

Methodology for the Development of Parameters for the Navigational Safety Risk Assessment Model in Port Approaches

F. Bojić, R. Bošnjak, Z. Lušić & A. Gudelj
Maritime University in Split, Split, Croatia

ABSTRACT: Risk of an accident is an ever-present component in the maritime transportation process, especially in congested waters such as port areas. Since safety is of crucial importance in the maritime industry, different models of risk assessments were developed to ensure minimal navigational danger. The aim of this paper is the development of modular, dynamic sets of parameters, applicable for future risk assessment models on port approaches by introducing top-down expert appraisal structure methodology organised in three steps. Firstly, approaches and criteria from relevant international recommendations and scientific studies on maritime risk assessment models were analysed and compared, in order to obtain general categories of navigational safety parameters. Secondly, existing risk assessment parameters were structured and combined into new dynamic sets. In the third step, these dynamic sets of parameters were selected, and numerical values were assigned to them according to the specific context of the port. Finally, this top-down methodology aims to provide relevant dynamic sets of criteria for navigational safety risk assessment development that are flexible and widely applicable for the needs and characteristics of different ports.

1 INTRODUCTION

Shipping, as the most efficient transportation mode is responsible for more than 80% of global trade by volume [13]. So, increased activity of the global market corresponds with higher shipping demand that can result in large traffic volume inside port areas. Even though seaports tend to attract more shipping activity, traffic overcapacity can increase overall risk of accident. In order to continue the growth trend of demand for services while maintaining a high standard of safety, port communities developed navigation risk assessment models based on different methodologies.

General guidelines for developing navigation risk assessments are provided by global organisations like International Maritime Organisation (IMO),

International Association of Marine Aids to Navigation, Lighthouse Authorities (IALA), World Association for Waterborne Transport Infrastructure (PIANC), etc. While some researches used approaches provided by mentioned organisation, individual risk assessments combined them with or established own location-specific methodologies for securing safety of maritime traffic in ports.

Most of existing risk assessments are based on either historical data of the accidents or assumptions derived from expert knowledge. Main benefit from constructing models based on historical accident databases is that causal factors are more obvious and learning from a mistake process can be easily applied. Drawback of this approach is often manifested as limitation of accident case numbers in targeted area or when data is incomplete. Also, historical data of the

accidents does not take into account near miss situations that involve high level of uncertainty to the potential threat, therefore it not possible to have full perspective of number, weight and interactions between different risk factors. To compensate for the lack of data on navigational accidents, some researchers used expert analyses in their approach to determine relevant navigation risk factors. Use of expert judgment in complex system such as port approach operations, can improve relevancy of different risk components and make up for the ever-present lack of information important for developing risk assessment. Expertly approach can contribute to the proactive nature of the methodology and may improve quality of the historical data. Further historical data may be evaluated by the use of expert judgment by which the quality of the historical data may be improved [5].

Although navigational risk understanding in variety of scenarios can deepen the insight of potential accidents and can extend the relevance of the results, it won't erase the uncertainty of the evaluation in the process of predicting the final outcome. Because of the uncertainty of processes inside maritime traffic, some researches applied fuzzy logic methodology that allows development of risk predicting models based on imprecise or incomplete data. It was found that deployment of fuzzy logic should enable taking into account the insufficient information and the evolution of available knowledge [1]. But since fuzzy logic tolerates some level of data deficiency and uncertainty, process of criteria election and validation must rely on expert's judgement. To ensure additional relevancy of expert's appraisal of risk criteria in fuzzy logic setup, quantification of and examination of previous risk assessment methods and models can be used.

In this paper, top-down expert approach with fuzzy logic background was applied throughout three steps in order to define dynamic sets of criteria for navigational safety risk assessment development. Paper arrangement is compliant with mentioned approach. So, in Section 2, after the presentation of brief general methodological background, three subsections are introduced. Initial subchapter contains analysis and quantification of risk criteria from relevant researches. In subsection 2.2. aggregated risk criteria are selected and classified into fuzzy sets. Also, causal connections between risk parameters are clarified. In final subsection, method for validation of risk criteria and its applicability are explained. Finally, conclusion of proposed method is presented and course of research development in the future is pointed out.

