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METHOD OF AUTOMATED IDENTIFICATION OF QUALIFICATION PARAMETERS FOR MARINE OPERATORS UNDER RISK CONDITIONS

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The objective of the study is to enhance maritime safety by applying a method for identifying and predicting the qualification parameters of ship operators based on fuzzy logic. The core challenge of this research lies in the necessity to control internal uncertainty factors of ship operator actions and develop a system that identifies their qualification parameters to ensure safe decision-making in complex navigational conditions.

The research methodology comprises: a) an algorithm for automatic data processing of ECDIS to reduce subjectivity in defining fuzzy membership functions related to navigational factors; b) formalization of the structure of fuzzy functions and establishment of a rule base for identifying risks in complex navigation scenarios; and c) simulation-based fuzzy modeling that investigates the influence of qualification parameters on the overall risk index of ship motion management.

The research outcomes involve the development of an intelligent system predicting navigational risks in intricate maritime conditions. Through simulation modeling, it has been identified that ship operators' qualification parameters significantly impact the risk associated with vessel management. For instance, an increase in parameters across four indicators can elevate the overall risk by 15.8%, shifting the situation into a hazardous or critical category.

The practical significance is manifested by the efficiency of automated ECDIS data processing, which reduced subjective errors and refined navigational risk prediction. The revealed influence of ship operators' qualification parameters on risk levels underscores the importance of individualized forecasts tailored to each operator. The practical value also lies in the potential to enhance maritime safety by precise risk prediction and management, considering the human factor of each operator. Future research will focus on integrating this method into other ship motion management systems, creating even more effective decision-support tools for operators under conditions of inherent uncertainty. Bibl. 23 fig. 19.

Key words: *automation; organizational-technical systems; risk; intelligent systems; qualification parameters; identification; fuzzy logic; uncertainty.*

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Introduction. In recent years, technologies based on artificial intelligence are increasingly being integrated into the management tasks of marine vessels in challenging navigational conditions. Neural network models are employed for predicting optimal maneuvering trajectories, computer vision systems for recognizing surrounding objects and determining their dynamics, as well as machine learning algorithms for analyzing meteorological conditions and automatically adjusting the ship's course. These innovations substantially enhance the safety and efficiency of maritime transport, especially in areas that are complex and hazardous for navigation [1–3].

Despite evident progress in this direction, the use of intelligent systems in various maritime transport tasks, and the emergence of e-navigation, in the vast majority of water transport, the decision to manage the vessel is made by the ship operator [4]. Navigational instruments, sensors, and devices provide the information upon which managerial decisions are made, carrying full responsibility for their consequences, regardless of the complexity and criticality of the situation [5]. Despite the high rate of disasters attributed to human error, over 70%, intelligent, automated, and automatic systems for trajectory forecasting, decision-making support, and optimal management cannot cover the full spectrum of navigational situations and mitigate the human factor throughout the ship's journey [6]. However, at the same time, the significance of the aforementioned information systems for navigational safety is quite substantial, as noted in several leading studies in this field [7–9].

Consequently, a contradiction arises between two concepts: the control over the situation by the ship operator-navigator and the comprehensive information systems for situational identification and vessel management. Distinguishing between these two concepts seems unfeasible due to the instability of the projected safety level as their primary objective function. While artificial information systems have clear algorithms and can be analyzed through computer simulation under given conditions and constraints, human decision-making processes are based on complexly formalized processes of intellectual activity of the operator as a subject.

Problem Statement. The above discussion highlights the evident complexity in delineating functions between the operator and the ship's information management systems. Indeed, the time it takes to transition from manual ship control during complex, non-standard maneuvers, considering various factors, will vary among operators [10]. At a given moment, each operator, while performing their functional duties, has a confidence level that varies relative to their colleagues and depends on the structural parameters of their qualifications. It is precisely the set of qualification parameters that influences the performance of specific ship management tasks in relation to conditions and factors defining the navigational situation.

It should be noted that in critical situations, where the operator's decision-making time is minimal and the body is under stress, the processes of restoring qualification parameters are severely hampered, leading to catastrophic outcomes [11].

The article [12] is concerned with the concept of human operators remotely controlling autonomous ships, with particular focus on the design of Remote Operation Centres (ROC) and the human factors involved in such operations. It discusses the role of automation in maritime navigation and the challenges of keeping a human 'in the loop' for decision making. Several tasks within a ROC are outlined, including managing the out-of-the-loop syndrome, ensuring proper automatic control, and providing manual control when necessary. Additionally, the paper covers tasks specific to maritime navigation like anti-grounding and anti-collision tasks and the design considerations for effective and safe operation in these domains.

Key points covered in the article include: Discussion of “out-of-loop syndrome,” where operators may be unaware of the situation due to over-reliance on automation. The importance of taking into account the appropriate qualification parameters for performing complex maneuvers is indicated, but the algorithm for ensuring such a parameter is not shown.

The paper [13] analyzes the work of maritime officers using the Operator Function Model (OFM) and examines recent ship accidents along the Korean coast. Introduced the concept of the Operator Function Model (OFM), which is used to characterize worker activity in complex systems, such as the operation of a ship. The analyzes specific OFM of ship navigation to evaluate cognitive demands and technological innovations in ship navigation. The text discusses specific types of errors, such as voyage planning errors, and mentions an example of a ship accident involving the Kumho Ferry No. 3. It seems to discuss the incident as an example of failure in appropriately identifying and responding to AtoN signals, resulting in a grounding accident. An important point is the creation of a model of the navigator’s behavior, but the principles of its application in real time during a navigational watch are not specified.

The research article [14] presented in the screenshots deals with the enhancement of video-based detection infrastructure for automated ship recognition and behavior analysis. Also discusses the complexities in the interaction between human operators and the ship's information management systems, especially during complex and non-standard maneuvers. It highlights the variability in the operators' confidence levels and the influence of their qualifications on the management of the ship, especially in critical situations where decision-making time is short, and stress levels are high. The research aims to improve the immediate and understandable on-site traffic situation awareness for operators, potentially impacting their confidence in the system's data. The article's methodology involves manual rectification of training images and interpretation of YOLO model outputs, which could be seen as analogous to the need for skilled operators to interpret and act upon complex information from automated systems in real time.

The framework proposed in the article aims to provide high-fidelity, immediate maritime traffic information, which could be crucial in high-stress situations where operators have minimal time to make decisions. Accurate and efficient automated recognition systems can potentially reduce the cognitive load on human operators, thus mitigating the risk of catastrophic outcomes due to delayed or incorrect human responses. The automated system's ability to recognize and analyze ship behavior consistently and accurately, even in varied maritime conditions, relates directly to the concerns about restoring qualification parameters under stress.

However, the study does not assume a prediction of the perception of the navigation situation, taking into account the specifics of the individual model of the navigator, which requires improvement in this part.

The article [15], discusses the complexity of delineating functions between the operator and the ship's information management systems, emphasizing the influence of operator qualifications and the difficulty in maintaining performance under stress during critical situations.

With more accurate models, the system could potentially reduce the cognitive load on human operators by providing more reliable predictions of ship behavior. By training with models that closely mimic real-world behavior, operators can develop better skills and confidence.

Just like in previous studies, the importance of maintaining the navigator's qualifications at a high level with the help of automated systems is emphasized. However, no method is specified to take into account multifactorial skill levels to assess possible risks based on incomplete data.

The article [16] discusses the complexity of delineating functions between the operator and the ship's information management systems, emphasizing the influence of operator qualifications and the difficulty in maintaining performance under stress during critical situations. Accurate ship response models could help in creating simulations and training programs that prepare operators for high-stress situations. By training with models that closely mimic real-world behavior, operators can develop better skills and confidence. The optimization of these parameters in simulations, as mentioned in the research, could enhance the training and qualifications of operators. At the same time, approaches are not indicated that allow the restoration of selected parameters of the navigator's qualifications, especially in real time conditions.

Consequently, there arises a clear need to control the internal uncertainty factors related to the operator's actions, which is a current challenge. The creation of an automated control system for safe decision-making by the operator will allow for forecasting, in the early stages of a ship's route, how adequate their qualification parameters are for performing tasks under specific conditions.

However, the challenges of creating systems that identify the qualification parameters of ship operators are significant. These challenges manifest in several categories:

1. Subjectivity of the Human Factor: The human decision-making process is difficult to formalize. It relies on intuition, experience, and other implicit factors, making it unpredictable and distinct from AI algorithms. Additionally, individual differences among operators should be taken into account: varying levels of confidence and qualification parameters can lead to different response speeds and problem-solving algorithms.

2. Human-Machine Interaction with Navigation and Ship Management Systems: The contradiction between manual and automatic control can lead to operator errors, especially during critical moments. Challenges also arise in determining where exactly automated system control should start and end, and where human operator control should take over. Improper delineation can result in errors and misunderstandings.

3. Determination of Qualification Parameters: The difficulty in defining and measuring the qualification parameters of operators can lead to inaccuracies in forecasting and ship movement control. This suggests that continuous updating of operator qualifications is essential for accurate control and forecasting, which can be a complex task in the dynamic environment of ship management.

4. Technological Constraints: At the current stage of automated and intelligent technology development, there are challenges in designing advanced tools for accurate and timely analysis of all necessary parameters.

The above points underscore that the stated problem is non-trivial, objectively exists, and requires solutions through the development of specialized automated and intelligent methods and approaches.

Research Purpose and Objectives. The purpose of this study is to develop a method for identifying the qualification parameters of ship operators in organizational-technical ship management systems using intelligent systems based on fuzzy logic. To address the stated problem, several tasks need to be accomplished:

1. Develop an algorithm for the automated processing of experimental ECDIS navigation data in complex navigation areas with the aim of reducing the subjectivity in determining parameters of fuzzy membership functions concerning navigation factors.

2. Based on the obtained fuzzy membership functions, describe their formal structure and construct a fuzzy rule base for the intelligent system identifying navigation risks while managing a ship under complex (critical) conditions.

3. Conduct simulated fuzzy modeling taking into account the model of the ship operator's qualification parameters. Investigate, based on the acquired experimental data, the influence of qualification parameters on the increase in the overall risk indicator when managing a ship.

Primary Research Material. In accordance with the first research task set, we will develop an algorithm for processing experimental ECDIS navigation data based on software tools for parameters of fuzzy membership functions concerning navigation factors.

To address this task, data was extracted from the TRANSAS simulator system [17] as follows. Authorization was performed in the capacity of an instructor, and from the main system menu, "Tools" was selected followed by the "Logs" section. This allowed access to the "Track History", a key section for analyzing the chronology of the ship's passage. Focusing on our desired time interval, the "Export" function was activated, choosing the CSV format. After saving the data, a detailed check of the exported file (Fig. 1) was carried out to ensure that all necessary data were successfully extracted and are ready for further analysis. Where: LAT – Latitude; LON – Longitude; COG - Course Over Ground - the direction of a vessel's movement relative to the base; SOG - Speed Over Ground - the speed of the vessel relative to the ground; HDG - Heading - the actual course the vessel is on; LOG - Log (or lag) - the distance the vessel has traveled from the start of navigation; SET - Direction of the current; DRIFT - Speed of the current; SPD F - Forward speed or speed by the bow; SPD A - Aggregate speed or speed by the stern.

