Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2020, 61 (133), 83–88
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/403

Received: *23.10.2019*
Accepted: *05.12.2019*
Published: *25.03.2020*

Improvement of good seamanship using specialized processes and algorithms onboard ships, in fleet operation centers, and in simulations

Łukasz Przeniosło[1]✉, Jörg Peschke[2], Jörg Hering[2]

[1] Westpomeranian University of Technology, Electrical Engineering Faculty
Department of Power Systems and Electrical Drives
e-mail: lukasz.przenioslo@zut.edu.pl
[2] MacGregor Germany GmbH & Co. KG, Germany
e-mail: {joerg.peschke; joerg.hering}@macgregor.com
✉ corresponding author

Key words: good seamanship, fuzzy logic, holistic algorithms, data fusion, maritime risk, vessels safety

Abstract
The recent rapid improvement of nautical equipment functionality allows one to better observe and predict the dangers related to seamanship. However, these new features come with added complexity, and large amounts of information can overwhelm vessel crews and fleet operation centers, and the current state-of-the-art tools cannot filter out only the most important data for a given time and location. This paper presents the concepts and the algorithms of a software suite that provides a user with problem-oriented advice about a particular risk endangering a vessel and its crew. Based on the calculated navigational dangers and their predicted development, actionable guidance is proposed in an easy-to-understand human language. The quality of good seamanship is improved by a holistic approach to vessel installation, automated fleet operation center priority queuing, and the evaluation of crew performance during simulator training and daily operations. Both the software user interface, as well as the insights provided by the algorithm, are discussed.

Introduction

Human error is a constant variable when it comes to sea navigation. By nature, humans make mistakes, and by investing efforts into self-development, mistakes can only be reduced but never entirely eliminated (Dekker, 2014). Human error is involved in nearly 80% of maritime-related accidents (Baker & McCafferty, 2005), and the vast number of sensors and instruments available on a vessel's bridge and inside fleet operation centers are believed to contribute to such errors. The operational application of these tools introduces some problems: they are not designed as a comprehensive and centralized system, but rather as a distributed system divided into modules that do not directly interact with each other, since they are produced as separate products, by different manufacturers (Weintrit, 2013). This system feature can further lead to an information overflow for operators in challenging or unclear situations since each device is encapsulated within its own environment (for example, it may have its own user interface, such as an LCD screen) (Manley, 2008).

As a result, the system provided to aid the user in the acquisition and processing of navigational data is not helpful but instead makes a given task even more difficult. In order to address such issues, a novel approach for maritime data processing and evaluation is presented in this paper, along with a description of the centralized ecosystem permitting its facile usage. To this end, the proposed system utilizes a fuzzy logic based algorithm that takes into account more than forty static and dynamic input parameters that are further processed via data fusion mechanisms. The main distinguishing feature of this method is that it utilizes so-called "linguistic" variables in addition to simple numerical variables (Zadeh, 1973). By using the available input parameters during a voyage, it is possible to provide a numerically-based expression of the current situation in terms of various hazards endangering the vessel and its crew.

System description

The proposed solution works as part of the vessel environment presented in Figure 1. Each ship-supported system consists of a data distribution module (later referred to as DDM) – basically a computer program serving as a node for gathering and merging various information (such as sensors placed along the vessel, weather, or crew data). The MRP (maritime risk processor) is the node in which the computation and data fusion is performed. The required input parameters are provided to the MRP via the DDM, which gathers data from all available sources.

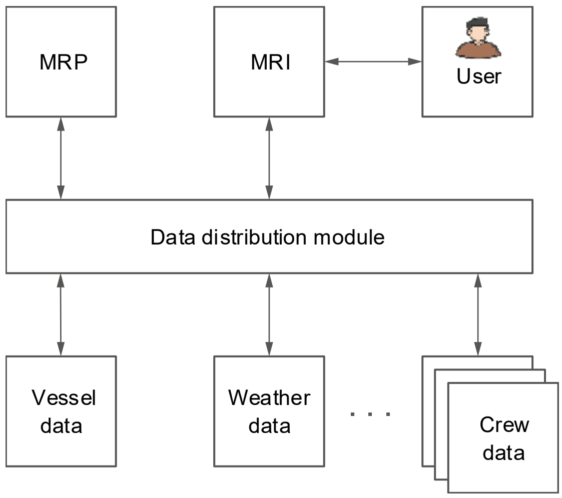

Figure 1. System data acquisition and distribution through the data distribution module (DDM) – the block diagram

