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Aim:

Journal of Eta Maritime Science (JEMS) aims to encourage and publish research studies about the challenges and opportunities associated with considerable numbers of understandings in the maritime sector. Besides, JEMS also aims to reach out to relevant audiences by publishing the latest scientific and technological developments. JEMS journal, which is published periodically and regularly in March, June, September, December, may also publish special issues related to the selected topics.

Scope:

Scope of the journal covers national, international and local studies regarding Marine Engineering, Marine Transportation Engineering, Naval Architecture Engineering, Marine Operations, Logistics, Logistics Engineering, Maritime History, Coastal Engineering, Marine Pollution and Environment, Fishing and Fisheries Technology, Shipbuilding and Ocean Engineering.

JEMS is indexed in **Web of Science Emerging Sources Citation Index (ESCI), TRID, Tubitak Ulakbim Science Database, Index Copernicus International, Directory of Open Access Journals (DOAJ)**, **EBSCO** and **J-Gate**.

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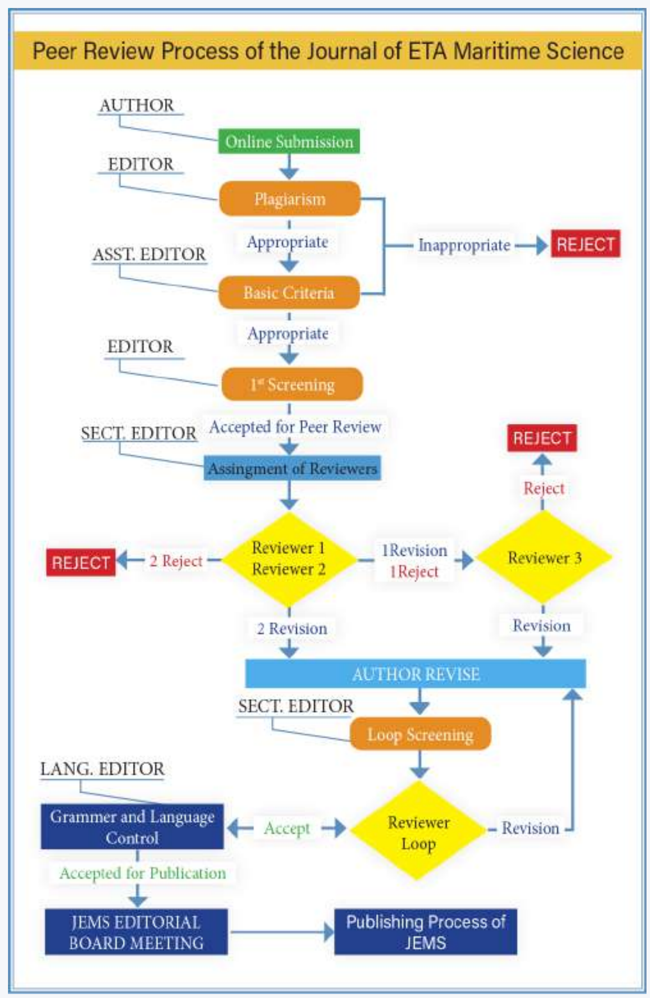

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Guide for Authors

Abstract

This sample includes the manuscript preparation guideline of Journal of ETA Maritime Science (JEMS). In the abstract section, a brief indicating the novelty and main findings of the study should be written. The text of the abstract should be written fully justified, in italics and 10 pt. The section should be no more than 200 words. The number of keywords should be between 3-5.

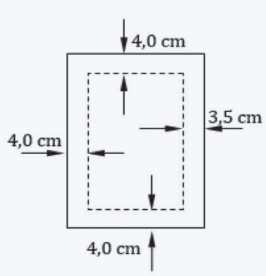
Keywords: JEMS, Author, Manuscript, Guide

1. Introduction

Journal of Eta Maritime Science (JEMS) aims to encourage and publish research studies about the challenges and opportunities associated with considerable numbers of understandings in the maritime sector. Besides, JEMS also aims to reach out to relevant audiences by publishing the latest scientific and technological developments. JEMS journal, which is published periodically and regularly, may also publish special issues related to the selected topics. Scope of the journal covers national, international and local studies regarding Marine Engineering, Maritime Transportation Engineering, Naval Architecture Engineering, Marine Operations, Logistics, Logistics Engineering, Maritime History, Coastal Engineering, Marine Pollution and Environment, Fishing and Fisheries Technology, Shipbuilding and Ocean Engineering

2. Page Layout and Format

JEMS publishes studies conducted in **English**. Text is to be prepared with justified alignment, without indentation in the paragraph beginning, in **"Cambria"** format with **10-point** font size and **1,0** line- spacing. There must be **initially 6nk and then 3nk** line spacing between the new launching paragraph and the previous paragraph. Worksheets must be on **A4** paper size, and margins should b**e 4 cm from the top, 4 cm from the bottom, 4 cm from left** and **3.5 cm from right**.



Studies must be submitted online from the journal's web address (http://www.jemsjournal.org). Articles printed or within CD, articles submitted by mail, fax etc., is not acceptable.

The main title of the article must be written in English and should be **set centered** in **12 point-size. Initially, 6nk and after 6nk** space should be left before the main title.

The first letter of the primary headings in the article should be capital letters. All headings and sub-headings should be designed **10 pt, bold** and **located to the left** with **numbering**, and also navy blue color should be used for sub-headings.

The use of tables and figures should be kept to a **minimum**. For readability purposes, the total number of tables and figures should be no more than **10** per article.

1 OrcaFlex Program

1.1 Axis Team

The table heading should be placed above the table. The figure heading should be placed below the figure. **2 nk** spaces should be added **before** the table heading and figure heading, and also **3 nk** spaces should be added next. The "table" and the "figure" should be written in bold and left-aligned. The first letters of the table, figure and equation headings should be written with capital letters. The heading and the content should be written with **"Cambria"** font and **10-point size**. Suppose tables, figures and equations in the study are cited. In that case, their references should be stated. **2 nk spaces** should be added **before** references, and **3 nk spaces** should be added **after**. If tables and figures don't fit into a single column, they should be designed to include two columns. Tables and figures which include two columns should be stated at the top or bottom of the page.

Table 1. Sample Table

Turkish Male Seafarers (n = 131,152)	BMI < 25.0	BMI 25-30	BMI > 30	Number of Participants
16-24 Ages Group	74.1%	22.5%	3.4%	34,421
25-44 Ages Group	44.1%	43.3%	12.6%	68,038
45-66 Ages Group	25.6%	51.1%	23.4%	28,693
All Turkish Male Seafarers	47.9 %	39.6 %	12.5%	131,152
Turkish Male Population	47.3 %	39.0 %	13.7 %	-

In the article, decimal fractions should be separated with dots and numbers should be separated with commas.

Average age: 28.624

Number of participants: 1,044 people

Page numbers, headers and footers should not be added to the study. The journal administration will make these adjustments.

Authors are deemed to have accepted that they have transferred the copyright of their studies to the journal by submitting their studies to our journal. Submitting a study to two different journals simultaneously is not suitable within the frame of academic ethics.

It is required that the studies are original and have not been published elsewhere before. If conference and symposium papers were published in a booklet, in this case, they should be published by JEMS on the condition that the copyright has not been transferred to the first publishing place. The information must be given to the journal editorship about where these kinds of papers were published before.

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research strategies and in making announcements to researchers and authors.

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This is a short article grounding upon the objectivity criteria, which the editor addresses to make comments, criticism, and contribution on a previously written and published article. Letter to the editor is used to allow sharing of feedback on the articles published in JEMS. Title, Author, Letter, References (Maximum 6000 words, 15 pages).

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Report (RP) Interview (RP)

This is an article pertaining to the short research using structured interview methods with a veteran, recognized with knowledge and expertise in a specific subject, to seek his/her advice in a predetermined topic concerning the maritime industry (Organized by the editor). Title, Author, Abstract, Short biography of the interviewee, Methodology, Questions and Comments, Results, Interview Permit Certificate (Maximum 3000 words).

Case Investigation (RP)

This is an article pertaining to short research prepared to unfold a problem determined during research concerning the maritime industry to offer a solution and develop a method for the solution. Title, Author, Abstract, Case, Problem and Solution Offers, Conclusion, References, Permission Letter (Maximum 2000 words).

Technical Report (RP)

This is an article pertaining to the short research containing the conclusions of analysis on relevant obtained data in matters concerning the maritime industry referenced upon a limited number of literature material. It covers conclusive reports of industrial research, particularly research reports carried out during the period of academic education, etc. Title, Author, Abstract, Introduction, Methodology, Results, References(Maximum 2000 words).

Book Review (BK)

This is an article where an invited reviewer evaluates a newly published book concerning the maritime industry in conformance with a specific methodology. (Maximum 1000 words).

Academic Perspective

This is an article in characteristics of a compilation or a plain text where veteran academicians who are recognized with their academic knowledge and expertise would share their contributions in maritime science, guide young academicians and researchers, and offer solutions for the demands of the maritime industry. (Invited by the editor).

Industrial Perspective

An article in conformance with a specified text format prepared by an expert as an invitee whose knowledge and experience related to their area of expertise is recognized as beneficial by the industry (Invited by the editor). Title, Author, Abstract, Foresight about the subject, Results (Maximum 6000 words, 15 pages).

After the Meeting This article is written to convey the impressions, congress conclusion reports, and information gathered during scientific conventions following a congress, conference, and symposium organized on such matters concerning the maritime industry. (Maximum 500 words).

5. References

The citation style used by our journal is Institute of Electrical and Electronics Engineers (IEEE) Reference Style.

The IEEE Style is used for publications in engineering, electronics, telecommunications, computer science and information technology.

IEEE Style uses a notational method of referencing when referring to a source of information within the text of a document.

You can achieve the IEEE reference style and all reference examples used in our journal at https://jemsjournal.org/guide-for-authors.

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JEMS Ethics Statement

JEMS Publication Ethics And Malpractice Statement

ournal of ETA Maritime Science is an independent publication regarding scientific research, and the editor decides its publication policy. The statement signifies the ethical behaviour of the publisher, the editor, the reviewers and the authors. The ethics statement for JEMS is based on ***COPE Code of Conduct and Best Practice Guidelines for Journal Editors and COPE Best Practice Guidelines for Journal Editors*** available at **www.publicationethics.org**.

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Duties of the Publisher

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The editor must not disclose any information about a submitted article to anyone other than editorial staff, reviewers, and publisher.

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Reviewers help the editor in making decisions and may also assist the author in improving the manuscript.

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Reviewers ought to identify a relevant published study that the authors have not cited. Reviewers also call to the editor's attention any substantial similarity or overlap between the manuscript and any other published paper of which they have personal knowledge.

D. Duties of Authors:

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A submitted manuscript should be original, and the authors ensure that the manuscript has never been published previously in any journal. Data of the research ought to be represented literally in the article. A manuscript ought to include adequate detail and references to allow others to replicate the study.

Originality

The authors who want to submit their study to the journal must ensure that their study is entirely original. The words and sentences getting from the literature should be appropriately cited.