TIME	LAT	LON	COG	SOG	HDG	LOG	SET	DRIFT	SPD F	SPD A
0	41,25713646	29,15372911	193	3,122	193	3,122	103	0	-0,002	-0,002
5	41,25707015	29,15370873	193	3,126	193	3,126	103	0	0	-0,006
10	41,25700185	29,15368768	193	3,13	193	3,13	103	0	-0,001	-0,006
15	41,25693353	29,15366677	193	3,134	193	3,134	103	0	-0,001	-0,008
20	41,2568652	29,15364579	193	3,139	193	3,139	103	0	0	-0,009
25	41,25679688	29,15362476	193	3,143	193	3,143	103	0	-0,001	-0,01
30	41,25672856	29,15360382	193	3,148	193	3,148	103	0	-0,001	-0,011
35	41,25666024	29,15358285	193	3,152	193	3,152	103	0	0	-0,012
40	41,25659192	29,15356183	193	3,156	193	3,156	103	0	-0,001	-0,013
45	41,25651973	29,15354089	193	3,16	193	3,16	103	0	-0,001	-0,013
50	41,25644615	29,15351991	193	3,164	193	3,164	103	0	-0,001	-0,014
55	41,25637263	29,15349888	193	3,202	193	3,202	103	0	0,009	-0,026
60	41,25629818	29,15347564	193	3,452	193	3,452	103	0	0,039	-0,059
65	41,25621476	29,153451	192	4	194	3,999	103	0,1	0,333	-0,515
70	41,25611476	29,15342222	192	4,92	195	4,909	105	0,3	0,693	-1,36
75	41,255991	29,15338443	193	6,125	199	6,094	108	0,6	0,934	-2,163
80	41,2558408	29,15333135	195	7,324	203	7,267	112	0,9	1,034	-2,859
85	41,25566894	29,15325865	198	8,299	208	8,185	118	1,4	1,269	-4,022
90	41,25548283	29,15315881	204	9,131	215	8,963	124	1,7	1,304	-4,793

Figure 1 – Fragment of data extracted from the ECDIS TRANSAS system

The Bosphorus location was chosen for analysis, which is characterized by specific features of its passage. The qualification indicators of a shipmaster play a critical role in the safe passage through the Bosphorus strait [18]. Experience in navigating ships under complex and restricted conditions, knowledge of local current features, as well as the ability to make quick decisions under challenging circumstances are essential. A lack of sufficient experience, inadequate preparation, or overestimation of one's abilities by the shipmaster can significantly increase the risks when crossing the strait. Each mistake or delay in decision-making can lead to catastrophic consequences, such as collisions or grounding of the ship, resulting in environmental, economic, and human losses.

Based on the presented data about the ship's speed and course, one can infer that the ship maintained a stable speed for most of the time.

However, there were moments of abrupt deceleration. This may indicate unexpected obstacles or maneuvers needed to avoid collisions. The ship's course also experienced fluctuations, suggesting challenges in navigation due to currents or other ships (Fig. 2).

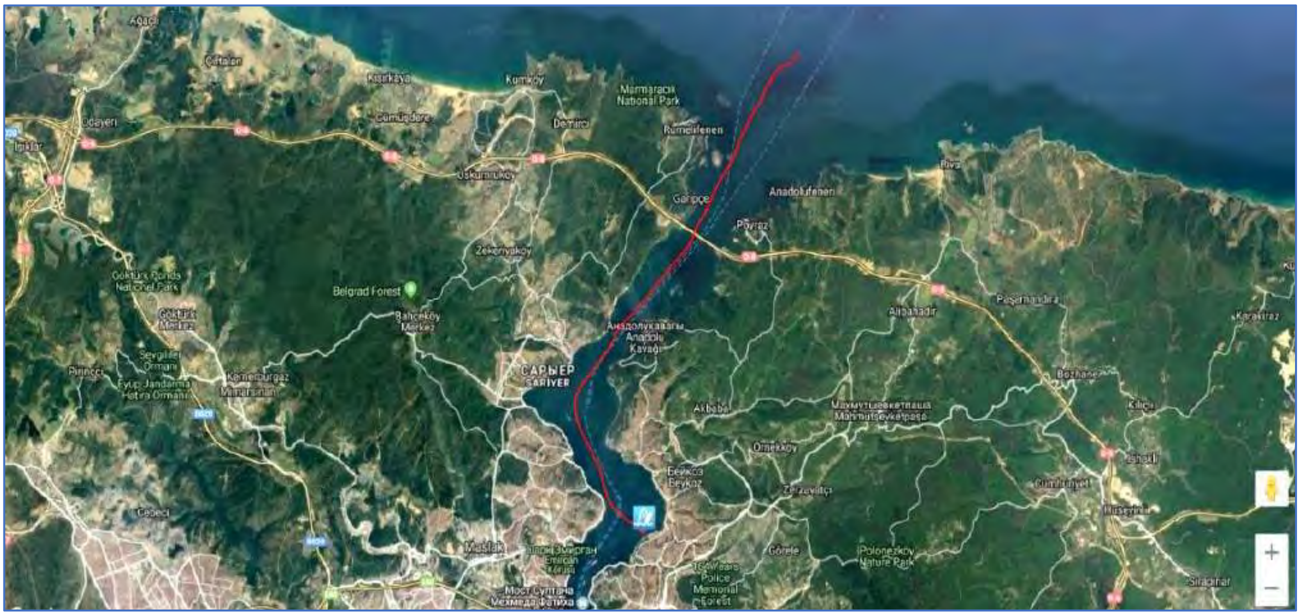


Figure 2 – Ship's trajectory in the Bosphorus location

The analysis of data based on the trajectory and numerical characteristics of the ship's movement allows for the formulation of fuzzy membership functions through automated means. For this purpose, we will develop software for processing numerical navigation data of the route, based on which the corresponding fuzzy membership functions will be constructed.

The program, developed in Python [19] (Fig. 3), analyzes data from a CSV file containing Speed Over Ground (SOG) values. Based on this data, the program performs two primary tasks:

1. Data Categorization: SOG values are divided into various categories such as "Very Slow", "Slow", "Medium", "Fast", "Very Fast", and "Critically Fast". The distribution of these categories is then displayed, and the program generates a bar chart to visualize this distribution.

2. Fuzzy Membership Generation: The program determines the membership functions for each speed category based on trapezoidal functions. These functions illustrate the degree to which each SOG value corresponds to different categories. The program then displays a graph showing the membership functions for each category. Subsequently, the program calculates and displays the degree of membership of each SOG value to each category.

Thus, the program analyzes the speed data and applies fuzzy logic to it for categorization and determination of the degree of membership to various categories. Let's consider a code fragment and the programming result based on the ship's Speed Over Ground (SOG) parameter:

Based on the software code, relevant graphs were generated that illustrate the ship's movement indicators based on its experimental data (Fig. 4).

```python
import pandas as pd
import matplotlib.pyplot as plt
import numpy as np
import skfuzzy as fuzz

# The path to the file
path = "C:\\Science\\fuzzy logic_1\\3.3+.csv"

def plot_category_distribution(data_path):
    # Loading Data
    data = pd.read_csv(data_path, delimiter=';')

    # Extracting SOG value and converting it to number format
    data['SOG'] = data['SOG'].str.replace(',', '.').astype(float)

    # Function for SOG categorization
    def categorize_sog(value):
        if 1 <= value <= 3:
            return "Very Slow"
        elif 4 <= value <= 7:
            return "Slow"
        elif 8 <= value <= 12:
            return "Moderate"
        elif 13 <= value <= 16:
            return "Fast"
        elif 17 <= value <= 19:
            return "Very Fast"
        else:
            return "Critically Fast"

    # Applying the categorization function
    data['Category'] = data['SOG'].apply(categorize_sog)

    # Displays the number of posts by category
    print(data['Category'].value_counts())

    # Distribution schedule
    data['Category'].value_counts().plot(kind='bar', color='skyblue')
    plt.title('Distribution of SOG values by category')
    plt.xlabel('Category')
    plt.ylabel('Number of records')
    plt.show()

def generate_fuzzy_membership(data_path):
    # Loading Data
    df = pd.read_csv(data_path, delimiter=";", decimal=",")
    sog = df['SOG'].values
```

```python
        # Definition of membership functions
    x_sog = np.arange(0, 31, 1)  # Speed range

    very_slow = fuzz.trapmf(x_sog, [0, 0, 1, 3])
    slow = fuzz.trapmf(x_sog, [1, 3, 4, 7])
    moderate = fuzz.trapmf(x_sog, [4, 7, 8, 12])
    fast = fuzz.trapmf(x_sog, [8, 12, 13, 16])
    very_fast = fuzz.trapmf(x_sog, [13, 16, 17, 19])
    critical_speed = fuzz.trapmf(x_sog, [17, 19, 20, 30])

    # Вывод графика
    plt.figure(figsize=(10, 6))
    plt.plot(x_sog, very_slow, 'b', label='Very Slow')
    plt.plot(x_sog, slow, 'g', label='Slow')
    plt.plot(x_sog, moderate, 'r', label='Moderate')
    plt.plot(x_sog, fast, 'c', label='Fast')
    plt.plot(x_sog, very_fast, 'm', label='Very Fast')
    plt.plot(x_sog, critical_speed, 'y', label='Critically Fast')
    plt.title('Accessory functions for SOG')
    plt.xlabel('Speed (knots)')
    plt.ylabel('Degree of affiliation')
    plt.legend(loc='upper right')
    plt.grid(True)
    plt.show()


    # Printing degree of membership values for each record in a file
    results = {
        'Very Slow': fuzz.interp_membership(x_sog, very_slow, sog),
        'Slow': fuzz.interp_membership(x_sog, slow, sog),
        'Moderate': fuzz.interp_membership(x_sog, moderate, sog),
        'Fast': fuzz.interp_membership(x_sog, fast, sog),
        'Very Fast': fuzz.interp_membership(x_sog, very_fast, sog),
        'Critically Fast': fuzz.interp_membership(x_sog, critical_speed, sog)
    }

    for key, value in results.items():
        print(f"{key}: {value}")

# Calling functions one by one
plot_category_distribution(path)
generate_fuzzy_membership(path)
```

Figure 3 – Software code for processing ECDIS experimental data

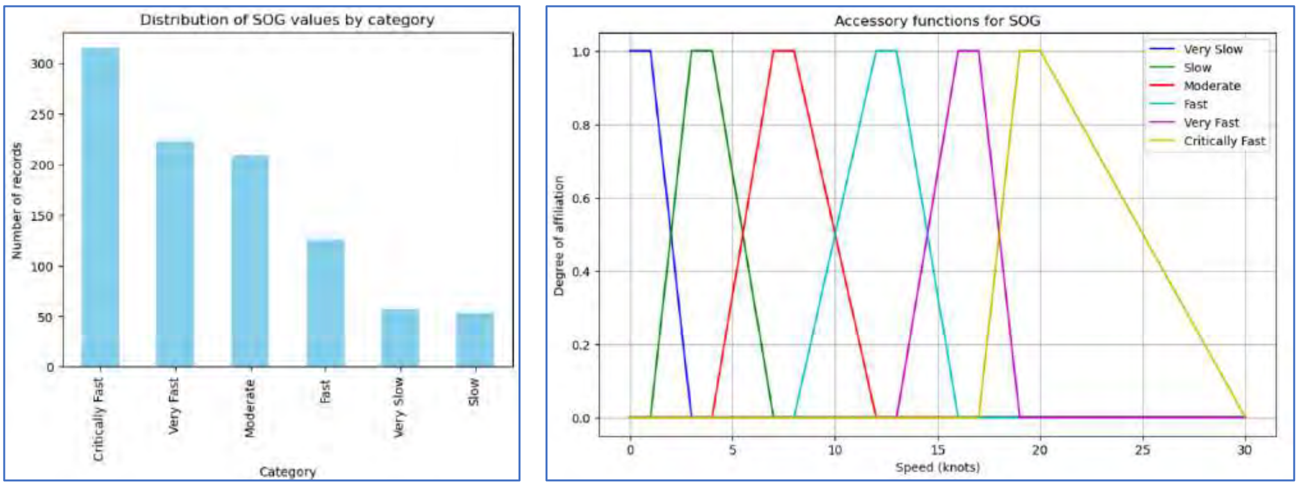


Figure 4 – Graphs of categorization and formulation of membership functions

The graphs depict two results of the program's operation:

1. Distribution of SOG values by categories.

The bar chart shows the distribution of Speed Over Ground (SOG) values across various categories. The "Critically Fast" category has the highest number of entries, making it the most prevalent in the presented data. The next most frequent categories are "Very Fast" and "Fast". The categories "Slow" and "Very Slow" are the least represented in the data.