Apart from the information that is automatically obtained (such as vessel speed, wind direction, or power generated by the engine), there are parameters that must be provided by the user. An example of such data is the information on which crew members are currently at the bridge. Another example is data that cannot be automatically gathered because a sensor is broken or missing. To satisfy the former, each crew member should register their presence on the watch, i.e. via biometric sensor installed at the bridge. For the latter, a GUI (graphical user interface) is used to enter all of the missing parameters. This program, described in Figure 1 as an MRI (maritime risk indicator), can be executed locally on the DDM vessel or remotely in a fleet operation center. The application can be used to enter missing parameters, but it is mainly used to present the MRP outputs to the user in a human-readable way.

A computation performed in the MRP block is presented to a user in the MRI block, via the DDM block, as presented in Figure 1. The user (either a local vessel crewmember or a remote fleet operation center operator) doesn't interact with the calculation program directly, but rather via dedicated, specialized interface.

Process goals

The end user output from the computation block consists of six specific nautical risk levels, expressed as a normalized number and readable description of the situation related to a certain risk. The six supported risks are:

1. COLL: the likelihood of a collision with another sea object (such as ships);
2. GROU: the likelihood of the vessel running to ground in shallow waters;
3. TRAC: the likelihood of the vessel going off its planned route (not reaching the destination in time or at all);
4. ENVI: the likelihood of the vessel being immobilized or drawn because of environmental conditions (such as waves or wind);
5. MANN: the likelihood of the vessel being immobilized or drawn because of manning-related reasons (insufficient number of crewmembers or their lack of knowledge, experience, or training);
6. ECON: the likelihood of the vessel being immobilized due to economic reasons (i.e. a vessel running out of fuel).

Figure 2 presents the MRI application running on an Android device.

The program is compatible with five operating system platforms (Windows, Linux, Mac OS, Android, and iOS/ iPadOS). The risk levels are shown for all mentioned indicators and can have values that range from 0.00 to 1.00, where 0.00 means there is no risk, and 1.00 represents the highest possible risk level.

The main user interface component is a hexagon (also referred to as the "Risk Spider"), which is visible in the bottom part in Figure 2. The longer the "arm" of a certain risk is, the higher its value. The same information is presented in a purely numerical form in the top part of Figure 2 under the "current risk indicators" section. When a risk level reaches

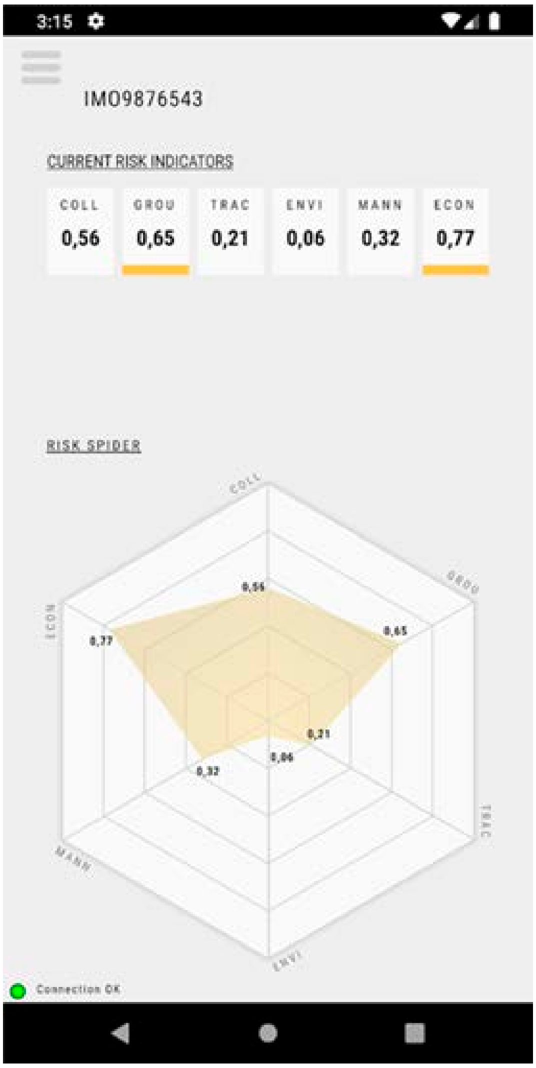

Figure 2. The MRI application running on a Pixel 2 XL Android 9.0 smartphone

Figure 3. A popup window showing the current risk description after its indicator was clicked or tapped by the user (in this example, the ECON indicator)