2 METHODOLOGY

To accomplish the goal of this research, top-down expert methodology was applied because accident data is frequently qualitatively and spatially restricted. Since the amount of casualties in ports is limited, maritime traffic in ports cannot be assessed based on single casualties. While it is impossible to anticipate the risk for a nonextant situations based on data-driven approach, this method also does not

allow the quantification of risk generated by near miss situations, high traffic volumes or environmental effects on navigation [3]. Various factors contributing to the risk of a potential accident that were not necessarily considered during the accident analysis have to be taken into account in order to achieve relevant results from risk assessment model. That is why data important for conducting risk assessments such as vessel information, weather influence or traffic properties had to be gathered, quantified and analysed by experts to determine their causal relationships what can serve as a foundation for developing a navigation risk model.

But to successfully apply different risk criteria on risk assessment model, that were previously selected through expert appraisal, it is necessary to have methodological background that is able to produce valid result in systems with incomplete data and level of uncertainty. Therefore, the application of non-binary fuzzy logic for creating connections and assigning values to different parameters was found suitable for predicting risk in uncertain, or in other words, unprecedented environments such as port approach operations and navigation in port basins. The fuzzy logic is an efficient approach for design a decision-making system in maritime domain. This technique allows solving a lot of problems related to dealing the imprecise and uncertain data [1].

So, focus of this paper was not on a historical casualties nor risk aspects relevant to single location but on providing modular fuzzy sets of risk criteria that, when connected inside a risk model, can give flexibility of defining realistic navigation risk scenario of different port approaches.

2.1 First step – top-down criteria quantification and analysis

To begin with the development of navigational risk criteria sets, quantification and analysis of accident factors from different navigation risk assessments was conducted. The first step in risk quantification is to define the boundaries and the objectives of the system to be analysed [11]. With top-down approach firstly general guidelines and recommended risk factors from three different international organisations where evaluated.

IMO presented methodology for risk control in "Formal Safety Assessment" (FSA) document. Through its five-step approach, guidelines regarding hazard identification, risk analysis and control, cost-benefit and decision-making recommendations are provided with the aim of enhancing maritime safety by developing and using risk analysis and cost-benefit assessment [5]. Although FSA is publication that offers detailed suggestions on data gathering and its evaluation, application of expert judgment, use of qualitative and quantitative methods or influence of human error, its scope is wide, thus often not completely applicable for the needs of different ports. Inside this research expert appraisal and quantification of risk data were considered, along with suggested navigational safety aspects that are generally presented in Table 1, while human error was avoided due to its complexity that requires different and thorough research.

Table 1. Overview and quantification of general risk criteria used in examined literature

Main category	General criteria	Specific criteria	Source						
Ship data	Size	Length	[5]	[16]	[6]	[3]	[11]	[6]	
		Breadth		[16]	[6]			[6]	
		Gross tonnage	[5]		[6]	[1]	[3]		[6]
	Dynamics	Draught		[16]	[6]				
		Speed		[16]	[6]		[3]		[6]
	Characteristics	Manoeuvrability		[16]			[3]	[11]	
		Type of ship	[5]	[16]	[6]	[1]		[11]	[2]
		Year of construction	[5]			[1]		[11]	
		Number of companies				[1]			
		Duration of detention				[1]			
		Type of hull	[5]			[1]			
		Crew		[16]				[11]	
		Flag				[1]			
		Pilotage requirements						[11]	
		Escorting requirements						[11]	
		Propulsion	[5]					[11]	
	Environmental influence	Wind effect	Steering					[11]	
			Electrical power					[11]	
		Sea effect	Structural integrity						[11]
Wind speed				[16]	[6]	[1]	[3]	[11]	[6]
Wind direction				[16]			[3]	[11]	[2]
Current				[16]	[6]		[3]	[11]	[6]
Sea State				[16]		[1]			[6]
Tides						[6]		[11]	[2]
Water density						[6]			
Ice				[16]		[6]			
Visibility effect	Visibility		[16]	[6]	[1]	[3]	[11]	[2]	
	Time of the day				[1]	[3]		[2]	
Traffic influence	Traffic size	Traffic volume		[16]		[3]		[6]	
		Time of year		[16]				[2]	
Port organisation and assistance	Traffic diversity	Traffic mix		[16]		[3]		[2]	
	Port organisation	Rules and regulations				[3]			
		Navigational equipment							
Port configuration	Port assistance	Pilotage		[16]		[3]			
		VTS assistance		[16]		[3]			
		Tug assistance						[2]	
	Port design	Water depth				[6]	[3]		
		Width				[6]	[3]		
Navigational aid	Location				[6]	[3]	[11]	[2]	
	Type of infrastructure				[6]	[3]	[11]		
	Traffic separation		[16]	[6]			[11]		