2. Membership functions for SOG:

The graph displays the trapezoidal membership functions for different speed categories. Each line (color) represents a specific speed category, and their intersections indicate the fuzziness of a speed value's membership to one or another category. For instance, a speed of 5 knots has a certain degree of membership to the "Slow" and "Medium" categories, as can be seen from the intersection of the green and red lines.

Thus, the first research task has been accomplished, allowing us to proceed to the next steps within the overall objective.

The subsequent challenge is to formally describe the structure of the obtained fuzzy membership functions and to construct a fuzzy rule base for an intelligent system that identifies navigational risks in ship management. For this, types of membership functions [20–22] were analyzed and identified that can best describe a series of the following navigational parameters:

Proximity of oncoming vessels (Fig. 5):

$$\mu_{VFar}(x)=\begin{cases}0, & if\ x\le -0,36\\ \dfrac{x+0,36}{0,04+0,36} & if\ -0,36<x\le -0,04\\ 1, & if\ -0,04<x\le 0,04\\ \dfrac{0,22-x}{0,22-0,04} & if\ -0,04<x\le 0,22\\ 0, & if\ x>0,22\end{cases};\ \mu_{Far}(x)=\begin{cases}0, & if\ x\le 0,1\\ \dfrac{x+0,1}{0,16+0,1} & if\ 0,1<x\le 0,16\\ 1, & if\ 0,16<x\le 0,2\\ \dfrac{0,31-x}{0,31-0,2} & if\ 0,2<x\le 0,31\\ 0, & if\ x>0,31\end{cases};$$

$$\mu_{Moderate}(x)=\begin{cases}0, & if\ x\le 0,23\\ \dfrac{x-0,23}{0,28-0,23} & if\ 0,23<x\le 0,28\\ 1, & if\ 0,28<x\le 0,32\\ \dfrac{0,37-x}{0,37-0,32} & if\ 0,32<x\le 0,37\\ 0, & if\ x>0,37\end{cases};\ \mu_{Close}(x)=\begin{cases}0, & if\ x\le 0,31\\ \dfrac{x-0,31}{0,42-0,31} & if\ 0,31<x\le 0,42\\ 1, & if\ 0,42<x\le 0,46\\ \dfrac{0,62-x}{0,62-0,46} & if\ 0,46<x\le 0,62\\ 0, & if\ x>0,62\end{cases};$$

$$\mu_{VClose}(x)=\begin{cases}0, & if\ x\le 0,45\\ \dfrac{x-0,45}{0,59-0,45} & if\ 0,45<x\le 0,59\\ 1, & if\ 0,59<x\le 0,65\\ \dfrac{0,83-x}{0,83-0,65} & if\ 0,65<x\le 0,83\\ 0, & if\ x>0,83\end{cases};\ \mu_{TClose}(x)=\begin{cases}0, & if\ x\le 0,56\\ \dfrac{x-0,56}{0,96-0,56} & if\ 0,56<x\le 0,96\\ 1, & if\ 0,96<x\le 1,06\\ \dfrac{1,46-x}{1,46-1,06} & if\ 1,06<x\le 1,46\\ 0, & if\ x>1,46\end{cases}.$$

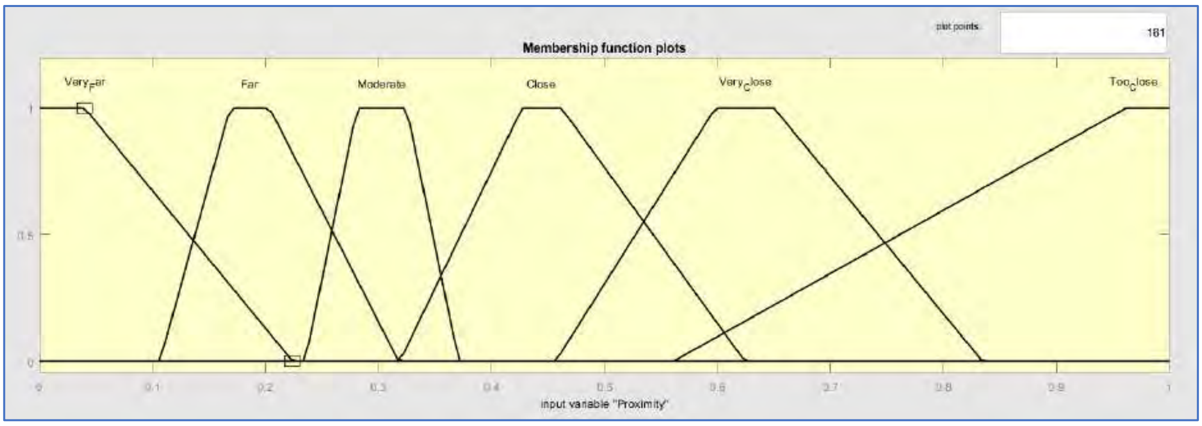


Figure 5 – Membership function: trapmf

2. Technical condition of the vessel (Fig. 6):

$$\mu_{Excellent}(x)=\begin{cases}0, & if\ x\le -0,26\, or\, x\ge 0,15\\ \dfrac{x-0,26}{0,25} & if\ -0,26\le x<0,00\\ 1, & if\ 0,00\le x<0,01\\ \dfrac{0,15-x}{0,13} & if\ 0,01\le x\le 0,15\end{cases};\ \mu_{Satisf}(x)=\begin{cases}0, & if\ x\le -0,08\, or\, x\ge 0,3\\ \dfrac{x+0,08}{0,25} & if\ -0,08\le x<0,18\\ 1, & if\ 0,18\le x<0,24\\ \dfrac{0,35-x}{0,1} & if\ 0,24\le x\le 0,35\end{cases};$$

$$\mu_{MinorHD}(x)=\begin{cases}0, & if\ x\le 0,25\, or\, x\ge 0,46\\ \dfrac{x+0,25}{0,08} & if\ 0,25\le x<0,33\\ 1, & if\ 0,33\le x<0,38\\ \dfrac{0,47-x}{0,08} & if\ 0,38\le x\le 0,47\end{cases};\ \mu_{MediumD}(x)=\begin{cases}0, & if\ x\le 0,34\, or\, x\ge 0,86\\ \dfrac{x+0,34}{0,148} & if\ 0,345\le x<0,49\\ 1, & if\ 0,49\le x<0,54\\ \dfrac{0,86-x}{0,323} & if\ 0,54\le x\le 0,86\end{cases};$$

$$\mu_{SevereD}(x)=\begin{cases}0, & if\ x\le 0,61\, or\, x\ge 0,9\\ \dfrac{x+0,61}{0,2} & if\ 0,61\le x<0,81\\ 1, & if\ 0,815\le x<0,817\\ \dfrac{0,9-x}{0,09} & if\ 0,817\le x\le 0,9\end{cases};\ \mu_{Critical}(x)=\begin{cases}0, & if\ x\le 0,84\, or\, x\ge 1,22\\ \dfrac{x-0,84}{0,107} & if\ 0,84\le x<0,95\\ 1, & if\ 0,95\le x<1\\ \dfrac{0,9-x}{0,09} & if\ 1\le x\le 1,22\end{cases}.$$

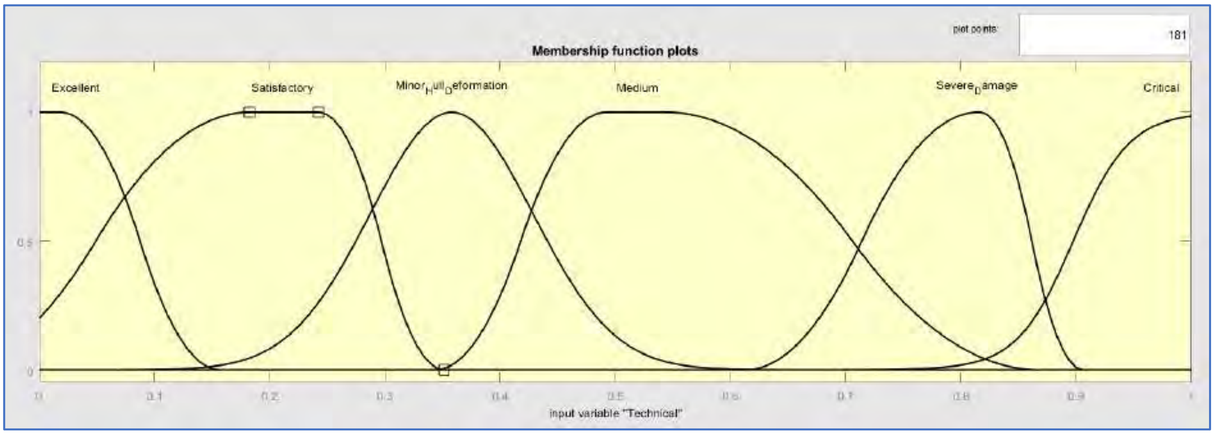


Figure 6 – Membership function: pimf

3. Proximity to dangerous isobaths and separation lines in straits (Fig. 7):

$$\mu_{VeryF}(x)=e^{-\frac{(x-0,175)^2}{2\times(-0.026)^2}};\quad \mu_{Far}(x)=e^{-\frac{(x-0,06)^2}{2\times 0.22^2}};$$

$$\mu_{Moderate}(x)=e^{-\frac{(x-0,04)^2}{2\times 0.37^2}};\quad \mu_{Close}(x)=e^{-\frac{(x-0,05)^2}{2\times 0.53^2}};$$

$$\mu_{VClose}(x)=e^{-\frac{(x-0,08)^2}{2\times 0.7^2}};\quad \mu_{TClose}(x)=e^{-\frac{(x-0,21)^2}{2\times 1^2}}.$$

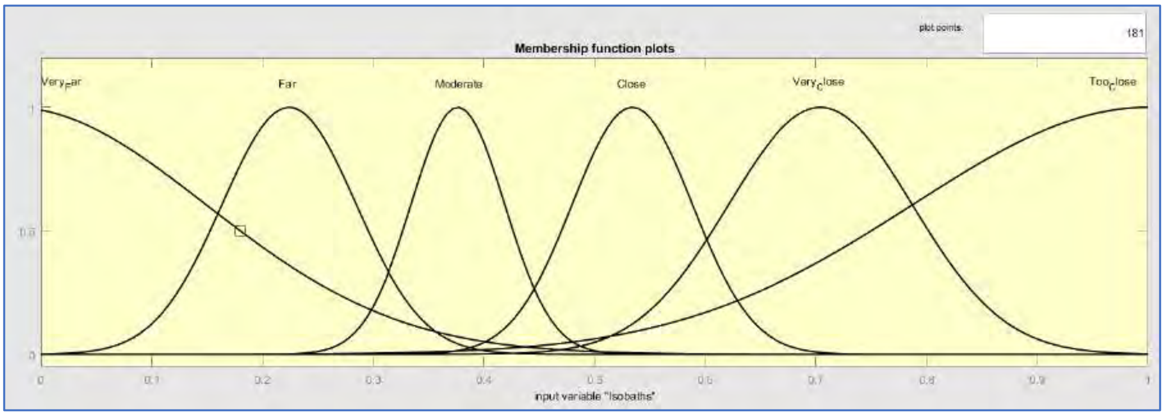


Figure 7 – Membership function: gaussmf

4. Currents (Fig. 8):

$$\mu_{Weak}\left(x\right)=\frac{1}{1+\left|\frac{x+0,01}{0,06}\right|^{2\frac{1}{3}}};\ \mu_{Moderate}\left(x\right)=\frac{1}{1+\left|\frac{x-0,17}{0,09}\right|^{2\frac{1}{2}}};$$

$$\mu_{Noticeable}\left(x\right)=\frac{1}{1+\left|\frac{x-0,35}{0,08}\right|^{2\frac{1}{2}}};\ \mu_{Strong}\left(x\right)=\frac{1}{1+\left|\frac{x-0,58}{0,05}\right|^{5\frac{2}{3}}};$$

$$\mu_{VStrong}\left(x\right)=\frac{1}{1+\left|\frac{x-0,77}{0,05}\right|^{5\frac{2}{3}}};\ \mu_{Critical}\left(x\right)=\frac{1}{1+\left|\frac{x-1}{0,1}\right|^{2\frac{1}{2}}}.$$