a predefined threshold, the internal hexagon shape and the corresponding indicator change colors (to yellow at the "warning" threshold and red at the "critical" threshold) in order to draw user attention more efficiently. The application also allows the user to view the description related to each risk after clicking its indicator (Figure 3). This text is an indirect output from the MRP block and is automatically generated in real-time when the risk levels and MRP inputs change.

When the MRI application is used in a fleet operation center, the number of supported vessels can be greater than one. In this case, the communication link between the MRI and DDM shown in Figure 1 is established remotely via the internet.

Figure 4 presents an additional user interface window available in the MRI in the "multivessel" mode. In this example, two remote vessels are being handled, and clicking on a vessel thumbnail brings the view from Figure 2 for that vessel.

To summarize, the system's aim is to minimize the visual overhead (for the crew and fleet operating center operators) required to maintain good seamanship, i.e. having a safe voyage. This is done by

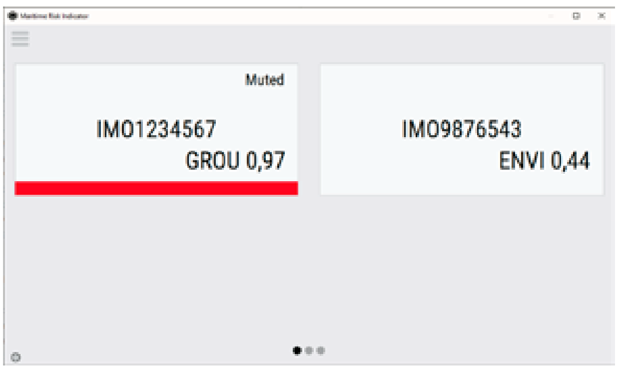

Figure 4. The MRI application running within Windows operating system in a fleet operation center, showing two different vessels "thumbnails" with the most important information in them (vessel ID and the highest risk)

reducing the number of handled parameters from several dozen to six basic risk values.

Theory of operation

In order to estimate the output value of a single risk, neither an algebraic attempt nor a classical closed-loop control approach (such as a PID controller) is sufficient. For the former, this is due to the fact that there are no clear and proportional correlations between the input and output values, thus, no single equation can be given. The latter suffers from the same shortcomings as the former, as well a number of input parameters that is so great that the number of series/parallel connected controllers would be too high, making the process very difficult to compile in practice (Åström & Hägglund, 2006; Bolton, 2015).

To this end, the MRP computation block utilizes a fuzzy logic control scheme since it is better suited for systems with multiple inputs that are not directly derived from each other (Ibrahim, 2004).

As stated in the process goals section, the aim is to give the user subjective, short, and readable information about the current situation. Since the fuzzy logic approach is designed to mimic how a human makes decisions and understands data (Wang, 1994), there is a second reason why this method was utilized in the algorithm. As an example, the estimation of the tracking risk level value will be presented. Figure 5 shows the top-level calculation block diagram. Many independent input parameters are fused in the processing module to produce a single risk value. Some of them are static (i.e. the vessel's breadth or length), and some change in real-time (i.e. vessel speed or draft). The watchman vigilance factor is an internal, unitless coefficient expressing (in a simplified way) the level of knowledge and experience of the person on watch. The navigation mode is an enumerator that indicates the type of waters (environment) in which the vessel is cruising. The possible types are:

- voyage in an open sea,
- voyage near the coast,
- voyage in the traffic separation lane,
- approaching another sea object,
- the ship is at anchor,
- voyage in a fairway (channel).

The vessel stopping distance characteristics is a static two-dimensional vector array. It expresses the required distance to stop the vessel at a given speed (the stopping distance [m] in a function of the vessel's speed [m/s]). It is prepared beforehand and is provided for the algorithm as a static data set. In order to interpolate the required stopping distance at the current vessel speed, a Lagrange polynomials-based method is utilized. It is suitable since the given set of velocity points does not consist of any identical value data, and the characteristics are nonlinear (Fortuna, Macukow & Wąsowski, 2015).