Multiple Publications

Authors should not submit the same study for publishing in any other journals. Simultaneous submission of the same study to more than one journal is unacceptable and constitutes unethical behaviour.

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Convenient acknowledgement of the study of others has to be given. Authors ought to cite publications that have been efficient in determining the study. All of the sources that used the process of the study should be remarked.

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Authorship of a paper ought to be limited to those who have made a noteworthy contribution to the study. If others have participated process of the research, they should be listed as contributors. Authorship also includes a corresponding author who is in communication with the editor of a journal. The corresponding author should ensure that all appropriate co-authors are included in a paper.

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All sources of financial support should be disclosed. All authors ought to disclose a meaningful conflict of interest in the process of forming their study.

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Journal of ETA Maritime Science 2022;10(2):96

Selçuk Nas

Dokuz Eylül University Maritime Faculty, Department of Maritime Education and Training, İzmir/Türkiye

Dear Readers,

This year, we became a member of The European Association of Science Editors (EASE) with the support of JEMS's publisher Galenos. We participated in the "Editorial School for Journal Editors" events organized by EASE in April 2022. We participated in many detailed case studies on journal management issues. In this way, the editors had the opportunity to share their experiences and share ideas among themselves. I would like to take this opportunity to thank EASE management and the organizing committee.

In March 2022, we held a strategic plan meeting with JEMS's board members and publisher in order to increase the internationalization level of the articles submit to JEMS. In this meeting, which was held with the contributions of Galenos, we had the opportunity to receive the analysis results and suggestions for JEMS from Tom Ciaverella, former Publisher Relations manager of Clarivate Analytics. In this context, we made special issue and guest editor plans for 2023. At the first stage, we planned a special issue on Marine Traffic Engineering. We agreed that Prof. Lucjan Gucma, one of the most experts in his field. Prof Gucma is the Head of the Marine Traffic Engineering Department at the Maritime University of Szczecin.

We are pleased to introduce JEMS 10 (2) to our valuable followers. There are valuable and intriguing studies in this issue of the journal. We hope that these studies will contribute to the maritime industry. Hereby, I would like to express our gratitude to the authors, who sent their valuable studies for publication in this issue, our reviewers, editorial board, section editors, and the publisher, who provided quality publications by diligently following our publication policies.

Yours Sincerely

Prof. Dr. Selçuk NAS

Editor in Chief

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ORIGINAL RESEARCH (AR)
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Meteorological Risk Assessment Based on Fuzzy Logic Systems for Maritime

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Abstract

In recent years, numerous casualties have been associated with a lack of safe navigation of ships. Despite advanced navigation systems and the implementation of safety management systems onboard ships, maritime safety is still one of the major concerns for the shipping industry. This research proposes a proactive modeling approach that utilizes Fuzzy Logic and Adaptive Neuro-Fuzzy Inference Systems (ANFIS). The model primarily provides continuous meteorological risk assessment for ships to improve marine navigational safety. In the study, Wind Speed, Sea Conditions, Visibility, and Day/Night Ratio are converted to meteorological risk factors using meteorological risk assessment system. Supported by ANFIS, the meteorological risk assessment system has demonstrated that the database contains details of over 180 marine casualty information involving navigation and traffic accidents. The results emphasize that environmental factors, as well as the Day/Night Ratio, significantly influence ship navigational safety. Hence, a meteorological risk assessment system can enhance navigational safety and prevent loss of life in the shipping industry. As a result, a meteorological risk assessment framework has enormous potential for preventing accidents and improving the safety and sustainability of the shipping industry. In this regard, the proposed model is a one-of-a-kind framework that will be extremely useful for mitigating and preventing the effects of maritime accidents.

Keywords: Decision support system, Fuzzy logic, Maritime accident dataset, Meteorological risk assessment, Ship navigation safety

1. Introduction

Marine science is progressing fast with the advancement of technology and engineering sciences [1]. Scientists study in various fields on advanced engineering models to tackle many issues in the marine industry [2]. Therefore, many jobs and transactions on ships are unmanned, even being planned for the future [3] and unmanned safety navigation is the most significant improvement [4]. One of the essential stages of making safety navigation unmanned is conducting the necessary risk assessments [5]. Afterward, it is possible to make safety navigation unmanned by taking the necessary action according to risk assessments [6]. From the first Day of maritime transportation, various risk assessments, such as maritime risk assessment (MARISA), have been carried out to prevent accidents and keep to a minimum risk for safety navigation [7]. However, MARISA has formed the basis for many other studies on adaptation to new technologies in shipping. This study presents a specific subject in the MARISA system in more detail, and meteorological risk assessment (MERISA) is created based on fuzzy logic and ANFIS.

There are two risk factors in the MARISA system: dynamic and static. MARISA is carried out bearing those risk factors in mind [8]. In this study, the dynamic risk factor, one of the risk factors in MARISA, has been handled with a different structure. The focus is on the meteorological risk factor. MERISA, which is the subject of this study, assesses this risk factor and is created based on detailed fuzzy logic. In this study, the dataset, which has information pertaining to 181 accidents from 1988 to 2019, is created according to

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accident reports prepared by the authorities of the United Kingdom and Turkey. MERISA has been tested on this accident dataset, and the meteorological risk factor has been created for each accident.

Experienced master mariners have previously assessed the meteorological risk for each accident. MERISA was then compared with the master mariners' assessment, and the program created by fuzzy logic was assessed.

The International Maritime Organization (IMO) has three conventions on the safety of navigation. These conventions refer to the International Convention for the Safety of Life at Sea, 1974 (SOLAS), the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREG), and the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers, 1978 (STCW). The IMO has also issued a series of resolutions and codes, including guidelines on navigation issues and performance standards for shipborne navigational and radiocommunications equipment. These convention codes and regulations offer seafarers standards on what to do in specific meteorological conditions. If conditions such as Wind, Sea Condition, Visibility, and Day/Night situation are considered together, it would be seen that they have a rather complex structure, and other factors such as fatigue and inexperience combine with those effects and could lead to marine accidents. A meteorological risk assessment system with a certain standard would be beneficial as a decision support tool for seafarers [9].

There are numerous studies on safe navigation in the literature, but only a few were considered for this study. A systematic literature review of the studies on navigational collision risk assessment provides studies conducted close to the subject of this article [10]. However, no articles were found that specifically discussed MERISA. Thus, this is the first study to address this issue in detail. A marine accident dataset has also been created with the present study. Besides, the present study has been focused only on the sea state following meteorological variables [11]. Therefore, this study is unique in the dataset by considering Wind, Sea State, Visibility, and Day/Night Rate. There are reports on the ship-bridge collision alert system [12]. Also, some maritime studies were made using fuzzy logic on navigational safety [13-16], which mentioned meteorological conditions. For instance, a study on bad weather as one of the vulnerabilities factors was involved in the fuzzy reasoning engines to evaluate the maritime conditions and environment; it has examined bad water in the vulnerabilities module [13]. However, the meteorological risk is an important issue and should be discussed in detail for safe navigation. Vessel traffic service also considers meteorological conditions for collision avoidance, using fuzzy logic [14]. Meteorological conditions are one of the factors considered while designing a two-dimensional (2D) asymmetrical polygonal ship domain [15]. The meteorological risk factor is created and handled in 29 marine accidents in the literature [16]; however, the handling is not as detailed and specific as the present study. This study is the most comprehensive study in the literature dealing with meteorological risk assessment on marine accidents and studying them in detail.

While some of the many studies on preventing marine accidents are more general, other studies such as this are more specific. The article entitled "Identifying Factors Influencing Total-loss Marine Accidents in the World: analysis and Evaluation based on Ship Types and Sea Regions" selects the dataset on the total-loss marine accidents that occurred in the world from 1998 to 2018, involving 16 ship types and 13 main navigation sea regions and is based on an improved the entropy weight-TOPSIS model. The results show that the most influential factors in both models, for ship type and sea region, are foundering, stranding, and fires/explosions [17]. However, it has no information about meteorological factors. The article "Maritime Navigation Accidents and Risk Indicators: an Exploratory Statistical Analysis using AIS Data and Accident Reports" presents the results of statistical analyses of maritime accidents datasets and AIS data from Norwegian waters to identify conditions that are associated with navigation-related accidents (groundings and collisions) and could be used as risk indicators [18].

Weather conditions are usually handled as one variable, but other variables such as Wind Speed, Sea Conditions, Visibility, and Day/Night Ratio are also considered in the present study. Heavy weather is a factor in most marine accidents, as indicated by marine accident analysis [19]. Furthermore, a unique meteorological risk assessment was made in this study to prevent marine accidents. Therefore, the dataset formed by maritime accidents serves as the starting point of this study. The assessment in this study was carried out using a real accident dataset.

Fuzzy logic has been used in maritime science of MARISA systems and many other studies. Examples include the assessment and mapping of maritime transportation risk in the South China Sea [20]; dynamic decision-making systems for intelligent navigation strategies within inland traffic separation schemes to the base [21]; comprehensive risk estimations of maritime accidents focusing on fishing vessel accidents in Korean waters [22]. Fuzzy logic is also used to create fuzzy cognitive maps, AHP, and other fuzzy-based hybrid models. These methods are designed to address specific issues in the literature. Meteorological risk factors are generally assessed as only one factor in the literature; therefore, fuzzy logic should be used when evaluating meteorology for ship safety navigation, as in MERISA. For this reason, the MERISA system created in this study is designed based on fuzzy logic.

MERISA provides navigational safety by establishing a decision support system in this paper. A continuous meteorological risk assessment based on fuzzy logic that handles MERISA in detail will improve safety standards by ensuring full clarity of the impact of weather conditions on shipping. If the MERISA system is integrated with systems designed to ensure safe navigation, it would be possible to switch to automatic ships in a shorter amount of time.

In this article, a dataset that could be used in other maritime studies has also been created. The dataset contains 181 accident data with 15 variables. Furthermore, with the assessment of MERISA to be made in this study, a program based on fuzzy logic is compared with expert opinions and is found to provide superior results. As a result, in cases where expert opinion is essential to the operation of the ship, this program may be used in its place.

Figure 1 presents the framework of this study. Before explaining modeling, the dataset has been explained.

2. Dataset

This paper used datasets with data pre-processing stages accepted in the literature with marine accident data [23]. Data collection, data reduction, data cleaning, data transformation, and data integration were involved.

Figure 2 presents a summary of what has been done in the chapter within the scope of this study.

2.1. Data Pre-processing Stages

In the first stage, marine accident reports and annexes were collected from the Marine Accident Research Center [Marine Accident Investigation Branch (MAIB)] and the Turkish Ministry of Transport and Infrastructure, Transport Safety Investigation Center (TSIC). From the MAIB and TSIC websites, 357 files containing marine accident reports and annexes were collected. The authors have checked to ensure no duplicate reports of the same accidents.

In the second stage for data reduction, It was decided to create 15 variables in the dataset by examining all accident reports and annexes. These variables are vessel details, accident classification, accident type, vessel type, flag, latitude, longitude, location of incident, date/hours, injuries/fatalities, damage/environmental impact, wind, sea state, visibility, and weather conditions. This dataset of the 181 accidents was directly taken as written in the accident reports and annexes, and the relevant accident data now makes up a dataset of 181 accidents with 15 variables. This dataset will be helpful in many fields of marine science.