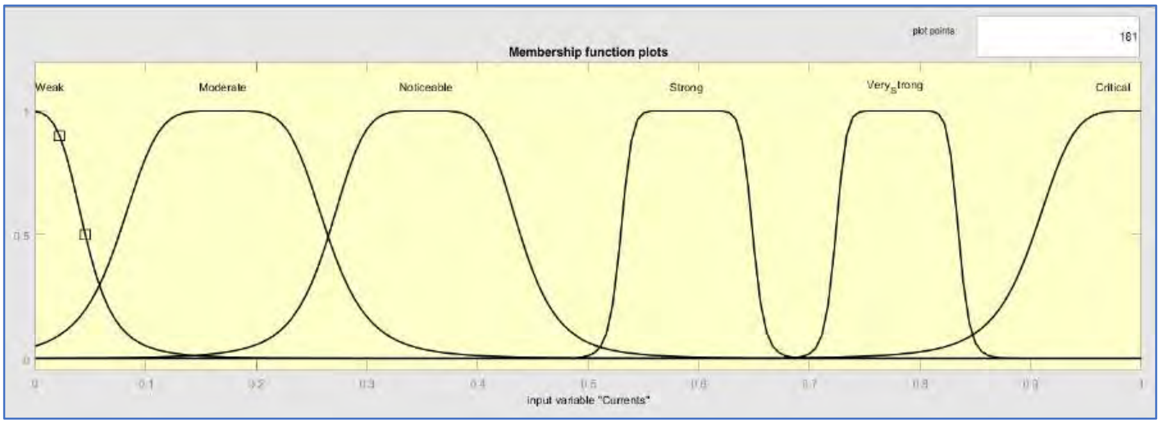


Figure 8 – Membership function: gbellmf

5. Wind (Fig. 9):

$$\mu_{Weak}\left(x_1\right)=\frac{x+0,4}{0,4};\qquad \mu_{Weak}\left(x_2\right)=\frac{0,12-x}{0,12};$$

$$\mu_{Moderate}\left(x_1\right)=\frac{x-0,03}{0,15-0,03};\ \mu_{Moderate}\left(x_2\right)=\frac{0,26-x}{0,26-0,15};$$

$$\mu_{Noticeable}\left(x_1\right)=\frac{x-0,17}{0,31-0,17};\ \mu_{Noticeable}\left(x_2\right)=\frac{0,45-x}{0,45-0,31};$$

$$\mu_{Strong}(x_1)=\frac{x-0,38}{0,5-0,38};\qquad \mu_{Strong}(x_2)=\frac{0,65-x}{0,65-0,5}$$

$$\mu_{VStrong}(x_1)=\frac{x-0,57}{0,69-0,57};\qquad \mu_{VStrong}(x_2)=\frac{0,82-x}{0,82-0,69}$$

$$\mu_{Critical}(x_1)=\frac{x-0,76}{0,93-0,76};\qquad \mu_{Critical}(x_2)=\frac{1,11-x}{1,11-0,93}$$

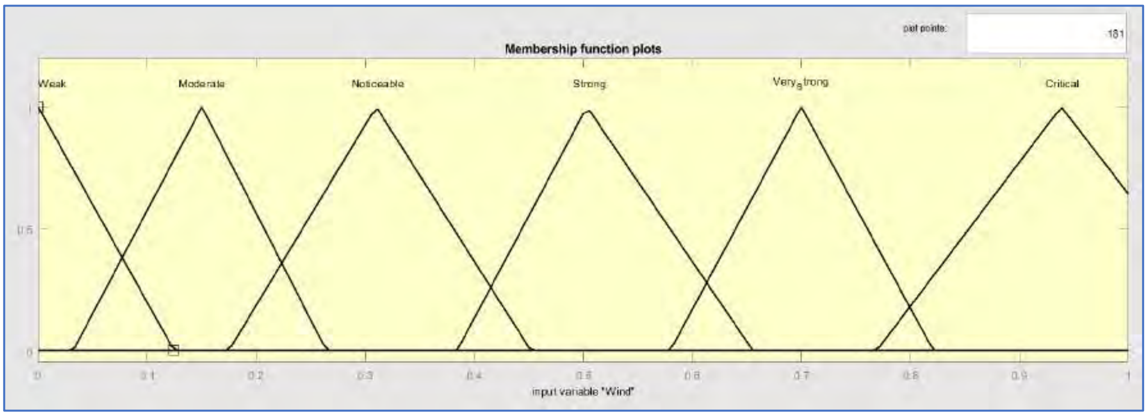


Figure 9 – Membership function: trimf

6. Visibility (Fig. 10):

$$\mu_{Excellent}(x)=\frac{1}{1+e^{-0,09(x-13,7)}}-\frac{1}{1+e^{94,85(x-0,17)}};$$

$$\mu_{Good}(x)=\frac{1}{1+e^{0,2(x-51,4)}}-\frac{1}{1+e^{39,3(x-0,32)}};$$

$$\mu_{Satisfactory}(x)=\frac{1}{1+e^{0,39(x-63,8)}}-\frac{1}{1+e^{66(x-0,55)}};$$

$$\mu_{Poor}(x)=\frac{1}{1+e^{0,5(x-17,4)}}-\frac{1}{1+e^{114(x-0,74)}};$$

$$\mu_{VPoor}(x)=\frac{1}{1+e^{0,78(x-130)}}-\frac{1}{1+e^{66,5(x-0,91)}};$$

$$\mu_{Critical}(x)=\frac{1}{1+e^{0,93(x-50,7)}}-\frac{1}{1+e^{36(x-1,17)}}.$$

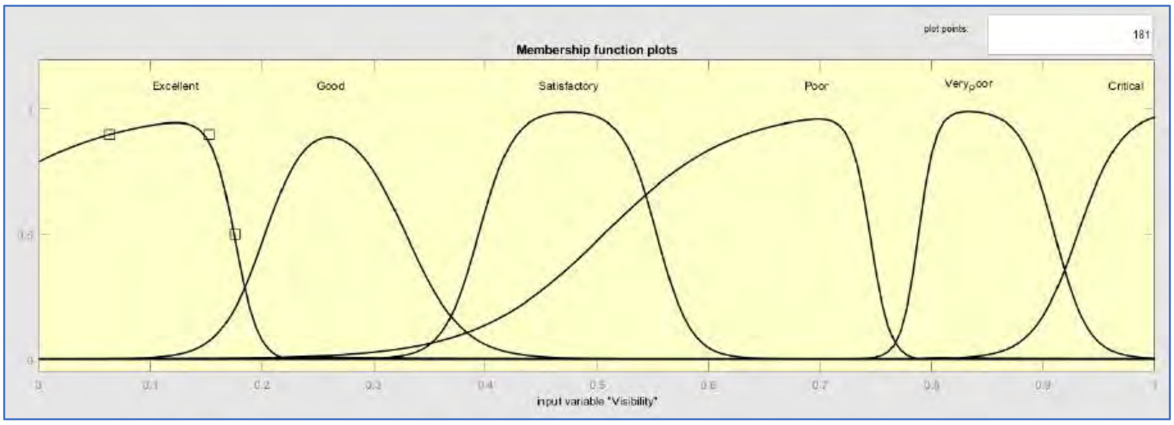


Figure 10 – Membership function: dsigmf

7. Current vessel speed (Fig. 11):

$$\mu_{VSlow}(x)=\begin{cases}0, & if\ x\le -0,36\\ \dfrac{x+0,36}{0,04+0,36} & if\ -0,36<x<-0,04\\ 1, & if\ -0,04\le x<0,18\\ \dfrac{0,18-x}{0,18-0,04} & if\ 0,04<x<0,18\\ 0 & if\ x\ge 0,18\end{cases};\quad \mu_{Slow}(x)=\begin{cases}0, & if\ x\le 0,04\\ \dfrac{x-0,04}{0,16-0,04} & if\ 0,04<x<0,16\\ 1, & if\ 0,16\le x<0,24\\ \dfrac{0,34-x}{0,34-0,24} & if\ 0,24<x<0,34\\ 0 & if\ x\ge 0,34\end{cases}$$

$$\mu_{Moderate}(x)=\begin{cases}0, & if\ x\le 0,25\\ \dfrac{x-0,25}{0,38-0,25} & if\ 0,25<x<0,38\\ 1, & if\ 0,38\le x<0,46\\ \dfrac{0,59-x}{0,59-0,46} & if\ 0,46<x<0,59\\ 0 & if\ x\ge 0,59\end{cases};\quad \mu_{Fast}(x)=\begin{cases}0, & if\ x\le 0,49\\ \dfrac{x-0,49}{0,59-0,49} & if\ 0,49<x<0,59\\ 1, & if\ 0,59\le x<0,65\\ \dfrac{0,75-x}{0,75-0,65} & if\ 0,65<x<0,75\\ 0 & if\ x\ge 0,75\end{cases}$$

$$\mu_{VFast}(x)=\begin{cases}0, & if\ x\le 0,66\\ \dfrac{x-0,66}{0,78-0,66} & if\ 0,66<x<0,78\\ 1, & if\ 0,78\le x<0,83\\ \dfrac{0,89-x}{0,89-0,83} & if\ 0,83<x<0,88\\ 0 & if\ x\ge 0,88\end{cases};\quad \mu_{Critical}(x)=\begin{cases}0, & if\ x\le 0,79\\ \dfrac{x-0,79}{0,78-0,66} & if\ 0,79<x<0,93\\ 1, & if\ 0,93\le x<1,04\\ \dfrac{1,44-x}{1,44-1,04} & if\ 1,04<x<1,44\\ 0 & if\ x\ge 1,44\end{cases}$$

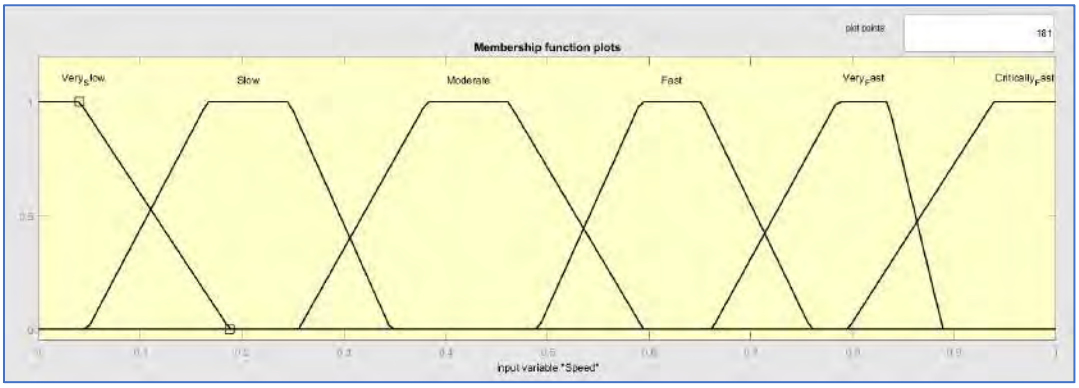


Figure 11 – Membership function: trapmf

8. Difficulty in maintaining the vessel's course (Fig. 12):

$$\mu_{VEasy}(x)=e^{-\frac{(x-0,06)^2}{2\times 0.0007^2}};\quad \mu_{Easy}(x)=e^{-\frac{(x-0,04)^2}{2\times 0.195^2}};$$

$$\mu_{Moderate}(x)=e^{-\frac{(x-0,09)^2}{2\times 0.36^2}};\quad \mu_{Difficult}(x)=e^{-\frac{(x-0,09)^2}{2\times 0.6^2}};$$

$$\mu_{VDifficult}(x)=e^{-\frac{(x-0,06)^2}{2\times 0.77^2}};\quad \mu_{CDifficult}(x)=e^{-\frac{(x-0,07)^2}{2\times 1^2}}.$$