For example, if we assume that the stopping distance must be calculated for a ship velocity of 17.5 kts, the given input data is:

X – the current velocity,
$x_1, x_2, x_3, \ldots, x_n$ – the velocity characteristics vector,
$y_1, y_2, y_3, \ldots, y_n$ – the stopping distance characteristics vector,

$$L(x) = \sum_{i=0}^{k} y_i l_i(x) \tag{1}$$

$$l_1 = \frac{(X - x_2)\cdot(X - x_3)\cdot\ldots\cdot(X - x_n)}{(x_1 - x_2)\cdot(x_1 - x_3)\cdot\ldots\cdot(x_1 - x_n)}$$
$$l_2 = \frac{(X - x_1)\cdot(X - x_3)\cdot\ldots\cdot(X - x_n)}{(x_2 - x_1)\cdot(x_2 - x_3)\cdot\ldots\cdot(x_2 - x_n)}$$
$$l_3 = \frac{(X - x_1)\cdot(X - x_2)\cdot\ldots\cdot(X - x_n)}{(x_3 - x_1)\cdot(x_3 - x_2)\cdot\ldots\cdot(x_3 - x_n)}$$
$$\vdots$$
$$l_n = \frac{(X - x_1)\cdot(X - x_2)\cdot\ldots\cdot(X - x_n)}{(x_n - x_1)\cdot(x_n - x_2)\cdot\ldots} \tag{2}$$

The interpolation polynomial in the Lagrange form is presented in Equation (1), which is a linear combination of Lagrange base polynomials (Equation (2)). The simplified form of Equation (1) is then presented in Equation (3):

$$L = l_1 \cdot y_1 + l_2 \cdot y_2 + l_3 \cdot y_3 + \ldots + l_n \cdot y_n \tag{3}$$

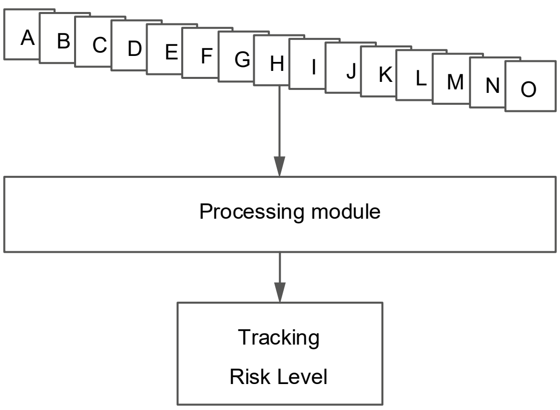

Figure 5. Top-level tracking risk level estimator block diagram. The input parameters are: A) track error [m], B) ship breadth [m], C) overwater speed [kts], D) ship length [m], E) maneuver radius under the keel, F) radar antenna distance [m], G) vessel rear draft [m], H) vessel front draft [m], I) total vessel draft [m], J) keel clearance limit [m], K) water depth along the fairway, L) water depth under the keel [m], M) watchman vigilance factor, N) navigation mode, O) vessel stopping distance characteristics

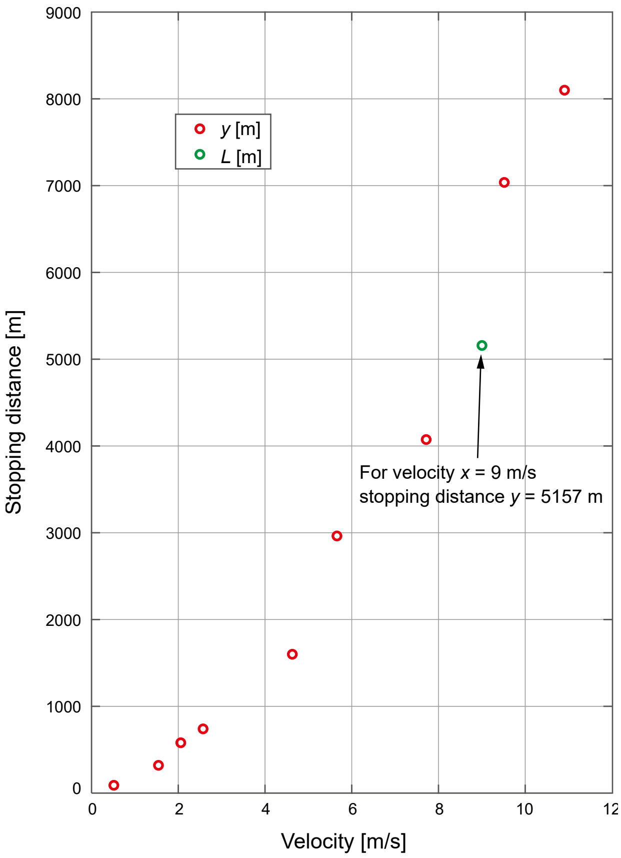

Figure 6. Exemplary stopping distance characteristics. A Lagrange polynomials method was used to find the stopping distance for a vessel at speed of 17.5 kts (~9 m/s)