IALA developed “Waterway Risk Assessment Program” (IWRAP), quantitative modelling tool useful for providing a standardized method of assessing the risks within most waterways [8, 16]. IWRAP can estimate the frequency of collisions and groundings in a given waterway based on information about traffic volume/composition, route geometry and bathymetry [16]. This model is convenient for acquiring relevant estimation of the annual number of collisions for specific area but it is difficult to calculate the level of risk for individual navigation scenarios, especially because causation of other risk factors inside model, like environmental influence or port organisation are quite uncertain. Also, it is difficult to apply in areas with complicated traffic tracks [8]. Risk factor used in this model are generally described in Table 1.

PIANC introduced “Harbour approach channels design guidelines”, a report that provides recommendations for the design of harbour approach channels, the manoeuvring and anchorage areas within harbours, along with defining restrictions to operations within a channel [9]. Even though focus of this document is primarily orientated towards the navigational design of ports and their approaches, its theoretical explanations and relationships between

criteria important for safe navigation in enclosed waters are well-defined and applicable for development of risk assessment for port approaches. General criteria presented in this document are illustrated in Table1.

In addition to the general recommendations from IMO, IALA and PIANC, five different relevant studies that tackled the problem of navigation safety with various methodologies where analysed and their navigational risk factors were examined and displayed in Table 1.

In research “Utilizing the fuzzy IoT to reduce Green Harbour emissions” conducted by S.L. Kao, J.L. Lin and M.R. Tu, fuzzy logic was applied inside risk model in order to determine safe manoeuvring speed which will contribute to better safety and air quality standards of Keelung Port [6]. For defining the Nautical Port Risk Index, in paper “Risk Assessment Methodology for Vessel Traffic in Ports by Defining the Nautical Port Risk Index”, X. B. Olba, W. Daamen, T. Vellinga and S. P. Hoogendoorn used expert validation and quantification method on several risk assessment researches to create risk factors from which risk assessment model was derived for Port of Rotterdam [3]. Paper “A decision-making system to maritime risk assessment” of J.F. Balmat, F. Lafonta,

R. Maifret and N. Pessel has also demonstrated the use of fuzzy approach for development of decision-making system for mitigating risk of accidents and pollution based on expert appraisal of factors from different sources [1]. In research "Risk based methodology for safety improvements in ports", V. M. Trbojevic and B. J. Carr offered methodology and risk criteria for development of navigational risk assessment relevant for seaports [11]. In paper "Simulation Method - Based Oil Spill Pollution Risk Analysis for the Port of Šibenik" conducted by G. Belamarić, Ž. Kurtela and R. Bošnjak risk factors from different relevant sources were applied inside risk matrix to determine the level of chance for accident occurrence in different scenarios relevant for navigation in Šibenik port approach channel [2].

Finally, the objective of first phase was to achieve transparent analysis of relevant studies and offer overview of their risk parameters illustrated in Table 1. that served as a foundation for developing valid dynamic sets of risk criteria based on expert understanding in next step of this research.

2.2 Second step – criteria aggregation and their classification into dynamic fuzzy sets

As can be seen in Table 1., five main categories of criteria are developed, along with twelve general criteria groups, all based on specific risk factors from sources examined in first step of this research. In this phase, risk factors that were previously quantified and analysed are now aggregated, classified and connected inside different fuzzy sets that interact with each other in a dynamic manner. All risk factors related to navigation should be assessed in a structured way, and a selection of the important factors should be made according to expert judgement for development of valid risk assessment [5]. With reliance on expert perception of the causal connections between aggregated safety parameters, dynamics sets of risk criteria are formed, and ones relevant for Port of Split case study are presented in Table 2.