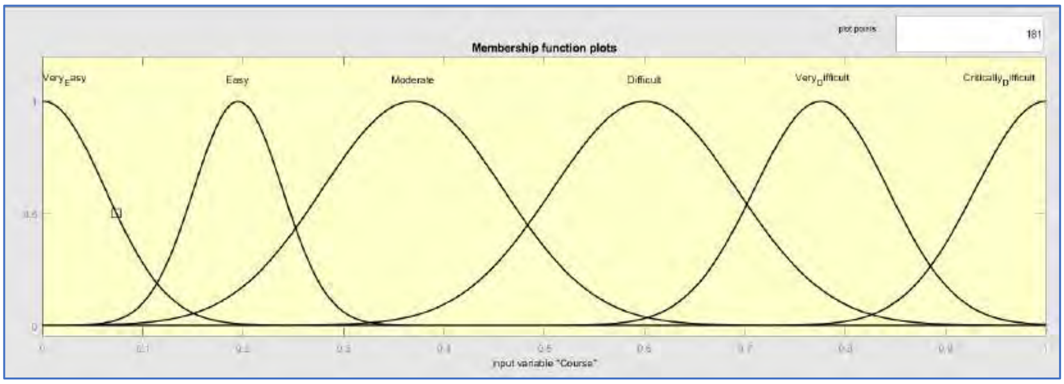


Figure 12 – Membership function: gaussmf

9. Time of day (Fig. 13):

$$\mu_{Day}(x)=\begin{cases}0, & if\ x\le -0,36\\ \dfrac{x+0,36}{0,04+0,36} & if\ -0,36<x<-0,04\\ 1, & if\ -0,04\le x<0,16\\ \dfrac{0,16-x}{0,16-0,04} & if\ 0,04<x<0,16\\ 0 & if\ x\ge 0,16\end{cases};\quad \mu_{Evening}(x)=\begin{cases}0, & if\ x\le 0,09\\ \dfrac{x-0,09}{0,13-0,09} & if\ 0,09<x<0,13\\ 1, & if\ 0,13\le x<0,21\\ \dfrac{0,34-x}{0,34-0,21} & if\ 0,21<x<0,34\\ 0 & if\ x\ge 0,34\end{cases}$$

$$\mu_{Dusk}(x)=\begin{cases}0, & if\ x\le 0,31\\ \dfrac{x-0,31}{0,36-0,31} & if\ 0,31<x<0,36\\ 1, & if\ 0,36\le x<0,44\\ \dfrac{0,58-x}{0,58-0,44} & if\ 0,44<x<0,58\\ 0 & if\ x\ge 0,58\end{cases};\quad \mu_{Night}(x)=\begin{cases}0, & if\ x\le 0,49\\ \dfrac{x-0,49}{0,55-0,49} & if\ 0,49<x<0,55\\ 1, & if\ 0,55\le x<0,65\\ \dfrac{0,78-x}{0,78-0,65} & if\ 0,65<x<0,78\\ 0 & if\ x\ge 0,78\end{cases};$$

$$\mu_{DNight}(x)=\begin{cases}0, & if\ x\le 0,68\\ \dfrac{x-0,68}{0,76-0,68} & if\ 0,68<x<0,76\\ 1, & if\ 0,76\le x<0,86\\ \dfrac{0,92-x}{0,92-0,86} & if\ 0,86<x<0,92\\ 0 & if\ x\ge 0,92\end{cases};\quad \mu_{Dawn}(x)=\begin{cases}0, & if\ x\le 0,81\\ \dfrac{x-0,81}{0,81-0,68} & if\ 0,81<x<0,92\\ 1, & if\ 0,92\le x<1,01\\ \dfrac{1,38-x}{1,38-1,01} & if\ 1,01<x<1,38\\ 0 & if\ x\ge 1,38\end{cases}.$$

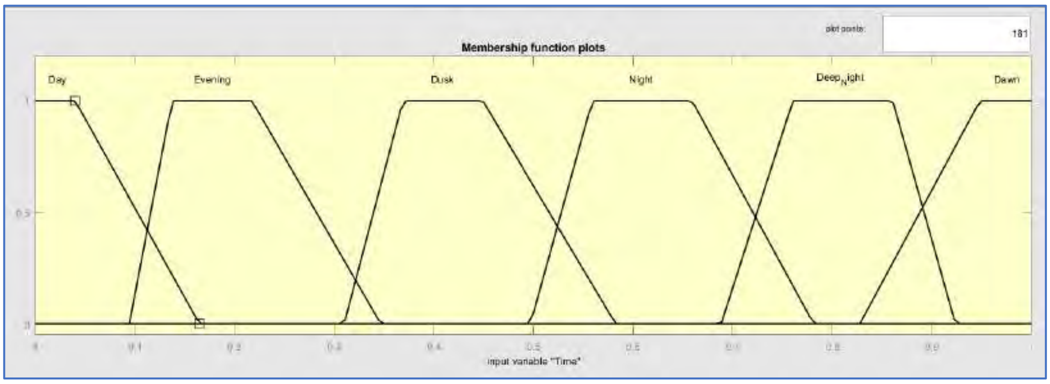


Figure 13 – Membership function: trapmf

10. Shipping intensity at the current route point (Fig. 14):

$$\mu_{VLow}(x)=\frac{1}{1+\left|\frac{x-0,02}{0,12}\right|^{4\frac{1}{2}}};\ \mu_{Low}(x)=\frac{1}{1+\left|\frac{x-0,26}{0,08}\right|^{4\frac{1}{2}}};$$

$$\mu_{Moderate}(x)=\frac{1}{1+\left|\frac{x-0,48}{0,06}\right|^{4}};\ \mu_{Hight}(x)=\frac{1}{1+\left|\frac{x-0,65}{0,05}\right|^{4\frac{1}{2}}};$$

$$\mu_{VHigh}(x)=\frac{1}{1+\left|\frac{x-0,8}{0,06}\right|^{4\frac{1}{2}}};\ \mu_{Critical}(x)=\frac{1}{1+\left|\frac{x-1}{0,07}\right|^{4\frac{1}{2}}}.$$

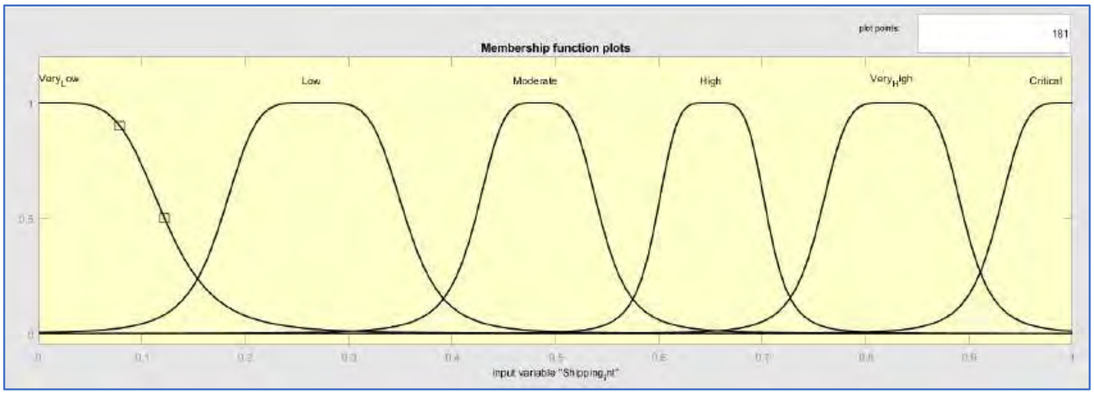


Figure 14 – Membership function: gbellmf

Thus, based on the experimental data, formal expressions of fuzzy membership functions of the type depicted in Figures 5–14 were obtained. Subsequently, fuzzy modeling will allow for the identification of factors stemming from the combination of basic qualification parameters concerning operations with navigational devices. Moreover, considering an individual qualification model will enable the determination of an individual level of danger in relation to the navigational situation based on fuzzy membership functions.

From the above, it follows that it is essential to transition to the task of simulation fuzzy modeling, taking into account the qualification model of the operator-navigator. In this context, it is necessary to investigate, based on the obtained experimental data, the influence of qualification parameters on the increase in the overall risk indicator during operations performed by the operator-navigator. For structuring, the language of fuzzy sets and fuzzy logic was utilized to determine risk and the number of factors based on various conditions and parameters. The rules are written in a structured format, commonly used for fuzzy control systems. This format allows for easy interpretation of how the system responds to different input parameters. The language used is represented by the syntax of the MATLAB Fuzzy Logic Toolbox software package for fuzzy modeling.

Let's formulate fuzzy rules regarding the Bosphorus location, based on observations:

```
IF (Proximity == Very_Far) OR (Technical == Excellent) OR (Isobaths == Very_Far) OR (Currents == Weak) OR (Wind == Weak) OR (Visibility == Excellent) OR (Speed == Very_Slow) OR (Course == Very_Easy) OR (Time == Day) OR (Shipping_int == Very_Low) THEN (Risk = Low) AND (Number_of_factors = Moderate)

IF (Proximity == Moderate) OR (Technical == Satisfactory) OR (Isobaths == Far) OR (Currents == Moderate) OR (Wind == Weak) OR (Visibility == Excellent) OR (Speed == Very_Slow) OR (Course == Critically_Difficult) OR (Time == Dawn) OR (Shipping_int == Critical) THEN (Risk = V_High) AND (Number_of_factors = Medium)
```

IF (Proximity == Very_Far) OR (Technical == Satisfactory) OR (Isobaths == Far) OR (Currents == Weak) OR (Wind == Weak) OR (Visibility == Excellent) OR (Speed == Slow) OR (Course == Difficult) OR (Time == Dawn) OR (Shipping_int == Very_Low) THEN (Risk = High) AND (Number_of_factors = Moderate)

IF (Proximity == Moderate) OR (Technical == Satisfactory) OR (Isobaths == Far) OR (Currents == Moderate) OR (Wind == Moderate) OR (Visibility == Good) OR (Speed == Slow) OR (Course == Critically_Difficult) OR (Time == Critical) OR (Shipping_int == Critical) THEN (Risk = High) AND (Number_of_factors = Moderate)

IF (Proximity == Moderate) OR (Technical == Satisfactory) OR (Isobaths == Close) OR (Currents == Moderate) OR (Wind == Moderate) OR (Visibility == Good) OR (Speed == Average) OR (Course == Difficult) OR (Time == Day) OR (Shipping_int == Medium) THEN (Risk = Moderate) AND (Number_of_factors = Medium)

IF (Proximity == Close) OR (Technical == Good) OR (Isobaths == Close) OR (Currents == Moderate) OR (Wind == Strong) OR (Visibility == Good) OR (Speed == Fast) OR (Course == Moderate) OR (Time == Dusk) OR (Shipping_int == High) THEN (Risk = V_High) AND (Number_of_factors = High)