This study aims to assess meteorological risk, where 15 variables should have been reduced for clear and effective work. According to the literature [6-8,16], Wind Speed, Sea Condition, Visibility, and Day/Night ratio variables are widely used for meteorological risk assessment. Thus, the dataset is divided into four variables and contains 181 accidents. Due to the absence of marine accident reports and annexes, 40 accidents data were not included as meteorological variables in this dataset. Hence, 40 errors were removed from the dataset at the third stage as a data cleaning. The dataset was then organized by including four variables and 141 accidents.

MERISA is a meteorological risk assessment, so it is a specific assessment and has been tested on only marine accidents in

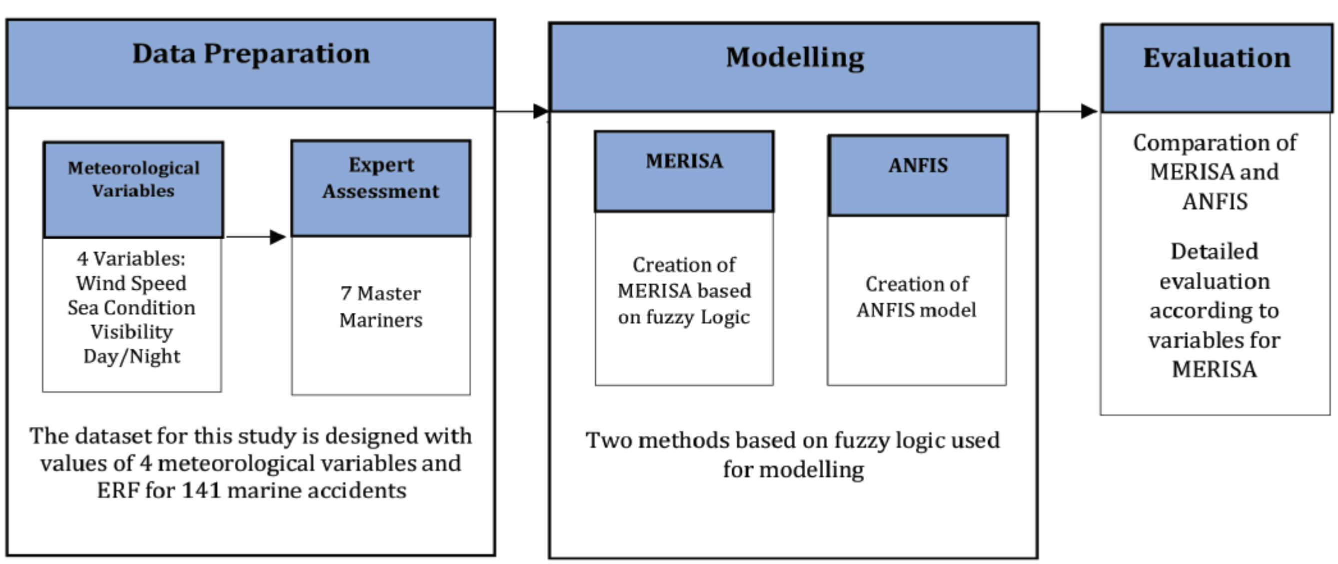


Figure 1. *The framework of this study*

this study. Weather conditions may not be directly related to accidents, but it is safe to say that meteorology always has an indirect effect. In order to clear up any doubts, before removing 11 variables in the data cleaning stage, the distribution of the dataset according to maritime accident types is examined, and the resulting graph is shown in Figure 3.

For a simple and effective study, making a constant conversion for each variable unit is necessary. Wind speed and sea condition variables had to be converted to constant according to the Meteorological Beaufort Scale, the Visibility variable had to be converted to standard values in the optical range Table, and the Day/Night variables had to be converted to standard values in the range of numbers

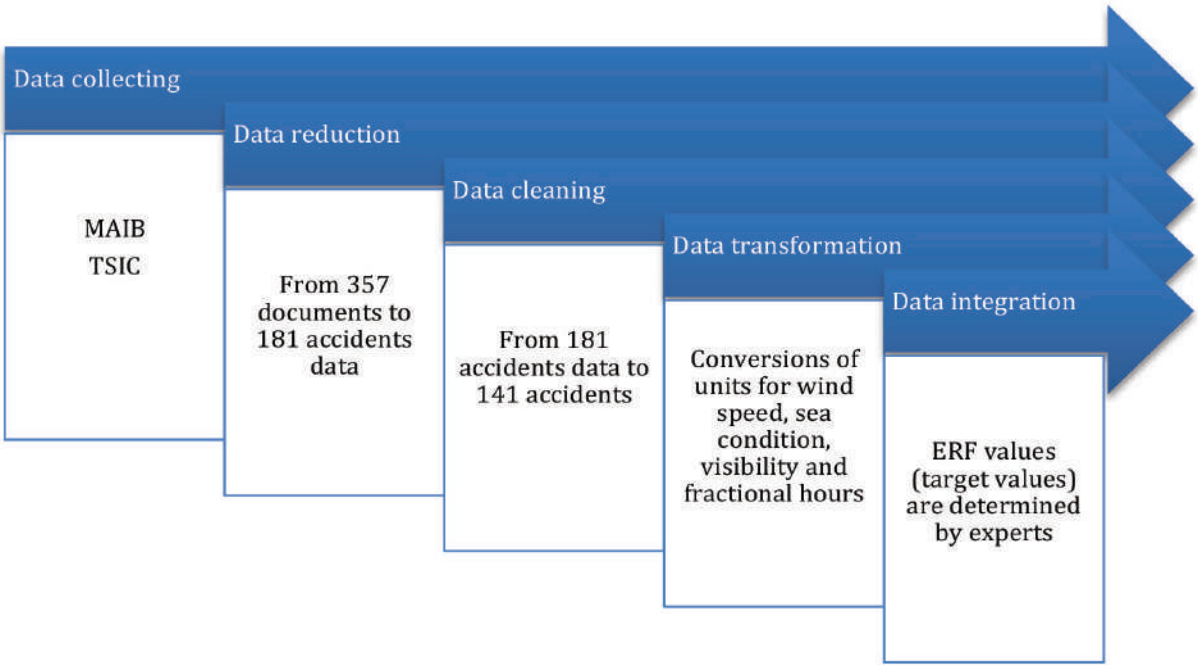


Figure 2. *Data pre-processing stages*

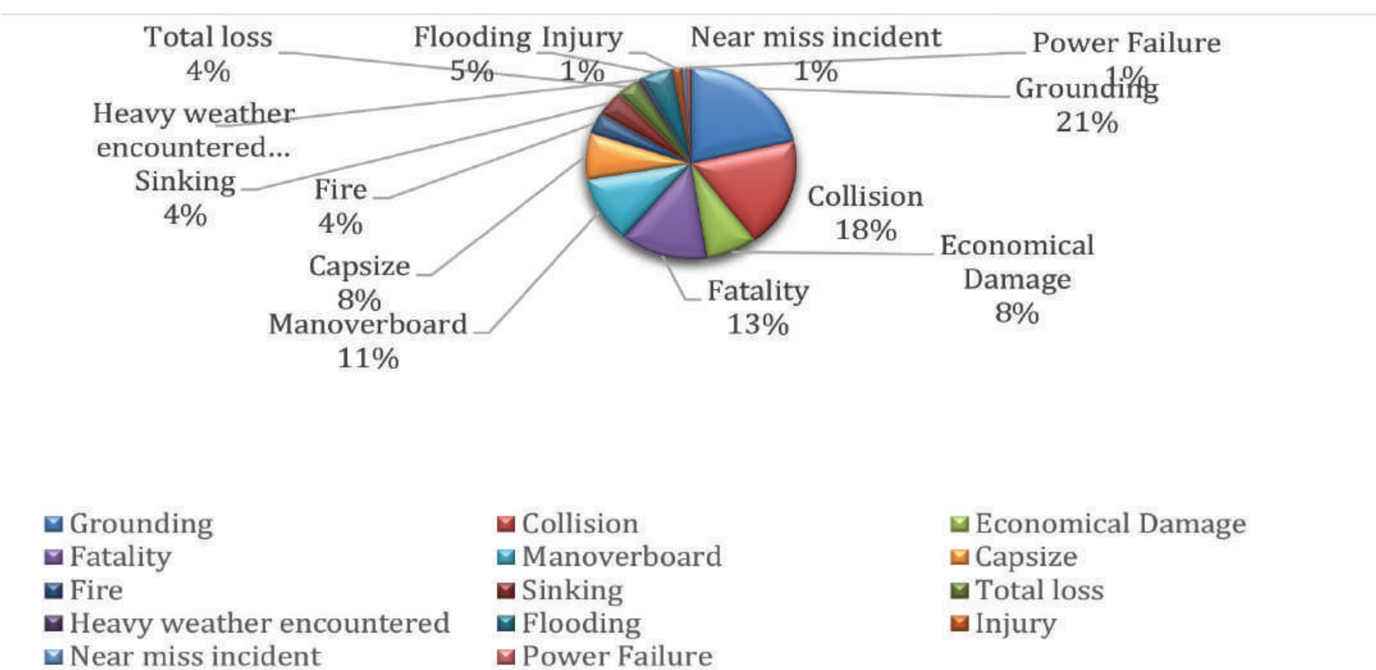


Figure 3. *Distribution of the dataset according to maritime accident types*

from 1 to 24. Therefore, units for all variables for accidents are transformed to a constant value in data transformation.

The dataset was arranged after the first four pre-processing stages, including values according to their constant conservation of four meteorological variables for 141 accidents.

2.2. Expert Assessment

In this study, the meteorological risk estimation is aimed at the ship. In maritime practice, no system determines this risk. Also, target values were needed to compare the accuracy of the proposed models. In other studies, no system calculated only meteorological risk values. For this reason, the dataset was needed for expert assessment to evaluate the proposed models in this study.

Based on the dataset mentioned in Chapter 2.1, the MERISA form is presented. MERISA form that explains the research content asked them to indicate their experience and contained only the meteorological variables for each accident. There are two parts to MERISA form. In the first part, there are two questions about the expert's professional experience. In the second part of the form, a Table has five columns and 142 lines. The first line has variable names, and other lines express 141 marine accidents information. Four of the columns include the variables entered in MERISA, and the last column remains blank. Experts anticipated determining meteorological risk as a percentage for 141 accidents to the blank columns. Thus, the MERISA form has been sent to the experts, and they have been expected to assess the dataset and determine the Expert Risk Factor (ERF) for each accident.

MERISA form was sent to seven experienced master mariners whose watchkeeping experience onboard ranges from 1 to 18 years. These experts have been asked to assess the meteorological data for each accident data separately. They were asked to assess the meteorological risk rather than the general risk on the bridge and determine a value range between 0-100 applicable in all conditions.

$$ERF = \bar{x} = = \frac{1}{n}\sum_{k=1}^{k=n} x_k \quad (1)$$

$\bar{x}$ is the risk factor determined by the experts for each accident, and n is the number of experts. The average of the values given by the experts for each accident was calculated as shown in equation (1). ERF is thereby calculated for each accident.