Table 2. Dynamics fuzzy sets of risk criteria relevant for Port of Split case study

1 Ship data	
Ship size	Gross tonnage
Ship dynamics	Speed
2 Environmental influence	
Ship characteristic	Type of vessel
Wind effect	Wind speed
3 Traffic influence	
Traffic size	Time of year
Traffic size	Traffic volume

The aim of categorising selected criteria was to connect them inside sets that could be applicable for navigation scenarios in different ports. By adding or removing preconfigured risk sets, flexible model design is enabled. But since focus of this research is on methodology for development of risk parameters, process of aggregation, classification and connection of criteria displayed in Table 2 is examined.

Since vessel length can be associated with gross tonnage (GT) of individual vessel type, first set of criteria demonstrates connection between vessels size which is described by a function of its mass expressed in metric tons and vessel speed expressed in knots (KT). This way level of risk for individual ship motion can be assessed [6]. In second set, windage area of different ship kinds is represented by type of vessel criteria and related with wind speed expressed according to Beaufort scale (BF), so that environmental influence can be measured as level of wind effect on diverse freeboard designs and surface sizes [10]. Traffic influence is manifested as traffic size that is relevant to its dynamic throughout the year and its anticipated volume inside port basin and port approach in different day periods [7].

All three criteria sets, illustrated in Table 2. are structured based on expert comprehension of the causal relations between navigation risk criteria, and to develop functional navigation risk assessment they need to be connected in a same manner. The interaction between parameters denotes changes in the risk profile due to changes in port management, ship characteristics, or other parameter sets [11]. But before model designing and obtaining any results, each component has to be transformed into numerical data.

2.3 Third step – assigning data-based values to risk criteria

Complex operations like port approaches, here defined through individual dynamic sets of risk criteria, are described as processes with degree of uncertainty. The maritime risk evaluation can find an interest in the fuzzy logic approach because much data are linguistic variables [1]. That is why in this research top-down expert appraisal with fuzzy logic background was used to quantify, select, classify and finally characterise risk parameters by assigning data-based values to them. Each value is represented by membership function that defines the degree of truth as an extension of its valuation [14]. Although there is no clear limitation for number of criteria and membership functions in each fuzzy set, by increasing their quantity connection between them will grow exponentially, thus potential model will become too complex and inadequate for intended application. That is why usually there are two to five membership functions per criterion that is represented by average value.

Databases and publications of local relevancy are examined in this phase to determine the membership function of each criterion in fuzzy sets, presented in Table 2 for Port of Split case study. The reason for considering data from port-oriented sources is to ensure the adaptability of the final risk model to the specific needs of that area.

To establish three categories for average sizes of ships that arrive in Port of Split, available database of Split Port Authority (SPA) and Croatian Register of Shipping (CRS) were analysed. For acquiring information about average ship speeds, Automatic Identification system (AIS) was used. Types of vessels, determined also by examining SPA database, served as a three membership functions of windage areas

relevant for each vessel type inside environmental influence fuzzy set. Membership functions that represent wind speed mean values were established by relying on information from Maritime navigation study, navigating area of Split and Dubrovnik, Admiralty sailing direction NP 47, Mediterranean Pilot Vol.3 and Croatian Hydrographic institute Pilot. [4, 12, 15]. Maritime navigation study, navigating area of Split and Dubrovnik, SPA database, AIS data served as basis for validating traffic size and the navigation risk area. First, vessel arrivals throughout the year were analysed to determine traffic volume in different periods. Similar approach was applied on three periods of the day where AIS was used to track the number of vessels in motion around estimated manoeuvring port area of about 1 square nautical mile (NM²). This way, approximate number of active vessels per 1 NM² (V/NM²) could be anticipated temporally, so year and day periods are used as membership functions to express assumed traffic quantity. Average values of all risk criteria relevant for Port of Split case study are presented in Table 3.