IF (Proximity == Close) OR (Technical == Poor) OR (Isobaths == Very_Close) OR (Currents == Strong) OR (Wind == Strong) OR (Visibility == Poor) OR (Speed == Very_Fast) OR (Course == Very_Difficult) OR (Time == Night) OR (Shipping_int == Very_High) THEN (Risk = Critical) AND (Number_of_factors = Critical)

IF (Proximity == Very_Close) OR (Technical == Average) OR (Isobaths == Very_Close) OR (Currents == Average) OR (Wind == Average) OR (Visibility == Satisfactory) OR (Speed == Average) OR (Course == Moderate) OR (Time == Dusk) OR (Shipping_int == Medium) THEN (Risk = Moderate) AND (Number_of_factors = Medium)

IF (Proximity == Moderate) OR (Technical == Satisfactory) OR (Isobaths == Moderate) OR (Currents == Moderate) OR (Wind == Noticeable) OR (Visibility == Satisfactory) OR (Speed == Moderate) OR (Course == Very_Difficult) OR (Time == Night) OR (Shipping_int == High) THEN (Risk = High) AND (Number_of_factors = High)

IF (Proximity == Moderate) OR (Technical == Minor_Hull_Deformation) OR (Isobaths == Moderate) OR (Currents == Moderate) OR (Wind == Strong) OR (Visibility == Satisfactory) OR (Speed == Moderate) OR (Course == Difficult) OR (Time == Dusk) OR (Shipping_int == High) THEN (Risk = High) AND (Number_of_factors = Medium)

IF (Proximity == Too_Close) OR (Technical == Minor_Hull_Deformation) OR (Isobaths == Moderate) OR (Currents == Moderate) OR (Wind == Strong) OR (Visibility == Satisfactory) OR (Speed == Moderate) OR (Course == Very_Difficult) OR (Time == Evening) OR (Shipping_int == Very_High) THEN (Risk = V_High) AND (Number_of_factors = High)

IF (Proximity == Very_Close) OR (Technical == Medium) OR (Isobaths == Moderate) OR (Currents == Strong) OR (Wind == Strong) OR (Visibility == Satisfactory) OR (Speed == Very_Fast) OR (Course == Very_Difficult) OR (Time == Evening) OR (Shipping_int == Very_High) THEN (Risk = High) AND (Number_of_factors = High)

IF (Proximity == Very_Close) OR (Technical == Medium) OR (Isobaths == Moderate) OR (Currents == Strong) OR (Wind == Noticeable) OR (Visibility == Satisfactory) OR (Speed == Moderate) OR (Course == Very_Difficult) OR (Time == Dawn) OR (Shipping_int == Critical) THEN (Risk = V_High) AND (Number_of_factors = Medium)

IF (Proximity == Too_Close) OR (Technical == Minor_Hull_Deformation) OR (Isobaths == Close) OR (Currents == Noticeable) OR (Wind == Strong) OR (Visibility == Very_Poor) OR (Speed == Fast) OR (Course == Critically_Difficult) OR (Time == Night) OR (Shipping_int == Critical) THEN (Risk = V_High) AND (Number_of_factors = Medium)

IF (Proximity == Moderate) OR (Technical == Medium) OR (Isobaths == Close) OR (Currents == Strong) OR (Wind == Strong) OR (Visibility == Poor) OR (Speed == Very_Fast) OR (Course == Critically_Difficult) OR (Time == Night) OR (Shipping_int == High) THEN (Risk = V_High) AND (Number_of_factors = Medium)

IF (Proximity == Too_Close) OR (Technical == Minor_Hull_Deformation) OR (Isobaths == Moderate) OR (Currents == Noticeable) OR (Wind == Strong) OR (Visibility == Poor) OR (Speed == Fast) OR (Course == Very_Difficult) OR (Time == Evening) OR (Shipping_int == Very_High) THEN (Risk = High) AND (Number_of_factors = Medium)

IF (Proximity == Very_Close) OR (Technical == Minor_Hull_Deformation) OR (Isobaths == Moderate) OR (Currents == Strong) OR (Wind == Strong) OR (Visibility == Poor) OR (Speed == Very_Fast) OR (Course == Critically_Difficult) OR (Time == Night) OR (Shipping_intensity == Very_High) THEN (Risk == Very_High) AND (Number_of_factors == High)

IF (Proximity == Too_Close) OR (Technical == Medium) OR (Isobaths == Close) OR (Currents == Very_Strong) OR (Wind == Very_Strong) OR (Visibility == Satisfactory) OR (Speed == Moderate) OR (Course == Critically_Difficult) OR (Time == Night) OR (Shipping_intensity == Critical) THEN (Risk == Very_High) AND (Number_of_factors == High)

```
IF (Proximity == Too_Close) OR (Technical == Medium) OR (Isobaths == Very_Close) OR (Currents == Strong) OR (Wind == Very_Strong) OR (Visibility == Satisfactory) OR (Speed == Poor) OR (Course == Fast) OR (Time == Deep_Night) OR (Shipping_intensity == Very_High) THEN (Risk == Very_High) AND (Number_of_factors == High)

IF (Proximity == Very_Close) OR (Technical == Medium) OR (Isobaths == Moderate) OR (Currents == Noticeable) OR (Wind == Very_Strong) OR (Visibility == Very_Poor) OR (Speed == Fast) OR (Course == Critically_Difficult) OR (Time == Deep_Night) OR (Shipping_intensity == Critical) THEN (Risk == Very_High) AND (Number_of_factors == High)

IF (Proximity == Close) OR (Technical == Medium) OR (Isobaths == Very_Close) OR (Currents == Strong) OR (Wind == Very_Strong) OR (Visibility == Very_Poor) OR (Speed == Fast) OR (Course == Very_Difficult) OR (Time == Dusk) OR (Shipping_intensity == Very_High) THEN (Risk == High) AND (Number_of_factors == High)

IF (Proximity == Too_Close) OR (Technical == Medium) OR (Isobaths == Very_Close) OR (Currents == Very_Strong) OR (Wind == Strong) OR (Visibility == Critical) OR (Speed == Fast) OR (Course == Critically_Difficult) OR (Time == Dawn) OR (Shipping_intensity == Critical) THEN (Risk == Very_High) AND (Number_of_factors == High)

IF (Proximity == Very_Close) OR (Technical == Medium) OR (Isobaths == Close) OR (Currents == Critical) OR (Wind == Very_Strong) OR (Visibility == Critical) OR (Speed == Very_Fast) OR (Course == Difficult) OR (Time == Evening) OR (Shipping_intensity == High) THEN (Risk == High) AND (Number_of_factors == High)

IF (Proximity == Very_Close) OR (Technical == Medium) OR (Isobaths == Close) OR (Currents == Strong) OR (Wind == Very_Strong) OR (Visibility == Critical) OR (Speed == Very_Fast) OR (Course == Critically_Difficult) OR (Time == Night) OR (Shipping_intensity == Critical) THEN (Risk == Very_High) AND (Number_of_factors == High)

IF (Proximity == Very_Close) OR (Technical == Severe_Damage) OR (Isobaths == Far) OR (Currents == Critical) OR (Wind == Noticeable) OR (Visibility == Very_Poor) OR (Speed == Critically_Fast) OR (Course == Difficult) OR (Time == Dusk) OR (Shipping_intensity == High) THEN (Risk == Medium_High) AND (Number_of_factors == High)

IF (Proximity == Close) OR (Technical == Severe_Damage) OR (Isobaths == Far) OR (Currents == Critical) OR (Wind == Strong) OR (Visibility == Very_Poor) OR (Speed == Very_Fast) OR (Course == Very_Difficult) OR (Time == Evening) OR (Shipping_intensity == Very_High) THEN (Risk == Medium_High) AND (Number_of_factors == High)

IF (Proximity == Too_Close) OR (Technical == Severe_Damage) OR (Isobaths == Close) OR (Currents == Critical) OR (Wind == Noticeable) OR (Visibility == Very_Poor) OR (Speed == Critically_Fast) OR (Course == Difficult) OR (Time == Night) OR (Shipping_intensity == Critical) THEN (Risk == Medium_High) AND (Number_of_factors == High)

IF (Proximity == Very_Close) OR (Technical == Minor_Damage) OR (Isobaths == Far) OR (Currents == Very_Strong) OR (Wind == Noticeable) OR (Visibility == Very_Poor) OR (Speed == Fast) OR (Course == Very_Difficult) OR (Time == Dusk) OR (Shipping_intensity == High) THEN (Risk == Medium) AND (Number_of_factors == Medium)

IF (Proximity == Close) OR (Technical == Minor_Damage) OR (Isobaths == Far) OR (Currents == Strong) OR (Wind == Noticeable) OR (Visibility == Critical) OR (Speed == Very_Fast) OR (Course == Critically_Difficult) OR (Time == Evening) OR (Shipping_intensity == High) THEN (Risk == Medium) AND (Number_of_factors == Medium)

IF (Proximity == Too_Close) OR (Technical == Minor_Damage) OR (Isobaths == Close) OR (Currents == Very_Strong) OR (Wind == Very_Strong) OR (Visibility == Very_Poor) OR (Speed == Critically_Fast) OR (Course == Difficult) OR (Time == Night) OR (Shipping_intensity == Critical) THEN (Risk == Medium_High) AND (Number_of_factors == Medium)
```

The formulated rules will be incorporated into the Mamdani rule base [23] (Fig. 15, 16):

1. Fuzzy Rule Activation (1):

For each rule R_i, $i = 1, 2, ..., 30$, the degree of truthfulness of the rule is determined:

$$\alpha_{R_i} = T\left(\mu_{A_1}(x_1), \mu_{A_2}(x_2), ..., \mu_{A_m}(x_m)\right), \tag{1}$$

where T is the T-norm (the "and" operation in fuzzy logic),

μ_{A_j} is the membership function for the input variable x_i,

x_i the i-th input variable.

2. Fuzzy Implication (2):

Using fuzzy implication, we derive the conclusions for each rule:

$$B_i^* = I\left(\alpha_{R_i}, B_i\right), \quad (2)$$

where B_i^* the conclusion or output for the i-th rule after its activation,
I is the implicational function (often, the Minimum or Product is used),
B_i the i-th output set or variant.

3. Aggregation of All Conclusions (3):
All individual conclusions are aggregated into a single overall membership function:

$$B^* = S\left(B_1^*, B_2^*, \ldots, B_n^*\right), \quad (3)$$

where B^* the overall aggregated membership function for all conclusions,
S is the S-norm (the "or" operation in fuzzy logic).

4. Defuzzification (4):
Using a defuzzification method, we obtain a crisp output value. Typically, the Center of Gravity (COG) method is used:

$$y^* = \frac{\int y\mu_{B^*}(y)dy}{\int \mu_{B^*}(y)dy}, \quad (4)$$

where y^* is the crisp output value,
$\mu_{B^*}(y)$ the aggregated membership function for the output value y,
y the output value being integrated over all possible variants.