Expert portraits who will best evaluate meteorological variables for ships were determined. While choosing experts, we paid attention to the experts' experience and their current activeness to have representatives from different positions. It was asked seven experts to assess meteorological risk carefully by explaining the content and scope within the research. Professional experience periods of experts are 18 (Master), 13 (Master), 10 (Master), 7 (Chief Officer), 5 (Chief Officer), 3 (Second Officer), 1 (Third Officer) years from highest to lowest. Experts have not been informed about other variables of the dataset outside the research scope because they were asked to make a general assessment.

Therefore, ERF values and target values for each accident have been determined for the modeling of this study. In this way, a pure and general assessment is conducted, and the necessary data are accessed for the final arrangement in the dataset. It was needed to add ERF values to the dataset. Data integration is the final stage of data pre-processing for this study. In this stage, ERF values are added being as variables. Finally, the dataset has been arranged by including values of four variables and ERF. Table 1 presents the sample dataset used in this study.

Table 1. *Sample of the dataset used in this study*

Number	Wind Speed	Sea Conditions	Visibility	Day/Night	ERF
1	2	2	7	00:00	22.14
2	4	3	1	07:00	73.57
3	3	2	2	08:00	62.86
4	2	1	7	03:00	22.57
5	4	4	7	23:00	40
6	9	5	7	18:00	57.86
7	2	1	7	12:00	15.71
8	2	1	7	05:00	22.86
9	9	7	7	05:00	67.86
10	2	2	7	18:00	21.43
⋮	⋮	⋮	⋮	⋮	⋮
141	9	6	0	16:00	93.57

3. Methodology

The dataset was designed following the data pre-processing stages in the previous chapter. The dataset has been arranged following this study about meteorological risk assessment. In this chapter, MERISA system is designed based on fuzzy logic with a fuzzy inference system (FIS) considering expert opinions. In this study, ANFIS is used to estimate meteorological risk factors. Therefore, in this chapter, fuzzy logic that is the basis of FIS and ANFIS methods is explained. After this explanation, information about evaluation methods in this study is presented. In the next chapter, the Implementation of MERISA is performed, and modeling is explained.

3.1. Fuzzy Logic and Systems

According to the fuzzy set theory, a proposition is either a member (1) or not (0) [24,25]. While this theory is used in many areas, it is impossible to accept it in areas such as risk assessment. Fuzzy logic and fuzzy clusters can be used in risk assessments because no event can be completely risky or completely risk-free [25,26]. A Meteorological Risk Factor (MRF) has been calculated in this study. While calculating MRF, a proposition underlying fuzzy logic must be expressed as membership values in the range 0-1 as true or false. Moreover, for MERISA, the Mamdani type FIS accepted in the literature is used [27]. Therefore, according to fuzzy logic theory, the MERISA system has been designed based on fuzzy logic by paying attention to membership functions and fuzzy relationships and rules. While determining these, opinions of experts on safe navigation were taken, and IMO codes and conventions such as COLREG, SOLAS, and MLC were examined. Literature on this subject and accident information has also been considered. Simultaneously, the conformity of the established rules and relationships is tested by scientists who are experts in fuzzy logic.

ANFIS is a widely used method for modeling non-linear or chaotic systems and was first described as suggested [28]. It requires previously collected data about the problem to be modeled. It uses fuzzy logic and artificial neural networks together while modeling. In the fuzzy logic and fuzzy inference part, Sugeno FIS (Sugeno FIS) is usually included. The training model in the artificial neural network combines least squares and the least squares and backpropagation algorithms. ANFIS has a single output in its structure and uses weighted average defuzzification. It supports various fuzzy membership functions. The fuzzy rules in its structure have equal priority. After the model is created with a specific data group, it can be tested with a different test data group. In this study, ANFIS was used to compare MERISA using meteorological variables and expert evaluation. The ERF values represent the risk assessment of experts. These values are target values for meteorological risk assessment.

3.2. Evaluation Methods

In this study, expert evaluation, in which meteorological variables turn into a risk factor, was used both in the formation of mean error (ME), mean absolute error (MAE), mean squared error (MSE), root mean square error (RMSE), mean absolute percentage error (MAPE) and symmetric mean absolute percentage error (sMAPE) methods, which are the evaluation methods of the MERISA program created by FIS, and the ANFIS application, which we compared with MERISA.

Assessment of a machine learning application is a critical part of the process. Therefore, in this study, ERF values are target values after creating MRF. *t* is the number of marine accidents; *m* is a difference when MRF (for each accident) is subtracted, and then the ME was calculated according to the following equation,

$$ME = \frac{1}{t}\sum_{k=0}^{k=t} m_k \qquad (2)$$

ME was calculated according to equation (2);

$$MAE = \frac{1}{t}\sum_{k=0}^{k=t} |m_k| \qquad (3)$$

e is ERF (for each accident), MAE was calculated according to equation (3);

$$MAPE = \frac{100}{t}\sum_{k=0}^{k=t} \frac{|m_k|}{|e_k|} \qquad (4)$$

MAPE was calculated according to equation (4);

$$MSE = \frac{1}{t}\sum_{k=0}^{k=t} m_k^2 \qquad (5)$$

MSE was calculated according to equation (5);

$$RMSE=\sqrt{MSE} \qquad (6)$$

RMSE was calculated according to equation (6);

$$sMAPE = \frac{100}{t}\sum_{k=0}^{k=t} \frac{2\,|m_k|}{|s_k| + |e_k|} \qquad (7)$$

And *s* is MRF (for each accident), sMAPE values were calculated according to equation (7) to compare MRF and ERF values [28-30].

4. Implementation

The first step of a good scientific study is to identify the problem correctly. The most appropriate method for solving this problem should be chosen to achieve success. However, despite all this, a study could fail if the application of a scientific method is not carried out correctly. In this chapter, the methods described so far have been applied, and this application has been explained in detail. MERISA is applied in Chapter 4.1, and then ANFIS is applied in Chapter 4.2.

4.1. Implementation of MERISA

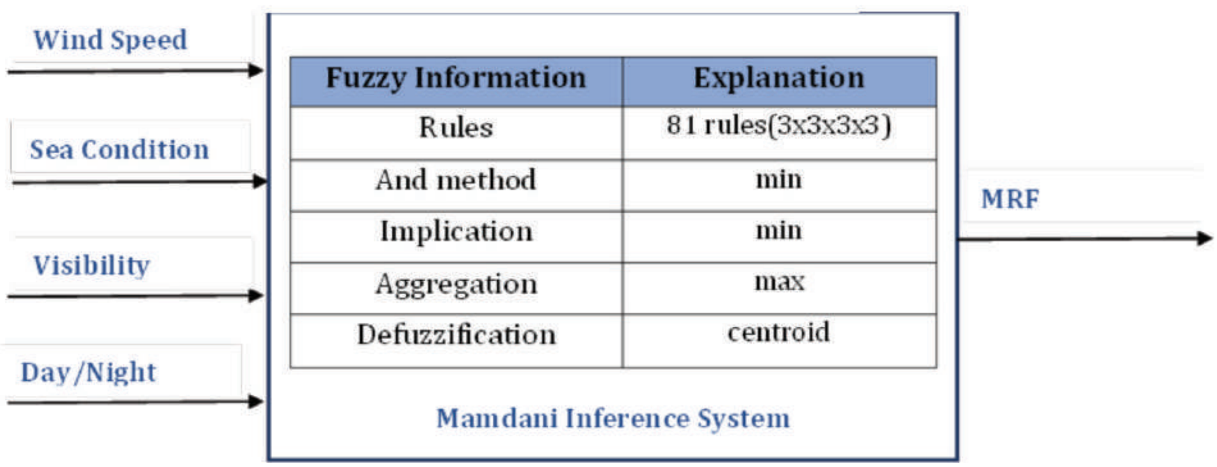
In this chapter, MERISA modeling is explained in detail. MATLAB Fuzzy Toolbox is used for this study.

There are four inputs and one output in MERISA based fuzzy logic. There are three fuzzy sets for each input and five sets for the output. MERISA is designed with 81 rules considering all input sets. Rules, function members, and sets are determined for MERISA model based on experience and similar studies in the literature [6-8]. Wind speed, Sea Condition, Visibility, Day/Night variables of 29 marine accidents have been validated by three expert assessments in [16]. While determining the rules and membership functions, every possibility was made by considering literature and accidental information, and the best results were obtained. Thus, MERISA has been revised and improved. The minimum is used as "and method" and "implication"; maximum (max) is used as "or method" and "aggregation" for MERISA. The Mamdani inference system is used for MERISA as the defuzzification method is central to MERISA. Figure 4 presents a FIS.

The MERISA system has four inputs, and one output variable is shown in Figure 5. These four inputs are Wind Speed, Sea Conditions, Visibility, Day/Night, and the one output is the risk factor. Table 2 presents the information on these functions.

Wind speed, Sea Conditions, Visibility, Day/Night are inputs, and MRF is the output for MERISA system. Limits and membership function types have been made specifically for this study to obtain the most accurate result by doing trial and error, considering the previously mentioned literature and marine accident data.

Wind speed is another input function for the MERISA system. It has three fuzzy sets: Light Air, Breeze, and High Wind. Figure 5 depicts membership function plots for Wind Speed. The Meteorological Beaufort Scale has been used for these membership functions limits, where the range is 0-12.



Fuzzy Information	Explanation
Rules	81 rules(3x3x3x3)
And method	min
Implication	min
Aggregation	max
Defuzzification	centroid

Figure 4. Fuzzy box for MERISA system

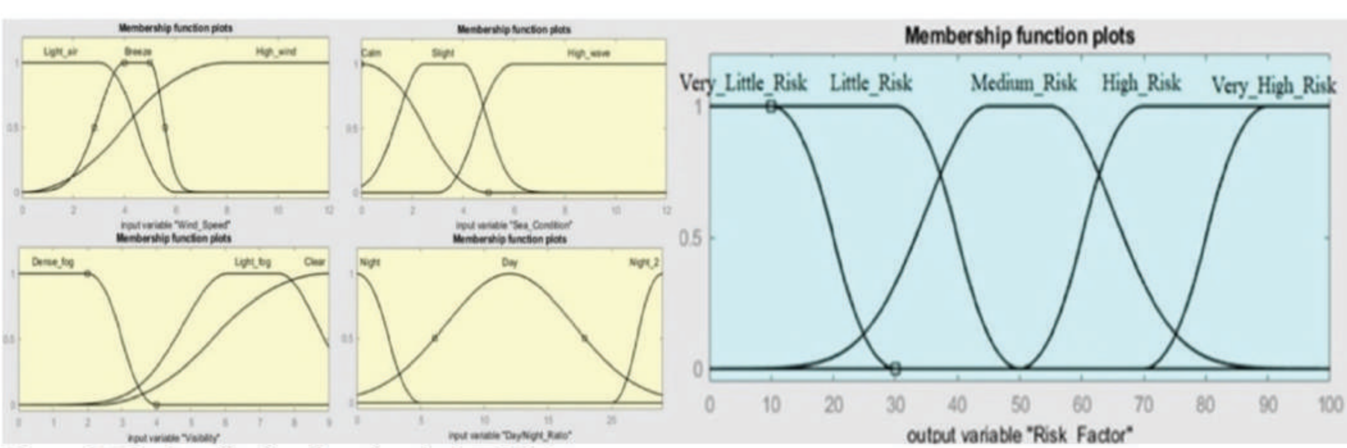


Figure 5. Membership function plots for MERISA system

Table 2. *Fuzzy membership functions' details*

Function	Wind Speed	Sea Condition	Visibility	Day/Night	Risk Factor
Input/Output	Input	Input	Input	Input	Output
Range	0-12	0-12	0-9	0-24	0-100
Number of Fuzzy Sets	3	3	3	3	5
Fuzzy Sets	Light Air	Calm	Dense Fog	Night	Very Little Risk
					Little Risk
	Breeze	Slight	Light Fog	Day	Medium Risk
	High Wind	High Wave	Clear	Night 2	High Risk
					Very High Risk

Sea Conditions is the second input function for the MERISA system. It has three fuzzy sets: Calm, Slight, and High Wave. Figure 5 presents membership function plots for Sea Conditions. The Meteorological Beaufort Scale has been used for these membership functions, where the range is 0-12.