Figure 6 presents the calculated stopping distance for a given velocity of 17.5 kts (the data point values shown in Figure 6 x and y were not explicitly mentioned in order to not obfuscate the presented equations). The calculated stopping distance becomes a direct input for an internal process module (Figure 7).

The calculations inside sub-process module 2 will be explained (Figure 7) since they are not complicated and do not require much space to explain. First, the ratio of the utilized space under the keel to the available space is calculated using Equation (4) (an analogous equation is also applied in the GROU risk procedure calculations).

$$\text{Ratio} = \left| \frac{L+I}{J+I} \right| \tag{4}$$

where:

L – current water depth under the keel,

I – the total/maximum vessel draft (front or rear draft; whichever is greater),

J – the keel clearance limit.

Next, the fuzzy rules table based on expert knowledge (Table 1) is utilized to obtain the inputs for the summing and averaging module. Similar methods

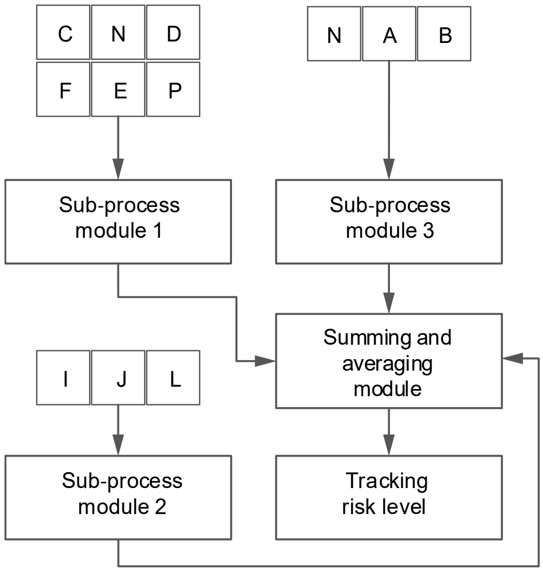

Figure 7. The processing module (Figure 5) sub-block schematics. The newly introduced *P* parameter represents the calculated stopping distance [m] (Equation (3))

based on fuzzy tables are used in sub-process modules 1 and 3. Their internals are omitted here due to space limitations. After obtaining all three outputs, they are merged in the summing and averaging module. The first step inside this block is to find the difference quotient of the membership functions for the given fuzzy sets (Equation (5)). The standard (typical) to sub-module output compliments ratio (y_n) is obtained and normalized with a predefined weight:

$$y_n = \frac{1-a}{1-b_n} w_n \tag{5}$$

where:

n – sub-process module index,

a – a typical output value for an acceptable risk within good seamanship boundaries,

b_n – sub-process module of index n output value (see Table 1),

w_n – preassigned weight coefficient.

Table 1. Sub-process 2 output fuzzy rules set

Ratio	Output
≤ 1.2	0.95
> 1.2 && ≤ 1.25	0.9
> 1.25 && ≤ 1.3	0.85
> 1.3 && ≤ 1.35	0.8
> 1.35 && ≤ 1.4	0.75
> 1.4 && ≤ 1.5	0.7
> 1.5 && ≤ 1.6	0.6
> 1.6 && ≤ 1.7	0.5
> 1.7 && ≤ 1.8	0.4
> 1.8 && ≤ 1.9	0.2
> 1.9	0

The final risk value is obtained via summing and averaging the outputs from the sub-modules (Equation (5)). This is an indication between "no risk at all" and "highest possible risk" (Equation (6)):

$$\text{Risk}_i = \frac{y_1 + y_2 + y_3}{w_1 + w_2 + w_3} w_i \tag{6}$$

where:

i – the risk index (from 0 to 5),

w_i – risk-specific weight. For the tracking risk, it is the watchman vigilance factor.