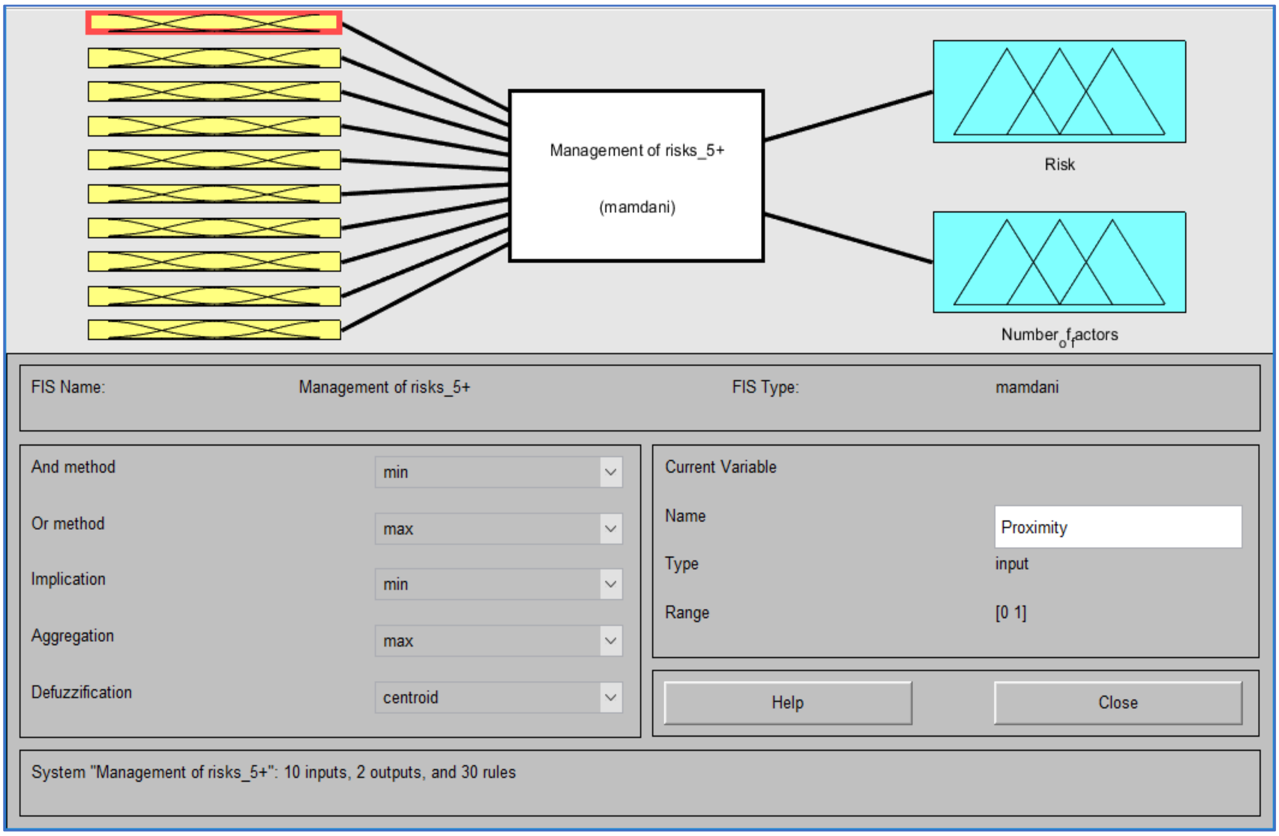


Figure 15 – Construction of the fuzzy inference system

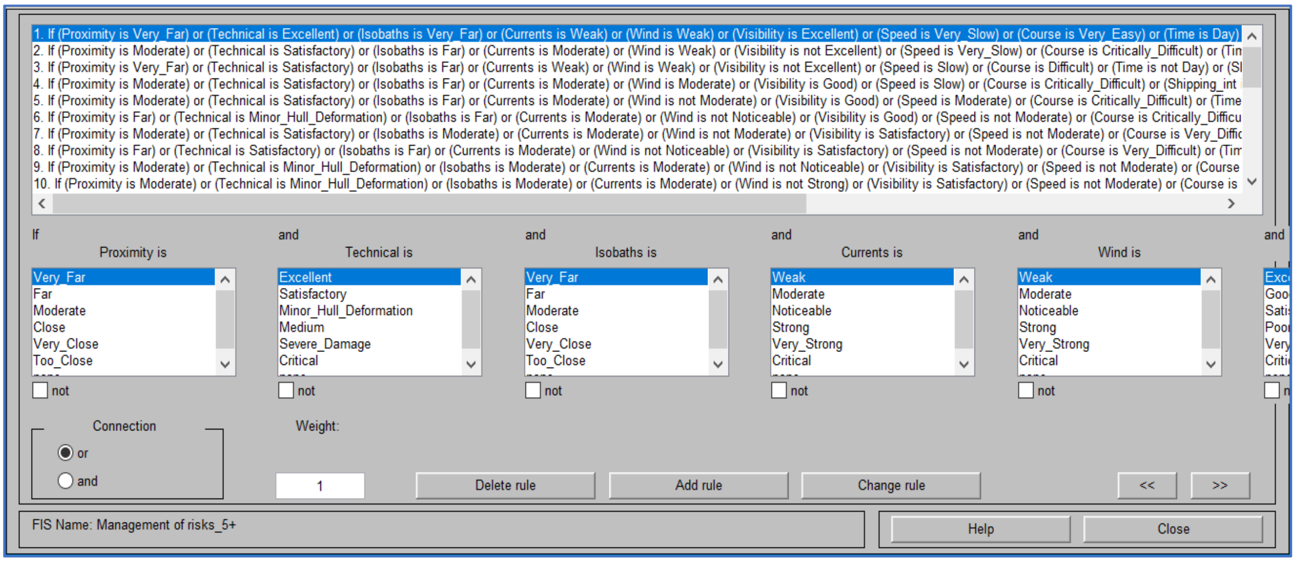


Figure 16 – Formation of the fuzzy rules system

Let's consider the first waypoint in the Bosphorus strait and the risk formulation concerning a neutral situation, with indicators of 0,5 and 0,636 related to the factors (Fig. 17 *a*, *b*) to trajectory (Fig. 18).

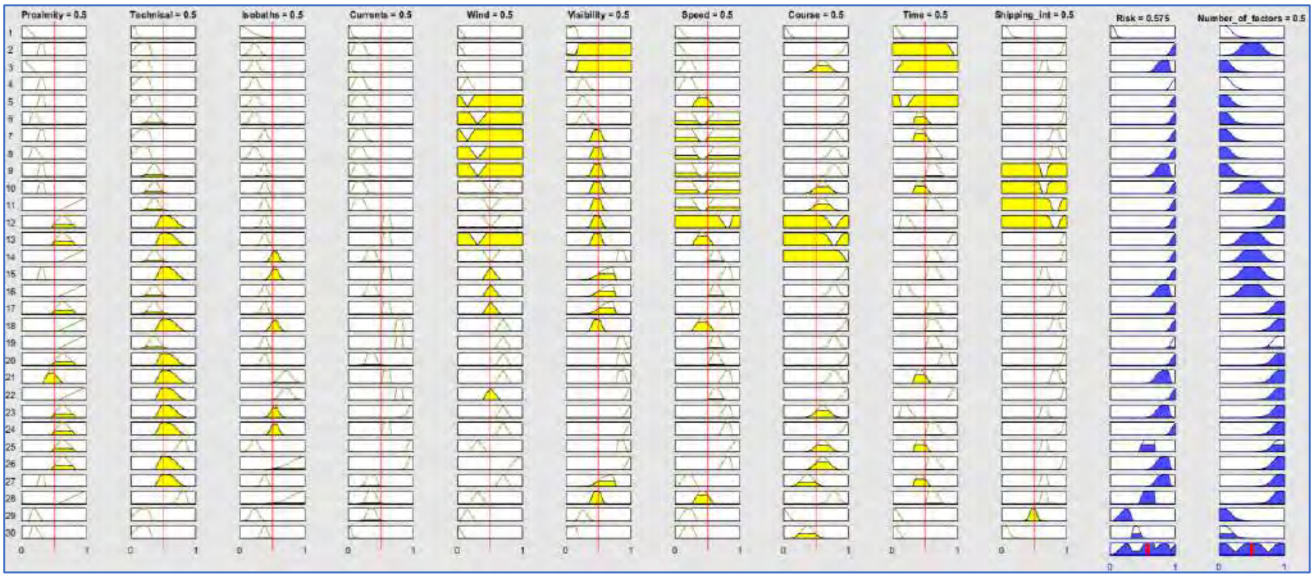
In terms of modeling results for the first waypoint, the following groups can be distinguished:

1. Rule activation: Many rules are activated at the given input values, especially those corresponding to input data equal to 0,5. This is indicated by yellow triangles in the respective columns for each rule.

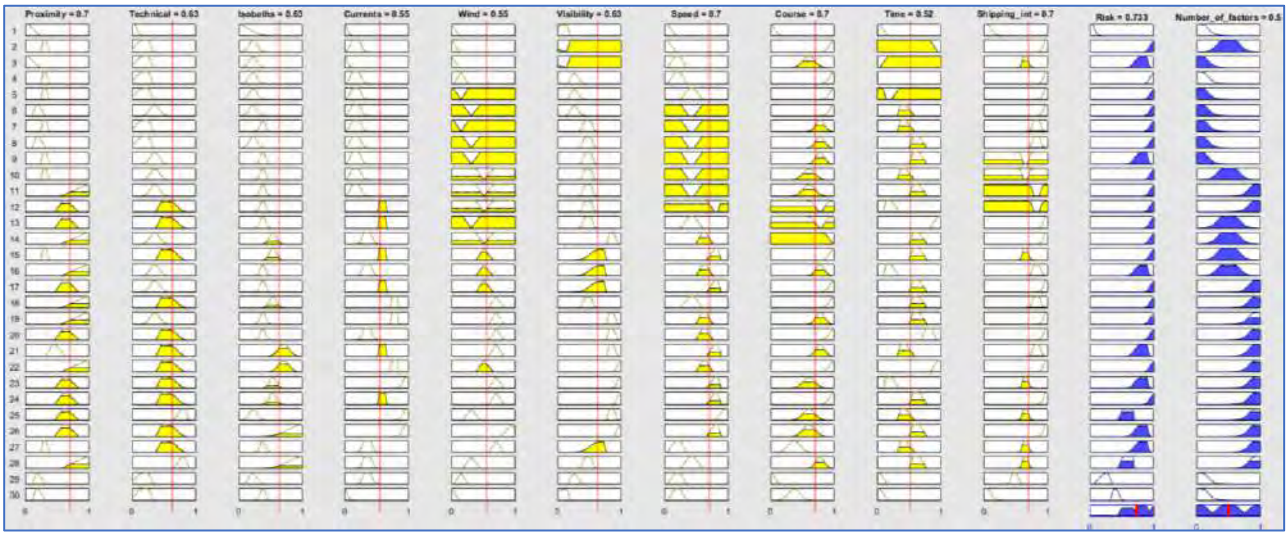
2. Risk distribution: Risk varies depending on the activated rules. Some rules lead to a higher level of risk (closer to 1), while others result in a lower risk level (closer to 0).

3. Parameter activation: "Proximity", "Technical", and "Isobaths" are mostly activated at the 0,5 level. "Currents", "Wind", and "Visibility" also have activations, but not in all rules. "Speed", "Course", "Time", and "Shipping_int" are activated at various levels in different rules.