Visibility is the third input function for the MERISA system. It has three fuzzy sets: Dense Fog, Light Fog, and clear. Membership function plots for Visibility are shown in Figure 5. An optical range Table has been used for these membership functions, where the range is 0-9.

Day/Night Ratio is the fourth input function for the MERISA system. It has three fuzzy sets: Night, Day, and Night 2. Membership function plots for Day/Night Ratio are shown in Figure 5. Local time has been used for these membership functions, where the range is 0-24.

MRF is the output function for the MERISA system. It has five fuzzy sets: Very Little Risk, Little Risk, Medium Risk, High Risk, and Very High Risk. Membership function plots for MRF are shown in Figure 5. Percentage evaluation has been used for MRF's 5 membership functions, where the range is 0-100.

4.2. Implementation of ANFIS

In this study, the second system is designed for meteorological risk assessment based on ANFIS.

ANFIS models have a different structure that gives the best results sought by giving alternative values. Table 3 presents the parameter determined in this study. A 2-fold cross-validation method was chosen to evaluate ANFIS. For 2-fold cross-validation, the dataset is divided into two parts: training data and test data., The system is run twice. The dataset in this study contains 141 accidents, divided into two parts: 70 accidents and 71 accidents. Each part is used for both training data and test data.

Table 3. *Information about the ANFIS*

Fuzzy Information	Explanation
Generate FIS	Grid partition
Number of Membership Functions	3+3+3+3
Type of Input Membership Functions	Triangle
Optimal Method	Hybrid
Type of Output Membership Functions	Constant

5. Evaluation

In this chapter, there are evaluations for MERISA and ANFIS modeling.

A detailed evaluation of MERISA suggested in this study is given in Table 4, which contains the results obtained from the six statistical evaluation methods given in Chapter 3.2. The use of these various statistical evaluation methods reveals the performance of the MERISA system from different perspectives.

The RMSE value should be essential in evaluating the MERISA program since it increases the error rate in the larger values. Because the MERISA program is a risk assessment program, it is expected to be error-free in risky situations. Conversely, the MAPE value is also important because it gives MERISA's percentage error.

Because MERISA is a decision support program for meteorological risk assessment, it is required to know which value ranges MERISA works better according to the variables. Thus, a more accurate decision in risky situations is desired. Also, it is necessary to examine RMSE and MAPE values of MERISA according to variables ranges. Table 5 presents these values. Also, RMSE and MAPE values for variables have informed the performance of MERISA. Apart from these, Table 5 provides the range distribution of the dataset according to the variables.

Table 5 shows the values of RMSE and MAPE for Wind Speed. When these values were analyzed, it was found that our MAPE value is lower in the range of 7-11 bft, where the meteorological risk should be higher. This shows that MERISA provides more accurate results at increased risk for Wind Speed. Values of RMSE and MAPE for Sea Conditions are shown in Table 4.

Table 5 depicts the values of RMSE and MAPE for Sea Conditions. When the values in Table 5 are analyzed, it is clear that our MAPE value is lower in the range of 7-9 bft, where the meteorological risk should be higher. This demonstrates that MERISA provides more accurate results in high risk Sea Conditions.

Table 5 also presents the values of RMSE and MAPE for Visibility. When these values were analyzed, it was found that our MAPE value is lower in the range of 3-0, where the meteorological risk should be higher, implying that MERISA gives more accurate results at increased risk for Visibility.

Table 4. *Evaluation results for MERISA*

Evaluation method	Result
ME	-4.94
MAE	6.63
MSE	64.70
RMSE	8.04
MAPE	21.15
sMAPE	18.43

Values of RMSE and MAPE for the Day/Night Ratio are shown in Table 5. When these values were analyzed, it was found that our MAPE value is lower in the range of 20-23 and 8-13, where the meteorological risk should be higher, implying that MERISA gives more accurate results at higher risk for Day/Night Ratio. MAPE value lies between 0–3 in the range of 0–4, which is expected to be high due to the effect of all variables in the MERISA system.

Values of RMSE and MAPE for MRF are shown in Table 5. Analyzing these values shows that our MAPE value is lower in the ranges 50.1-75 and 75.1-100, where the meteorological risk is higher.

It has been observed that MERISA gives values closer to the target value in risky ranges for all variables. This means that MERISA meets the target. Subsequently, modeling that will be introduced in this topic can improve MERISA. For this, it is necessary to give better results than the values given in Tables 4 and 5.

A detailed evaluation of ANFIS mentioned in Chapter 4.2, RMSE value, 9,131, is obtained. RMSE value of MERISA is 8,043. MERISA, which is designed in this study, is better than ANFIS for RMSE value. Consequently, two fuzzy logic

Table 5. *Values of RMSE and MAPE for variables*

Variable	Range	Number of Accident	RMSE	MAPE
Wind Speed	**0-2 Beaufort (bft)**	35	5.97	22.46
	3-5 bft	75	8.32	23.47
	6-7 bft	13	12.22	23.10
	7-11 bft	18	6.41	7.50
Sea Condition	**0-2 bft**	61	8.04	26.49
	3-4 bft	55	7.57	18.65
	5-6 bft	17	9.88	14.67
	7-9 bft	8	8.56	11.43
Visibility (Optical Range Table)	**8-7**	107	8.29	24.62
	6-4	16	7.37	13.84
	3-0	18	7.07	4.86
Day/Night Ratio	**0-3**	24	9.17	26.81
	4-7	21	8.67	19.79
	8-11	16	5.69	17.25
	12-15	31	7.66	21.97
	16-19	32	8.54	23.26
	20-23	17	7.07	18.24
MRF	**0-25**	11	3.52	15.70
	25.1-37.5	54	6.49	24.51
	37.5-50	35	9.93	27.86
	50.1-75	36	8.93	12.88
	75.1-100	5	8.80	9.58

models are designed and evaluated in this study. For future studies, this study will be an incentive.

6. Conclusion

It is a well-known fact that meteorological and Sea Conditions are unstable, which can have a significant impact on the safe navigation of ships. In this unique working environment, the risks and hazards associated with work on the sea are specific. At this point, continuous risk assessment is required to create and maintain a safe working condition and/or environment. Continuous risk assessment is a form of evaluation that should be integrated with existing safety management systems. Navigational safety, however, remains one of the shipping industry's top priorities, despite advanced navigation systems and the deployment of safety management systems onboard ships. Furthermore, numerous deaths have been linked to a lack of safe ship navigation in recent years. Thus, the present study provides continuous meteorological risk assessment for ships to improve marine navigational safety. The suggested model is a proactive modeling approach that uses fuzzy logic and ANFIS. The dataset, consisting of 181 accidents and 15 variables, has been presented in this study. To develop the MERISA system, fuzzy sets, fuzzy relationships, and fuzzy functions have been established. It clearly shows that fuzzy logic and ANFIS can prove robust modeling that could be used in meteorological risk assessments and other risk assessments in shipping operations. Based on the findings, the proposed risk assessment model, MERISA, can provide reasonably competitive results when assessing risky situations in terms of meteorological variables. It is a key factor influencing decision-making regarding accident prevention onboard ships. However, further studies are required to speed up the launch of smart ships and help to improve the technology associated with them. Especially, data analytics approaches are demanded to improve ship navigation safety.

Authorship Contributions

Concept design: İ. Karaca, Ö. Soner, R. Saraçoğlu, Data Collection or Processing: İ. Karaca, Ö. Soner, R. Saraçoğlu, Analysis or Interpretation İ. Karaca, Ö. Soner, R. Saraçoğlu, Literature Review: İ. Karaca, Ö. Soner, R. Saraçoğlu, Writing, Reviewing and Editing: İ. Karaca, Ö. Soner, R. Saraçoğlu.

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Indoor Positioning Technology Selection Using a Combined AHP and PROMETHEE Method at SEDEF Shipyard

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Abstract

Shipyard 4.0 refers to the application of Industry 4.0 principles to shipyards. To keep up with the challenges, the shipyard industry, like other industries, strives to realize Shipyard 4.0 in its industry. The goal of this study is the creation of an indoor positioning system (IPS) to determine the positions of all assets in the shipyards, such as employees, welding machines, cranes, and carriers, and track their movements using an IPS. Users can use positioning systems to find and track the location of a particular object. The most well-known position tracking system is the Global Positioning System, which is widely used in determining the location and position of objects in the external environment. The GPS for locating and tracking an object indoors is not recommended for indoor use, as indoor signals transmitted from a satellite to a device are weakened by indoor obstructions. Many different IPSs are in development that track and position objects indoors. Choosing the most suitable IPS for a shipyard is a multicriteria decision problem. A combined AHP and PROMETHEE method is proposed in this study to determine which IPS technologies would be most suitable in shipyards. In the literature review, it is shown that the AHP and PROMETHEE methods are used separately or together in solving problems in many areas. However, no study has been conducted in which the AHP and PROMETHEE methods are used together for the IPS selection problem. For this purpose, an application of the proposed method in IPS selection and evaluation was carried out at the SEDEF shipyard, and the most suitable technology was determined by evaluating different IPS technology options.