The remaining risks (COLL, GROU, ENVI, MANN, ECON) are obtained via a similar method at the end. The difference is how the input parameters are fused into usable *b* values (Equation (5)).

An additional note must be made about the output interpretation. Even though the given processes are fuzzy logic-based, this does not require the risk values to be thread because they were ambiguous, in a sense of their membership level. That is, a GROU output of 0.5 does not suggest that the vessel is already 50% grounded (assuming the level of being completely grounded was given). It suggests (in an intuitive sense) that there is a 50% probability of grounding soon under the given conditions.

Probability theory and fuzzy logic theory tend to answer different questions: "whether" and "how much" (Kosko, 1990). However, probability and fuzziness have common features, such as (Łukasiewicz, 2011; Heald, 2017):

- fuzzy logic is based on a Lukasiewicz's probabilistic logic,
- membership functions and density functions are similar to each other, and their values range from 0 to 1,
- unclear linguistic terms can be taken as probabilistic terms,
- fuzzy logic theory can be viewed as probability theory, but not vice versa.

Based on the described qualities, it is fair to interpret the algorithm outputs as risks based on the dictionary definition of "risk" (Merriam-Webster, 2019).

Conclusions

The data distribution module ecosystem (Figure 1) provides a feasible way for a vessel's crew and fleet operation center operators to monitor the various possible events endangering a ship. It is performed by using a method that allows excess information to be filtered out and the current situation to be narrowed down to six human-readable risk levels and their descriptions. The depicted algorithm can be used to simulate how an actual person would react to various danger indicators as if their data acquisition and processing capacities were significantly greater. The algorithm does not intend to replace a human operator, but rather to aid him in the bottleneck areas instead.

By the end of the year, there are plans to finish the simulations, as well as the "in the field" testing procedures. If successful, future plans are to develop an additional module based on neural network technology which will provide risk trends for both the near and far future, based on historical input parameters and the behavior of human operators.

References

1. Åström, K.J. & Hägglund, T. (2006) *Advanced PID control.* ISA – The Instrumentation, Systems, and Automation Society.
2. Baker, C.C. & McCafferty, D.B. (2005) *Accident database review of human-element concerns: what do the results mean for classification?* London: The Royal Institution.
3. Bolton, W. (2015) *Mechatronics: Electronic Control Systems in Mechanical and Electrical Engineering.* 6th Edition. Pearson Educational Limited.
4. Dekker, S. (2014) *The Field Guide to Understanding 'Human Error'.* 3th Edition. Routledge.
5. Fortuna, Z., Macukow, B. & Wąsowski, J. (2015) *Metody Numeryczne.* Warszawa: WNT.
6. Heald, G. (2017) The Similarities between Fuzzy Logic and Probability. *ResearchGate*, April.
7. Ibrahim, A.M. (2004) *Fuzzy Logic for Embedded Systems Applications.* Elsevier Science (USA).
8. Kosko, B. (1990) Fuzzines vs. Probability. *International Journal of General Systems* 17, 2–3, pp. 211–240.
9. Łukasiewicz, D. (2011) On Jan Łukasiewicz's many-valued logic and his criticism of determinism. *Philosophia Scientiae, Studies in the history of Science and Philosophy*, pp. 7–20.
10. Manley, P. (2008) *Practical Navigation for the Modern Boat Owner: Navigate Effectively by Getting the Most Out of Your Electronic Devices.* 1st Edition. Fernhurst Books Limited.
11. Merriam-Webster (2019) *Difinition of 'risk'.* [Online] Available from: https://www.merriam-webster.com/dictionary/risk [Accessed: October 20, 2019].
12. Ross, T.J. (2004) *Fuzzy Logic With Engineering Applications.* 2nd Edition. John Wiley & Sons Ltd.
13. Wang, L.-X. (1994) *Adaptive fuzzy systems and control: design and stability analysis.* Prentice Hall.
14. Weintrit, A. (2013) *Marine Navigation and Safety of Sea Transportation: Advances in Marine Navigation.* 1st Edition. CRC Press.
15. Zadeh, L.A. (1973) Outline of a New Approach to the Analysis of Complex Systems and Decision Processes. *IEEE Transactions on Systems, Man, and Cybernetics* SMC-3, 1, pp. 28–44.