4. Overall risk: Considering the provided input data, the overall risk is 0,575. This value might be the result of aggregation or defuzzification of the outcomes from individual rules.



a



b

Figure 17 – Fuzzy risk analysis at the first waypoint of the Bosphorus strait:
a - average risk indicators within 0.5 at the beginning of the route
b - risk indicators in the central Bosphorus strait within 0.636 of the risk range

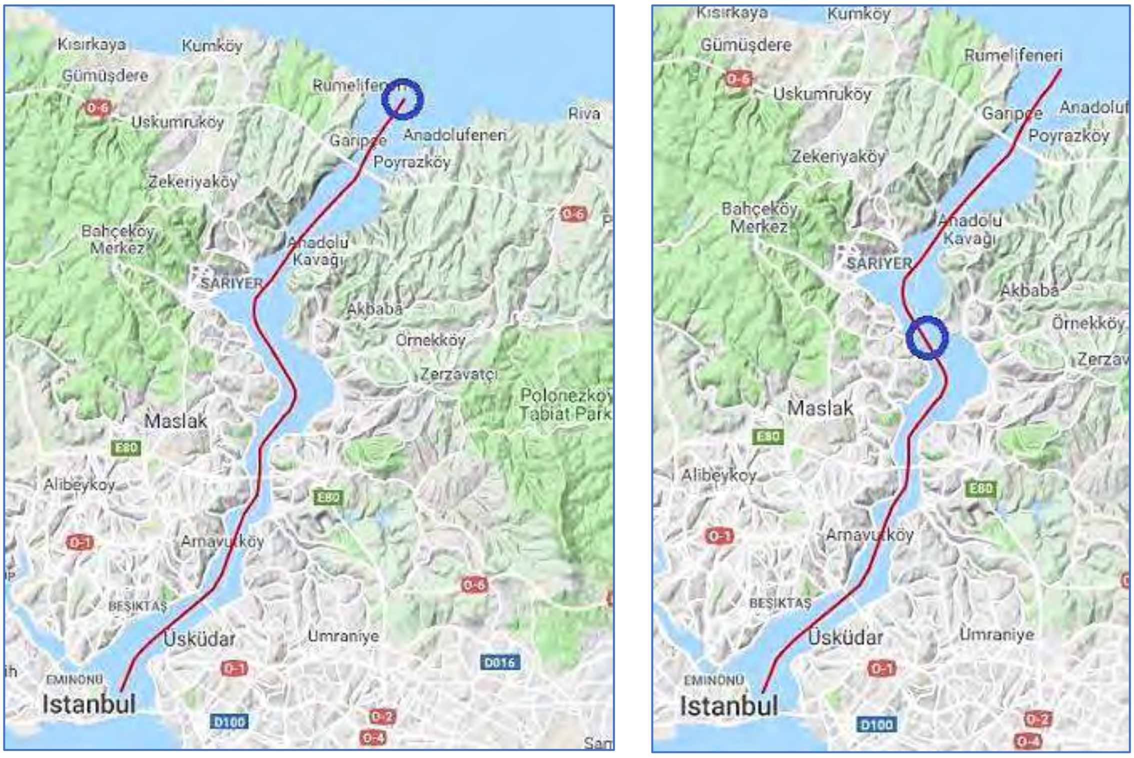


Figure 18 – Position of the vessel in the Bosphorus Strait relative to the trajectory of the vessel's route

Next, let's consider a situation where deviations in the qualification parameters of a particular shipmaster are evident. The operator's model code concerning key navigational factors is as follows: [0,7; 0,63; 0,63; 0,55; 0,55; 0,63; 0,7; 0,7; 0,52; 0,7]. This code describes the qualification level regarding each parameter, developed during training, simulator courses, and shipmaster experience in similarly complex sailing areas.

Despite the overall qualification level changing only slightly to 0,636, the risk has increased. This could classify the situation as "dangerous" since the factors demand high qualification values that are evidently lacking at this particular point in the strait. Deviations from the average value of 0,5 for each navigational parameter are accounted for by adding the missing fractions relative to the qualification parameter, thereby increasing the risk.

Overall, based on the presented chart (Fig. 18), the risk management systems indicate a relatively high risk (evaluated at 0,733) for the given set of input data. Active rules, especially in categories such as "Proximity of oncoming vessels", "Wind", "Speed", and "Course", highlight their significant influence on the overall risk assessment. Consequently, we will investigate these indicators separately (Fig. 19 *a*–*d*).

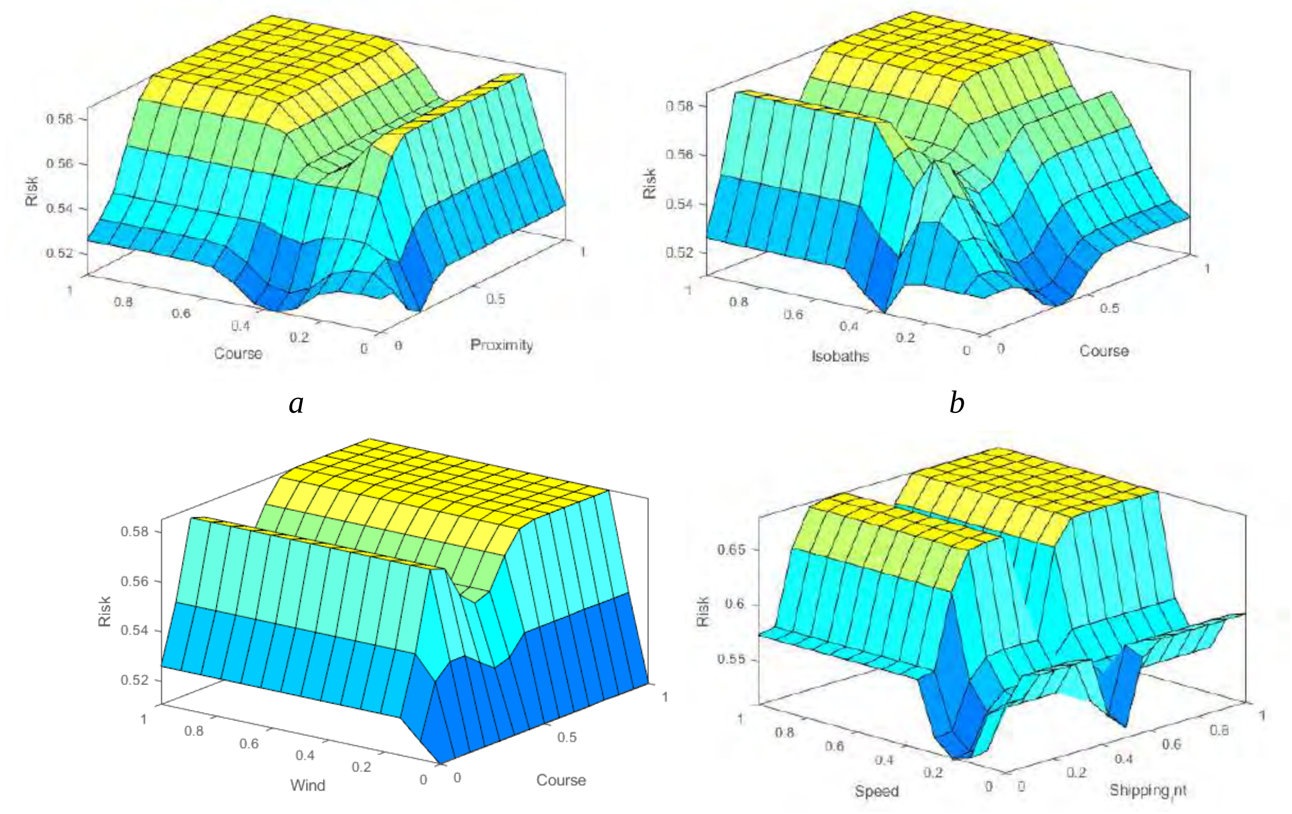


Figure 19 – Surface plots of primary factor categories influencing overall risk
a – attitude Course and Proximity; b – attitude Isobaths and Course;
c – attitude Wind and Course; d – attitude Speed and Shipping

As evidenced by the surface plots (Fig. 19), the qualification factor for the ability to manage the course, termed "Course", is pivotal and typically amplifies the risk in most scenarios. The interplay of other factors such as "Proximity", "Isobaths", "Wind", and "Shipping_nt" also play a crucial role in determining the overall risk, as affirmed by the dynamics of the surfaces depicted in the presented graphs.

It's essential to note that not all of the 30 available rules are activated, highlighting the specificity of the situation under consideration. The indicator for the number of navigational equipment demanding attention at this particular route point has also remained unchanged.

Conclusion. Within the scope of this research, and in line with its objectives, the automated processing of ECDIS experimental data in complex navigational areas was achieved. This phase helped reduce subjectivity in determining parameters of fuzzy membership functions concerning various navigational factors. Consequently, this allowed for the construction of a fuzzy forecasting system. Based on the derived fuzzy membership functions, their formal structure was identified, and a fuzzy rule base was established. This base is utilized by an intelligent system for identifying navigational risks while managing vessels under challenging conditions.

To determine the efficacy of the proposed fuzzy system, a simulation-based fuzzy modeling was conducted, taking into account the qualification model of the ship operator. Analysis of the experimental data revealed how qualification parameters impact the escalation of the overall risk index during vessel management.

As a result, it can be inferred that the navigator's qualification readiness significantly influences the criticality of a situation, introducing an element of uncertainty into the tasks of vessel safety and reliability. Modeling outcomes demonstrated that with a minor increase in individual parameters, the overall risk could surge by 15,8%, categorizing the situation as "dangerous" or even "critical."

All these findings indicate that risk forecasting is dependent on the specified segment of qualification parameters of a particular navigator-operator. By generalizing qualification parameters for each route waypoint, there arises the potential for anticipatory data retrieval about predicted hazards, thereby enabling risk management amidst the uncertainty of human factors.

The study successfully confirmed the feasibility of identifying qualification parameters of ship operators in intricate navigational situations using intelligent systems based on fuzzy logic. The findings can be leveraged to refine ship management systems and enhance maritime safety.

Prospects for further research might involve the collaborative use of the developed system with other artificial intelligence-based systems to establish more sophisticated management structures. Additionally, analyzing and modeling the behavioral aspects of ship operators aims to refine the risk identification system and, consequently, optimize and enhance existing algorithms considering new data and studies in the field of fuzzy logic.

The primary focus will be exploring the possibilities of integrating the devised automated system with other onboard systems, such as automatic control systems or collision avoidance systems.

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Пономарьова Вікторія, Носов Павло МЕТОД АВТОМАТИЗОВАНОЇ ІДЕНТИФІКАЦІЇ КВАЛІФІКАЦІЙНИХ ПАРАМЕТРІВ ДЛЯ МОРСЬКИХ ОПЕРАТОРІВ В УМОВАХ РИЗИКУ

Мета дослідження – підвищення безпеки мореплавства шляхом застосування методу ідентифікації та прогнозування кваліфікаційних параметрів операторів-судноводіїв на основі нечіткої логіки.

Основна проблема дослідження полягає у необхідності контролю над внутрішніми факторами невизначеності дій оператора-судноводія та створення системи, яка ідентифікує його кваліфікаційні параметри для забезпечення безпеки прийняття рішень у складних навігаційних умовах.

Методика дослідження включає в себе: а) алгоритм автоматичної обробки даних ECDIS для зменшення суб'єктивності у визначенні нечітких функцій приналежності відносно навігаційних факторів; б) формалізацію структури нечітких функцій та побудову бази правил для ідентифікації ризиків при керуванні судном у складних умовах плавання; і в) імітаційне нечітке моделювання, яке досліджує вплив кваліфікаційних параметрів на загальний показник ризику керування рухом судна.

Результати дослідження полягають у створенні інтелектуальної системи, що прогнозує навігаційні ризики у складних умовах плавання. За допомогою імітаційного моделювання виявлено, що кваліфікаційні параметри операторів-судноводіїв істотно впливають на ризик при управлінні судном. Наприклад, підвищення параметрів за чотирма показниками може значно збільшити загальний ризик, на 15,8%, переводячи ситуацію в небезпечну або критичну категорію.

Практична значущість представлена результативністю автоматизованої обробки даних ECDIS, яка зменшила суб'єктивні помилки та удосконалила прогнозування навігаційних ризиків. Виявлений вплив кваліфікаційних параметрів операторів-судноводіїв на рівень ризику підкреслює важливість індивідуалізації прогнозу, що адаптовано до конкретного оператора. Практична цінність також полягає в потенціалі поліпшення безпеки мореплавства завдяки точному прогнозуванню та управлінню ризиками, враховуючи людський фактор кожного оператора. Майбутні дослідження будуть направлені на інтеграцію методу в інші системи управління рухом судна, створюючи ще більш ефективні інструменти підтримки прийняття рішень оператора в умовах внутрішньої невизначеності. Бібл. 23 рис. 19.

***Ключові слова**: автоматизація; організаційно-технічні системи; ризик; інтелектуальні системи; кваліфікаційні параметри; ідентифікація; нечітка логіка; невизначеність.*

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