Keywords: Shipyard, Indoor positioning systems, MCDM, AHP, PROMETHEE

1. Introduction

Positioning systems can be classified into two main types: indoor and outdoor technologies [1]. Although GPS has been used successfully in outdoor environments for a long time, satellite-based positioning systems cannot be used indoors with the desired performance. Heavy metals and obstacles such as walls weaken the signal strength and drastically reduce its performance in areas such as shipyards and construction sites. Thus, the reliable service expected from positioning systems falls short of meeting the requirements as positioning accuracy is drastically reduced. There has recently been an increase in research on the use of IPS technologies in open environments. Most of the technologies developed in outdoor environments are used successfully. However, they cannot be considered fully successful indoors. Various technologies based on Radio Frequency, Infrared, Ultrasound, Magnetic, Optical, and computer vision are proposed in this context to improve indoor positioning [2]. Shipyards, ports, airports, warehouses, hospitals, hotels, and shopping malls all need IPS [3]. Currently, various IPS technologies such as Radio Frequency, Haptic Ground, Ultrasonic Sound, and High Sensitivity GPS technologies are applied independently in different fields. Indoor solutions that are currently available are highly dependent on the environment and the target application [4]. Sound-based IPS cannot provide the desired performance because

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shipyards are also noisy environments [5]. On the other hand, the presence of magnetic interference in the shipyard environment makes magnetic-based IPS an unsuitable high-performance alternative [6]. Considering these facts, radio frequency (RF)-based IPS seems to be more suitable for shipyard environments. In this context, the problem of determining which RF-based IoT technologies such as Wi-Fi, Bluetooth, RFID, ZigBee, UWB, NFC, SigFox, and LoRa is most suitable for shipyards is an important research topic [7].

It will be possible to build the shipyards of the future with IoT-based digital transformation, and IPS will provide many advantages to the shipyards. The shipyard will be fundamentally restructured as a result of digital transformation; without digitalization, the necessary new shipyard business models cannot be created, applications cannot be implemented, and the right technologies cannot be developed. First of all, the IPS not only reduces shipbuilding costs but also reduces design time by enabling engineers to test their capabilities in a matter of hours and days instead of weeks or months. Therefore, choosing the right IPS technology creates an infrastructure for all these works and increases success. It will strengthen close cooperation between all fields, integrating processes and ensuring end-to-end continuity by sharing real-time information. Through data-based processes and decision-making, efficiency will be increased productivity will be increased and profitability will be secured. The IPS detects the location of people and objects indoors. The obtained location information is transferred to the application software via servers, providing for real-time asset monitoring and asset management.

In the presence of dense metal blocks in the shipyard environment, presence of water, high probability of exposure to acids or other corrosive substances, possible signal reflections and communication interference, exposure to high temperatures from welding machines, high pressure in the environment, in terms of all factors such as time and cost, none of the existing IPS technology can meet the needs of shipyard environments. For example, while technology may show high performance in terms of energy use, it may be insufficient in terms of accuracy. In such a case, the multi-criteria-decision-making (MCDM) methodology is a very suitable and convenient method for solving this problem. Considering that there is not enough work done in the selection of IPS for shipyards, as can be seen from the literature research, this study provides an original contribution by presenting innovation in the analysis, evaluation, and selection of suitable IPS technologies in the shipyard sector.

This article proposes an MCDM model based on combined the AHP and PROMETHEE methods that can fully characterize an IPS and assist stakeholders in determining which IPS technology is suitable for shipyards thereby improving the design phase of IoT ecosystems in shipyards. This approach allows decision-makers to make better reasoning and more informed analyses of various and often conflicting criteria. With the help of experts, the necessary technologies, evaluation criteria, and all kinds of judgment situations are determined. Evaluations are often complex decision situations involving new technologies such as IPS and focus on examining a large number of different conflicting criteria. As a result, the main innovation of this article, which deals with the selection of the most suitable positioning technology for the shipyard environment to cope with the challenges, is that it provides decision support using the combined AHP and PROMETHEE methods. The combination of AHP and PROMETHEE has been used effectively in different fields [8-11], but has never been studied in advance for the evaluation of IPS for shipyards. This article also contributes significantly in this respect. This study aims to create a model that combines the strengths of the AHP and ROMETHEE methods and then uses that model to select the most suitable IPS for the SEDEF shipyard. The proposed model was used in the selection of IPS technologies at the SEDEF shipyard in Tuzla, Istanbul. While AHP defines the criteria weights, the alternatives are ranked and the most suitable one is determined by the ROMETHEE method. The reason for choosing the combined model is that AHP is very effective and easy to use in pairwise comparison and ROMETHEE in ranking options [12]. Methods are used separately, but hybrid use in this way is not common [13]. The selection measures should be first determined to be able to decide the most suitable IPS technologies among the mentioned technologies. From the point of view of users, the most important factors for IPS are accuracy, coverage, cost, power consumption, and privacy [14].

MCDM is one of the most widely used decision methodologies in science, business, government, and engineering. MCDM methods help to improve the decision-making process by being more clear, rational, and efficient and can help improve the quality of decisions. According to authors Hwang and Yoon [15], the term MCDM refers to making decisions based on multiple criteria, which are often contradictory. There are various techniques in MCDM. Some of the most well-known are AHP, ANP, MAUT, MAVT, SMART, SMARTER, PROMETHEE, ELECTRE, TOPSIS, and VIKOR [16,17].

The AHP is the most widely used and best known of these techniques. AHP is an MCDM technique that uses pairwise comparisons based on a numerical scale to systematize and structure the decision-making process [18,19]. Many studies have used AHP to support decision-making both alone and in combination with other techniques. AHP has been used all over the world and has been applied in many fields [20,21]. With its systematic and mathematical approach, AHP supports decision-making. As a result, it is widely used in research on practical applications. Yazıcı et al. [22] propose an MCDM approach for choosing a machine learning method for the IPS. The study uses AHP to select the appropriate machine learning algorithm for an IPS [22]. Ficco et al. [23] recommend GlobalPreLoc, a multi-purpose strategy for the selection of dynamic and optimal IPS technologies. The study is based on a multi-objective meta-heuristic for the optimal selection of mobile terminal location providers [23]. Mileo et al. [24] present an informed MCDM approach to support positioning. Basiri et al. [25] evaluate IPS Technologies for Pedestrian Navigation Services with AHP.

As in AHP, the PROMETHEE technique has been used effectively in many areas of MCDM, especially in recent years [26-29]. PROMETHEE is also combined with different weighting methods such as AHP to cope with criterion weights and strengthen the model [30-34]. Budak and Ustundag [35] developed a fuzzy decision model for the selection of real-time location systems, which was applied to a hospital in Istanbul by considering three types of systems: RFID hybrid, UHF RFID, and Active RFID. Silva and Jardim-Goncalves [36] propose a decision methodology for the selection of IoT hardware platforms in which AHP, ELECTRE, and PROMETHEE methods are used separately. Çil et al. [37] developed an MCDM model to determine which RF-based technologies will be used as IPS technologies in shipyards, and the problem is evaluated with Fuzzy MULTIMOORA and Fuzzy COPRAS Methods in the study. Kecek and Yüksel [38] researched the order of preference of the young people between the ages of 18-25 for the current alternatives in the smart mobile phone sector by using AHP and PROMETHEE in the study. Lee et al. [39] presented a comparative study of protocols consisting of Wireless Bluetooth, UWB, ZigBee, and Wi-Fi. Dukyil [40] presented an artificial intelligence and MCDM approach for a Cost-Effective RFID-powered tracking management system. Turcksin et al. [30] used the AHP method to assign weights between criteria based on pairwise comparison and PROMETHEE to rank the appropriate policy scenario from three possible scenarios. Oztaysi et al. [41] evaluated data collection technologies using the fuzzy TOPSIS method. Doulos et al. [42] others proposed a methodology based on the ELECTRE method to determine the optimal location of a suitable photosensor.

The rest of the article is organized as follows: First, information and explanations about the IPS and IPS in shipyards are presented. In this study, the proposed methodology and the MCDM methods used in the methodology are then explained in detail. And then, a case study is presented and a comparative analysis is conducted. The article ends with comments on the results obtained and future work suggestions.

2. Indoor Positioning Systems

Positioning systems are an emerging technology that detects the location of objects and guides them in real-time [2]. Satellite-based positioning systems such as GPS are used to detect the location of an object in open areas. The object to be determined by satellites must be in the line of sight for GPS to detect its true position. GPS cannot be used indoors because structures such as roofs and walls prevent satellite vision. Therefore, independent of satellite-based systems, Wi-Fi, Bluetooth, ZigBee, UWB, RFID, etc., wireless technologies have been used in various studies. Although there is not yet a standardized IPS for closed areas, the basic expectations from a system are high accuracy, high security, low cost, low-power consumption, and low maintenance need. With the developments in technology, wireless devices can be produced cheaper and with lower energy consumption. Easy installation is essential for an IPS to become widespread. As a result, systems that benefit from existing infrastructures without the need for additional hardware are one step ahead. However, depending on the targeted usage areas, a certain sensitivity target is also necessary.

Some references must be calculated and well defined in terms of cost, accuracy, precision, scalability, coverage, and limitations to constructing a successful IPS. References such as different dimensions, money, time, and space will affect the system. IPS integrated into building-dependent Wi-Fi technology is considered excellent in terms of cost. Because for the installation of technologies such as RFID, purchasing any tools and equipment, applying them, and integrating them into the system while maintaining their quality requires a long time and cost for system installation. Since the IPS works in real-time environments, it must perform with high precision. Ensuring this situation is ensured by accuracy testing. Accuracy is ensured as a result of the correct entry of the location notification and tracking system that is considered for the system or intended to be implemented, successful data acquisition with high sensitivity, and the result of many program analyses of the location determination and the same results. Accuracy is ensured by determining the same results by making many trials of the desired results from the system, and by increasing the performance effect of the system in indoor environments, it is ensured to give us an accurate result. This gives an idea that the installed system is working. In this respect, accuracy is critical for system performance and obtaining correct information from the system. For example, as a result of trials, the distance of the object or person determined for the IPS is determined as 20 cm with 95% accuracy. In this case, the system gave us the correct answer 95% of the time. Different technology-based IPSs have recently been developed [43].

2.1. Shipyards and IPS

The digital transformation within the scope of Industry 4.0 deeply affects all industries, as well as the shipbuilding industry, and creates revolutionary innovations in shipyards as well. The shipbuilding industry is a slow-moving industry that faces many challenges that need to be addressed to improve the efficiency of processes. In this context, IPS refers to technologies used to track the location of an entity or person in real or near-real time, usually in a restricted area. Shipyards need to install IPS to obtain data on the location of people and other assets in shipbuilding. Shipyards are mostly indoor spaces made up of large metal blocks, and most shipbuilding activities are carried out indoors. The IPS offers new opportunities for shipyards to make faster and better decisions based on real-time data. With modern IPS, shipyards can increase the productivity and safety of their people, equipment, and workplaces. Therefore, by focusing more on value-added activities, preventing misplacement of assets, reaching assets faster, increasing capacity utilization, enabling better shipyard workflows and utilization, responding more efficiently to shipyard emergencies or evacuations, and minimizing workplace injuries and accidents. It provides many benefits, such as downloading. IPS at the shipyard is particularly useful for many things, such as attendance, pandemic workplace applications, warehousing, logistics, and forklift operations. With the ability to quickly monitor and compare data, the IPS provides the infrastructure and convenience to find, monitor, and take effective action on all critical resources to improve processes and optimize workflows. The IPS provides insights on how to get the most value from resources, increase efficiency, and reduce costs.