Table 3. Classification of validated membership functions for each risk criteria in fuzzy sets relevant for Port of Split case study

1 Ship data			
Classification	Large	Medium	Small
Ship size (GT)	28411	6496	3156
Classification	Fast	Moderate	Slow
Ship dynamics (KT)	15	10.5	6
2 Environmental influence			
Classification	Large	Medium	Small
Type of vessel	Ro-Ro/ Passenger/ Yachts/ Boats	Bulk/ General/ Tankers - ballast	Bulk/ General/ Tankers - loaded
Classification	Gale	Moderate	Gentle
Wind speed (BF)	8	6	3
3 Traffic influence			
Classification	High	Moderate	Low
Time of year	Season	Pre/ Postseason	Offseason
Classification	High	Moderate	Low
Traffic volume (V/NM ²)	Daytime	Dusk/Dawn	Night-time

Implementation of membership functions in model designing allows graphical expression of fuzzy set elements. For this model, triangular membership function was found as most convenient for graphical description of values in each fuzzy set, since average values represent the highest degree of membership in each class. Classification of risk criteria, expressed through triangular membership functions was conducted in MATLAB software. Membership functions of Ship dynamic criteria are presented in Figure 1.

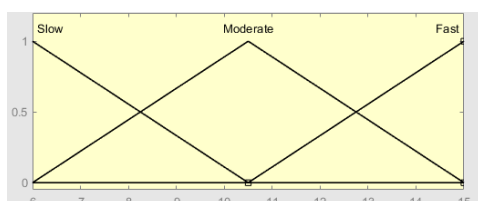


Figure 1. Triangular membership functions of ship's dynamic as part of ship data fuzzy set

Lastly, validation of risk criteria as a key element for the development of flexible navigational risk assessment model is ensured by completing the final phase of top-down expert methodology. After applying the final methodological step inside the model composed in MATLAB software, defuzzification process of realistic navigational scenarios produced output that had a high level of compatibility with the expert's expectations. Surface representation of defuzzification process is illustrated in Figure 2.

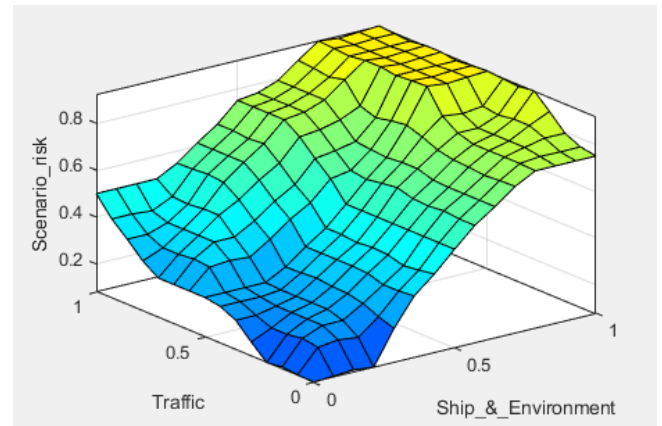


Figure 2. Surface representation of defuzzification process with three fuzzy sets from Table 3.

As can be seen in Table 3, both general relevancy and spatial flexibility of chosen dynamic fuzzy set can be established through the three-step process, where general risk criteria are structured in fuzzy sets, then selected and validated in relation to the port's needs.

3 CONCLUSION

Port-related navigation is a complex operation where the risk of an accident is an ever-present component. Various factors can negatively affect navigational safety, particularly in spatially limited port areas. To mitigate the risks of port approach activity, this study proposed the methodology for the development of parameters for the navigational safety risk assessment. Expert knowledge was used throughout three methodological segments to define modular dynamic sets of risk criteria that can serve as a foundation for the development of navigational risk assessment model based on fuzzy logic.

The model constructed according to the concept provided in this research should be able to estimate the level of navigational risk of realistic scenarios in different ports. To meet the diverse needs of particular ports while retaining universality of selected risk criteria, a top-down approach was used. With this method, the process of risk criteria development went from quantification and selection of general and global risk parameters to their validation based on specific and local data. For more accurate and prompt risk prediction of individual navigation scenarios, this study proposed use of AIS data for determining input values. But since not all ships that participate in maritime traffic are required to have an AIS device, limitation of partial

navigational safety surveillance could be bypassed by introducing novel Internet of Things (IoT) platform. Possibility of integration of devices and decision makers inside a unique risk assessment model can be secured through IoT web, what would in the end lead to better safety aspect of port approaches. Since the initial model has shown an adequate level of output validity, for now, the extension of this research will be directed towards design improvement of the model's architecture by adding more fuzzy sets, its programming inside the fuzzy logic software, and additional proofing of output based on realistic navigational scenarios.

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