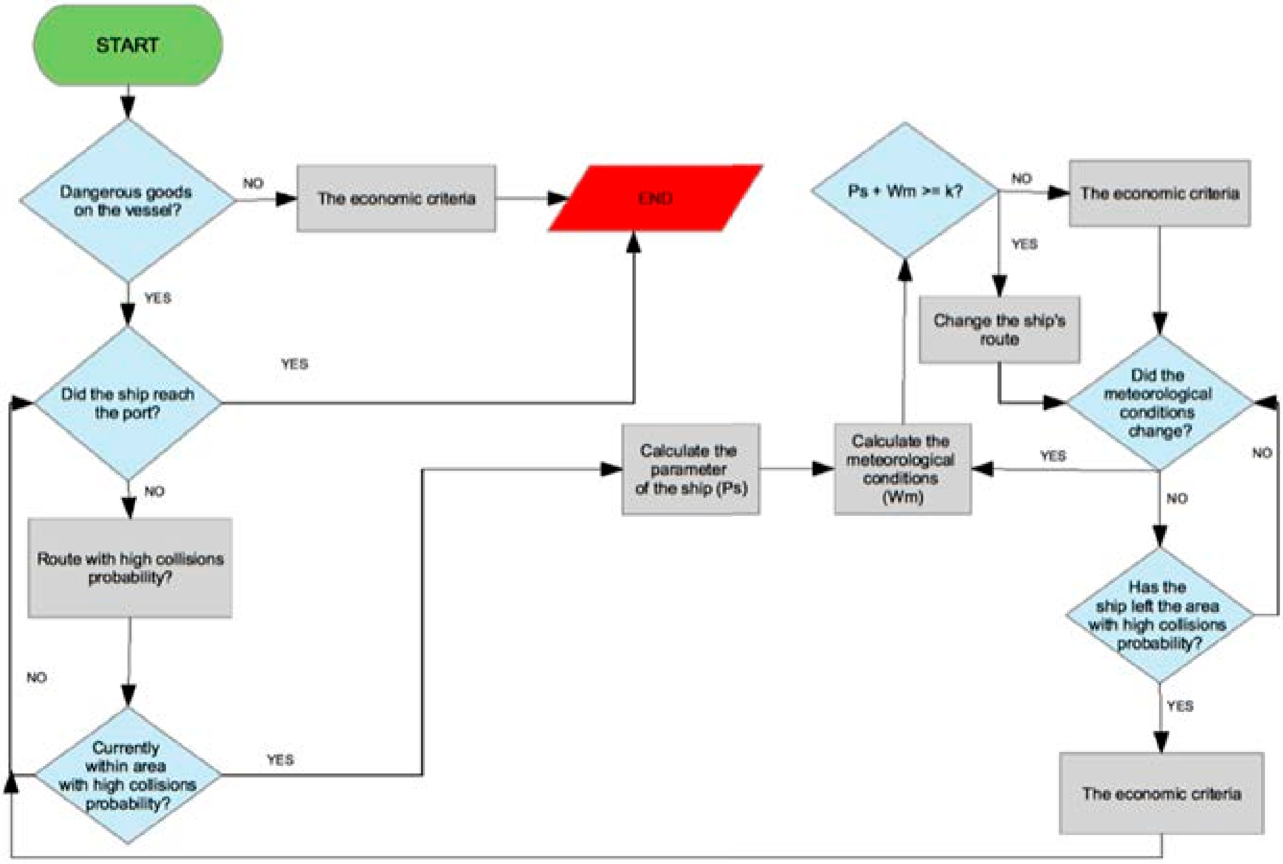

Figure 4. Algorithm for optimal route selection

Conclusions

Because of the complexity of the problem, construction of a mathematical model to optimize routes of vessels carrying dangerous goods requires firstly the determination of a domain for each parameter affecting the target function. The importance of the different parameters on the optimization problem should then be quantified.

In this paper, auxiliary issues that are necessary to build the mathematical model are indicated. Finally, the ways of determining the critical areas of navigation based on data from AIS are described. In order to create a computer application that will allow to verify the obtained results, some additional parameters still need to be systematized, classified and assigned with factors determining their impact on the navigational safety.

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References

1. Boć, R. & Gucma, L. (2016) Analysis of the traffic of chemical tankers in the Szczecin and Świnoujście seaports. *Scientific Journals of the Maritime University of Szczecin* 46 (118). pp. 122–128.
2. Jurdziński, M. (2014) Wybrane warianty planowania podróży statku w żegludze oceanicznej. *Zeszyty Naukowe Akademii Morskiej w Gdyni* 87. pp. 14–21.
3. Posti, A. & Häkkinen, J. (2012) *Survey of Transportation of Liquid Bulk Chemicals in the Baltic Sea*. Turku: University of Turku.
4. Przywarty, M. (2012) *Stochastyczny model oceny bezpieczeństwa nawigacyjnego na akwenach otwartych*. Dsc. Thesis. Maritime University of Szczecin.
5. Przywarty, M., Gucma, L., Marcjan, K. & Bąk, A. (2015) Risk analysis of collision between passenger ferry and chemical tanker in the western zone of the Baltic Sea. *Polish Maritime Research* 2(86), vol. 22. pp. 3–8.
6. Sormunen, O.-V.E., Goerlandt, F., Häkkinen, J., Posti, A., Hänninen, M., Montewka, J., Ståhlberg, K. & Kujala, P. (2015) Uncertainty in maritime risk analysis: Extended case-study on chemical tanker collisions. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 229 (3). pp. 303–320, first published on January 30, 2014.
7. Zhang, W., Goerlandt, F., Kujala, P. & Wang, Y. (2016) An advanced method for detecting possible near miss ship collisions from AIS data. *Ocean Engineering* 124. pp. 141–156.