Asset tracking with the IPS eliminates the time to search and find assets, reducing lost and misplaced assets. With employee tracking and value-added activities, workflows are improved and inefficiencies are eliminated. In the field, the use of multiple cranes, forklifts, and similar machinery and equipment maximizes workflows. With maintenance tracking, maintenance procedures are reduced and maintenance flow is optimized. Every aspect of shipbuilding processes is controlled for efficiency, quality, and traceability through process tracking. Material-handling processes, safety, and work safety are improved, and full control of the site is ensured by the shipyard site management. Workflow optimization identifies and eliminates bottlenecks using real-time and accurate data, and workforce and asset usage are effectively managed. Full traceability of assets is ensured. Every aspect of the production process is controlled for quality and traceability with more effective quality control. Solutions developed for shipyard environments allow monitoring of unsafe conditions, alerting of potential hazards, and enforcing geofencing rules and security restrictions. Everywhere, security rules are effectively enforced, with instant breach alerts. In emergencies, it ensures that the number of employees is determined accurately and quickly. Better risk management is achieved through monitoring of equipment and working in hazardous environments and immediate detection of unsafe conditions. Data is stored and reports are created in compliance with all security regulations. They can be used to generate detailed reports on asset usage and movement within the shipyard during working hours. In the case of workplace accidents and injuries, these reports constitute evidence in case of any claim. Based on location data, the IPS allows shipyard managers to monitor material flow, flow times, and other key statistics to gain meaningful insights about their equipment and workers. In summary, the IPS provides a faster and more effective response to emergencies, a high level of security, simplified processes, the avoidance of human factor problems, and many other advantages.

In recent years, some researchers have studied and made recommendations on the implementation of technological solutions in the direction of digitizing tasks in shipbuilding. Kim and others presented a study suggesting the use of automatic welding machines to be used by intelligent robots in shipyards [44]. In positioning the people inside the shipyard, Kawakubo et al. [45] conducted a study. In this article, the authors use Bluetooth technology. There are some review articles related to real-time positioning in areas such as shipyards and construction sites. Li et al. [46] analyzed ten different IPS technologies. As can be seen in the literature review below, studies discussing and comparing IPS techniques, especially for IPS applications in shipyards, are insufficient. More specific development for the construction of ships and offshore platforms in a shipyard is detailed in [47]. Here the authors consider sensor networks, virtual reality, and RFID technologies to improve the procurement process. RF communication is affected in environments with a high metal presence. This effect has been tested in a series of experiments with various labels. The signal strength has been found to decrease when tags are placed on a copper metal plate. Cil et al. [48] analyze the feasibility of affixing passive RFID tags on bent metal pipes in an environment close to the shipyard. To overcome harsh environments, multiple tags and components have been designed to enable RFID communication in metallic environments [49,50]. RF communication becomes even more complex if conditions such as high temperatures are added to the presence of metals. Therefore, components need to be adapted to demanding communication scenarios.

2.2. IPS Technology Alternatives

In this study, the following five alternative IPS technologies are evaluated to whether are suitable or not for shipyards.

Wi-Fi Technology: A Wireless Local Area Network connects different types of devices over high-frequency radio waves instead of cables. The devices are equipped with an IEEE 802 WLAN adapter. Moreover, WLAN technology has become widespread in the whole building, hospitals, shopping malls, and similar structures. It becomes possible for mobile devices to follow these transmitters by processing the reference signals emitted from them or by forming a network with other devices. Bluetooth is one step ahead of other wireless technologies with its high security, low cost, adjustable power, and small size. Indoor technologies such as BLE and Wi-Fi can provide a more reliable and precise location. Computable propagation characteristics may seem like they are easy to locate, but looking at actual outputs, their greater sensitivity means they are more susceptible to interference. In addition to these effects, the dynamism and inconsistency of environmental factors make it difficult to achieve an applicable structure in every field.

Bluetooth Technology: The Bluetooth-based systems need more hardware devices, unlike the Wi-Fi-based system. It can achieve high accuracy from these devices. Other advantages are low cost, low-power consumption, small size, and easy deployment. The Bluetooth-based IPS mainly uses proximity sensing and fingerprints. With the Bluetooth standard, which is common in many advanced smart devices today, these devices can communicate with smart devices around them. The most obvious difference between Bluetooth and other solutions is that with Bluetooth, multiple devices can communicate with each other at the same time. With the RF connection in Bluetooth technology, there is no need for visual contact as in infrared communication technology. Like other standards, Bluetooth also uses the 2.45 GHz, ISM band. The frequency hopping method is used to prevent interference to a great extent. Devices in the Bluetooth network are within 10-100 meters, 400 kbps symmetrical, or 700-150 kbps. It provides asymmetrical data transmission.

ZigBee Technology: ZigBee features proximity sensing and multi-sided positioning. Wireless technology based on the ZigBee standard wireless technology has many advantages, such as low cost and low power. Safety, reliability, robustness, and low data rates are other characteristics. ZigBee technology is widely used in IPS due to its advantages. ZigBee, an IEEE 802.15.4 standard, is a new generation of communication technology with a low data transfer rate, a battery life that can be sufficient for months or years, and low complexity. It operates in the frequency band without an international license. It uses 16 channels in the 2.4 GHz band, and the maximum data transfer rate for each band is 250 kbps. The disadvantages of ZigBee include a low data transfer rate and an insufficient number of compatible devices. The most important advantages of this technology are that it can be used for years with low-power consumption and that it supports a wide variety of network topologies.

RFID Technology: An RFID system consists of a reader that uses its antenna to listen for nearby active receivers or passive tags. Data can be transmitted from RFID tags to the reader via radio waves using RFID technology. Generally, this data consists of the unique identification number of the tag associated with the current location information of the RFID tag. The system for detecting the presence of a person wearing an RFID tag, also known as the Principal Cell, is the most commonly used positioning method based on the proximity principle. In this respect, the positioning accuracy of an RFID system is highly dependent on the density of the placed tags and the furthest reading distance. While it is preferred in indoor areas with RFID, it is preferred for its system simplicity, low cost of devices, portability, ease of maintenance, positioning, and diagnostic capacity, coverage up to approximately 1000 meters and variable tag sizes; one-sided communication, multipath disruptors, and unstable RSS values make widespread use difficult.

UWB Technology: UWB is a wireless technology that transmits large amounts of data over a wide range of low-power and short-range frequency bands as it have a bandwidth of more than 500 MHz. Also, in UWB, the duration of the pulses is short. It makes it possible to filter the reflected signal from the original, thus guaranteeing a high-precision system. The advantages of the UWB system are that it effectively penetrates walls and passes through obstacles, is isolated from any existing RF signals, and does not cause any interference (if any). Finally, UWB-based IPS is a very high-precision system. The disadvantage of this system is that it is costly and liquid and metallic materials cause interference. This interference condition prevents the system from operating with the correct sensitivity.

2.3. Evaluation Criteria

For an IPS to be widely adopted, it must be issued with a cost clearance, be issued with an energy clearance, have a large reception area, high accuracy, low latency, and high measurability. However, it is a well-known fact that it depends on the implementation of the systems and remains sufficient to meet all these measurements. These criteria are discussed briefly below [51].

Cost: The cost of an IPS should not be high. Ideally, the system should be able to install any infrastructure materials and be easy to maintain. It must be used by any high-end user device or system that does not use it as a broadcast. Operating costs should be low as well.

Accuracy: Accuracy is measured by the reliability of the technology. Accuracy is obtained by how accurately housing information is given by the openness of interior accommodation technologies. Different systems provide different accuracies. For example, the Wi-Fi system is 1.5 m of medium-level accurate health, and RFID technology is 1-5 m of high-level accurate health in the IPS.

Energy Efficiency: The energy efficiency of displacement systems is very important for their adoption everywhere. As of now, many of the current IPSs use relatively higher energy to provide higher accuracy and better range. For IPSs, it is extremely difficult to achieve high accuracy without straining the device battery. This is because its device, which is used for improved performance, must periodically take for certain signal messages or signals. Devices that use less energy should be selected.

Coverage area: Coverage area is the main key factor when the IPS needs to be reviewed in the ranking of interior technology selection. Different technologies have different characteristics for coverage. Therefore, its short-range technology may need more devices to cover the same area. The range of existing systems can vary from 5-50 meters.

3. Methodology

The most important point to be underlined here is that IPS technology selection is an MCDM problem [15,16]. It is a very difficult decision to choose since different alternatives stand out in terms of various criteria. For this reason, there is a need to use methods that will support decision-making and lead to correct and effective decisions. In summary, it can be said that the MCDM method is the most appropriate tool for evaluating IPS technologies. The idea of integrating AHP and PROMETHEE principles has previously been explored by other researchers [30]. This section provides detailed descriptions of the AHP and ROMETHEE techniques used for analysis in this study. It aims to propose an integrated approach in which AHP and PROMETHEE methods are used together, which can help with the selection of IPS technologies for shipyards more objectively and realistically. The proposed approach should be applied to any other project of IPS for different sectors.

3.1. Integration of AHP and PROMETHEE Methods

In MCDM, AHP is a method based on priority values determined through a pairwise comparison of criteria or alternatives, taking into account the judgments of the decision-maker. On the other hand, PROMETHEE is an outranking method. There are strengths and weaknesses in these two methods. This study aims to combine the strengths of these two methods to obtain a combined method that will also give a good ranking to find the best option among the options. The literature mentioned the weaknesses and advantages of these two methods. In the AHP method, since the problem is divided into sub-components and expressed hierarchically, even very complex problems can be expressed very easily. When the number of criteria in the PROMETHEE method exceeds seven, the problem becomes extremely difficult. There is no concrete weight calculation method proposed by the PROMETHEE method. The emphasis on the criteria is entirely left to the personal opinions of the experts who have defined the problem. This work is done more scientifically in the AHP method. Because all the criteria are pairwise compared, the relative importance becomes clearer. In the AHP method, since the problem consists of too many subsystems and pairwise comparisons are made for each criterion, too much data is generated to be studied. In the PROMETHEE method, the result can be achieved with fewer data. Data loss does not occur since the PROMETHEE method avoids tradeoffs. But since AHP and PROMETHEE are also evaluated on cumulative results, some data are lost. In the AHP method, a scale of 1-9 is used for relative importance when making a decision comparison between criteria. But this sometimes creates logical restrictions. The PROMETHEE method result can be expressed as high visual insight according to the AHP method, and the effect of each criterion on the result can be expressed more clearly. The use of the Geometric Analysis for Interactive Aid (GAIA) notation technique in the PROMETHEE method has a large share in this regard.

The AHP and PROMETHEE methods were used together in the IPS selection, taking into account the above-mentioned considerations. The combined AHP and PROMETHEE approach proposed in this study consists of eight steps, as follows:

1. Definition of the problem and collection of data.
2. The alternatives are selected and the criteria by which the alternatives will be evaluated are determined.
3. The creation of the hierarchy was done with AHP.
4. The criterion weights are calculated using AHP.
5. Creation of a rubric for PROMETHEE and determination of preference functions.
6. Performing partial ranking operations with PROMETHEE I and full ranking operations with PROMETHEE II, and conducting sensitivity analysis with Visual PROMETHEE.
7. Alternatives are evaluated and ranked via the GAIA plane.
8. Suggestions for the best compromise are determined.

It is possible to see the proposed solution method visually in Figure 1.

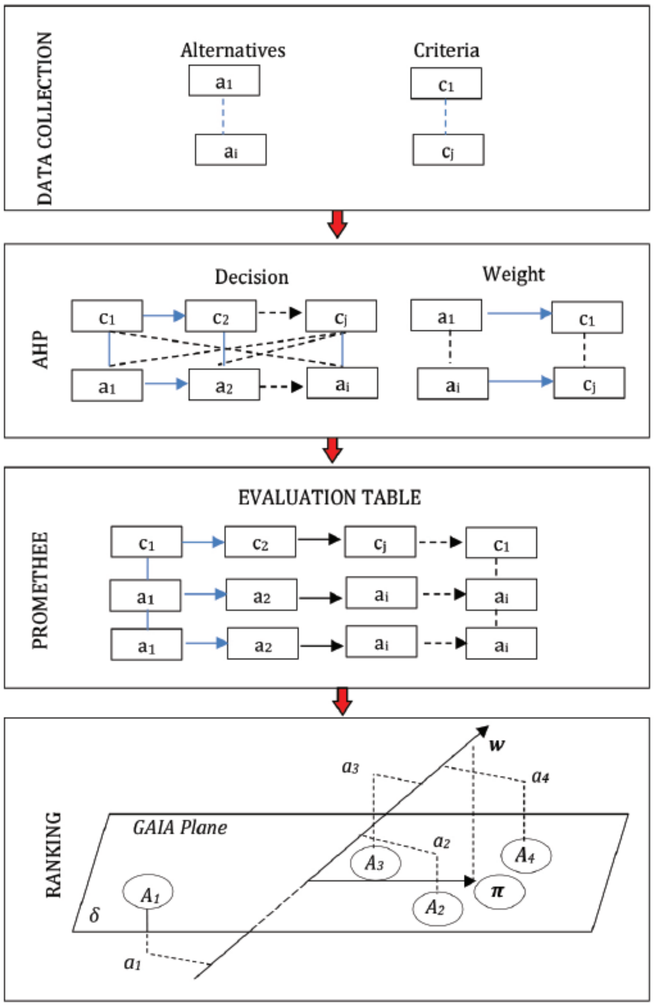

__Figure 1.__ The combined AHP and PROMETHEE approach

3.2. Analytical Hierarchy Process

The AHP is a powerful decision-making methodology developed by Saaty [52] based on the ranking of alternatives by pairwise comparison of multiple conflicting criteria. The AHP methodology consists of three stages [53].

Stage 1: Model Building and Formulation of the Problem: In AHP, the hierarchical structure combines all the components that will contribute to the purpose of a problem to be solved. The goal is at the top of the hierarchical structure. The lower level contains the main criteria for the problem. At the bottom of the hierarchy, options related to the problem are placed (Figure 2).

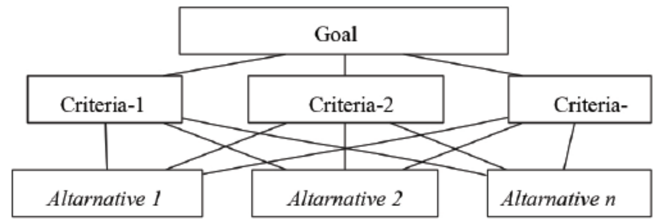

__Figure 2.__ The hierarchical structure of AHP

Stage 2: Creating the Pairwise Comparison Matrix: After the hierarchical structure is established, pairwise comparison matrices are obtained by using Saaty's 1-9 point preference scale, given in Table 1.

In the pairwise comparison matrix, the term w_i/w_j expresses how important criterion *i* is to criterion *j* to achieve the goal. For example, if this judgment value is 5, it is understood that the *i*th criterion is very important compared to the *j*th criterion. In this case, the *j*th criterion is also important at the 1/5 level compared to the *i*th criterion.

In the decision process, since there is a goal and a finite set of alternatives, $X = \{x_1,\dots,x_n\}$, the decision-maker is usually asked to choose the best option (Equation 1).

$$X = \{x_1,\dots,x_n\} \tag{1}$$

That is, given a set of alternatives, $X = \{x_1,\dots,x_n\}$ creates a decision-making weight vector (Equation 2).

$$w = (w_1,\dots,w_n)^T, \tag{2}$$

where w_i is a value that consistently predicts the score of the alternative x_i. Weight vectors are a rating, and their components w_i's are the weights of the decision elements.

To determine the weights, pairwise comparisons are made and the pairwise comparison matrix $A = (a_{ij})_{n\times n}$ structured as follows, is created (Equations 3).

__Table 1.__ Preference Scale with 1–9 Points

Scale	Description	Description
1	Equally Important	Both factors are equally important.
3	Moderately Important	One factor is slightly more important than the other.
5	Strongly Important	One factor is strongly more important than the other.
7	Very Strongly Important	One factor must be strongly favored over another.
9	Absolutely Important	One factor is very important to the other.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{3}$$

with $a_{ij} > 0$ expressing the degree of preference of x_i to x_j. More precisely, according to Saaty's theory, each entry is supposed to approximate the ratio between two weights (Equations 4).

$$a_{ij} \approx \tfrac{w_i}{w_j} \ \forall_{i,j} \tag{4}$$

This means that, if the entries exactly represent ratios between weights, then the matrix A can be expressed in the following form (Equations 5),

$$A = (w_i/w_j)_{n\times n} \begin{bmatrix} w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \ddots & \vdots \\ w_n/w_1 & \cdots & w_n/w_n \end{bmatrix} \tag{5}$$

Note that, as soon as we account for (Equations 4) and consider (Equations 5), a condition of multiplicative reciprocity $a_{ij} = 1/a_{ji} \ \forall_{i,j}$ holds, and A can be simplified and rewritten (Equations 6).

$$A = \begin{bmatrix} 1 & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ \frac{1}{a_{n1}} & \cdots & 1 \end{bmatrix} \tag{6}$$

At this stage, the priority vector needs to be calculated. The most popular method for estimating a priority vector is that proposed by Saaty himself, according to which the priority vector should be the principal eigenvector of A. The method stems from the following observation: Taking a matrix A whose entries are exactly obtained as ratios between weights and multiplying it by w, one obtains (Equations 7).

$$Aw = \begin{bmatrix} w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \ddots & \vdots \\ w_n/w_1 & \cdots & w_n/w_n \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} nw_1 \\ \vdots \\ n\, w_n \end{bmatrix} = n\, w_n \tag{7}$$

We know from linear algebra that for a formulation of the type Aw = nw, n and w are an eigenvalue and an eigenvector of A, respectively. From this, vector w can be determined from any pairwise comparison matrix A as the solution to the following system of equations (Equation 8),

$$Aw = \begin{cases} Aw = \lambda_{max}\, w \\ w^T 1 = 1 \end{cases} \tag{8}$$

where λ_{max} is the maximum eigenvalue of A, and $1 = (1,\ldots,1)^T$. After the weights are obtained in this way, the consistency of the comparison matrix should be checked using Equations 9 and 10. These weights cannot be used in the comparison matrix and are not consistent. For this, Saaty proposed the Consistency Index [52]. The accepted upper limit for the consistency ratio is 0.10. To calculate the consistency ratio, first of all, the consistency index (CI) is calculated using Equation 9. After the CI is found, the consistency ratio (CR) is calculated by Equation 10 using the Random Consistency values in Table 2.

$$\text{CI (A)} = CR = \frac{\lambda_{max} - m}{m - 1} \tag{9}$$

$$CR\ (A) = \frac{CI(A)}{RI_n} \tag{10}$$

Stage 3: Determining the Weights of the Criteria and Scoring of the Alternatives: The entire construction of the AHP is done separately according to the alternatives. The decision score of each alternative is multiplied by a simple matrix multiplied eigenvector, namely: matrix, A, transmitter, W^T.

3.3. PROMETHEE

The PROMETHEE method is based on pairwise comparisons of decision points according to evaluation factors. Its main difference from other multiple decision-making methods is that, in addition to the importance weights indicating the level of relationship between the evaluation factors, each evaluation factor also takes into account its internal relationship. As a result of comparing alternatives based on established criteria using the PROMETHEE I method, it is possible to determine partial priorities (partial ranking) and net priorities (full ranking) as a result of comparing alternatives based on established criteria using the PROMETHEE II method [55].

The algorithm of the processes of application of the PROMETHEE method consists of seven steps. These;

1. Creation of a Dataset
2. Determination of Preference Functions
3. Creation of Common Preference Functions
4. Determination of Preference Indices for Decision Points
5. Determination of Positive and Negative Superlatives
6. Partial ranking with PROMETHEE I

***Table 2.** Values of RIn [54]*

n	3	4	5	6	7	8	9	10
RIn	0.5247	0.8816	1.1086	1.2479	1.3417	1.4057	1.4499	1.4854

7. The Exact Sequence of Decision Points with PROMETHEE II

Step 1: The determined alternatives, criteria, criterion weights, and the values obtained by the alternatives according to the relevant criteria are tabulated in a data matrix. In the following data matrix, a data matrix is created as given in Table 3 for alternatives A= (a, b, c,...) evaluated by the criterion k with weights w= (w_1, w_2,..., w_k) c= (f_1, f_2,..., f_k).

Step 2: Preference functions are defined for the criteria. Preference functions are determined depending on the structure of the criterion and the characteristics sought based on the criterion in alternatives.

Step 3: Pairwise comparisons of decision points are made for each evaluation factor, taking into account preference functions. Common preference functions are determined. If A and B denote two decision points, the following Equation 11 is used for the joint preference function.

$$P(A,B) = \begin{cases} 0 & f(A) \le f(B) \\ p[f(A) - f(B)] & f(A) > f(B) \end{cases} \qquad (11)$$

Step 4: Preference indices for decision points compared using common preference functions are determined using Equation 12. The value of k in this formula indicates the number of evaluation factors.

$$\pi(A,B) = \sum_{i=1}^{k} w_i . P_i(A,B) \qquad (12)$$

Step 5: The positive (φ+) and negative (φ-) superlatives are determined for the alternatives. The positive superiority is calculated by Equation 13, and the negative superiority is calculated by Equation 14.

$$\varphi^{+}(a)=\frac{1}{n-1}\sum_{b}\pi(a,b) \qquad (13)$$

$$\varphi^{-}(a)=\frac{1}{n-1}\sum_{b}\pi(b,a) \qquad (14)$$

Step 6: Partial priorities are determined with PROMETHEE I. Partial priorities allow you to determine the preference of alternatives included in the alternative set relative to each other, alternatives that are no different from each other, and alternatives that cannot be compared with each other. While A and B are the two alternatives in the alternative set, there are the following situations in determining partial priorities:

If any of the following situations is provided, alternative A is preferred over alternative B.

$$\begin{cases} \phi^{+}(A) > \phi^{+}(B) & \text{and} & \phi^{-}(A) < \phi^{-}(B) \\ & \text{or} & \\ \phi^{+}(A) > \phi^{+}(B) & \text{and} & \phi^{-}(A) = \phi^{-}(B) \\ & \text{or} & \\ \phi^{+}(A) = \phi^{+}(B) & \text{and} & \phi^{-}(A) < \phi^{-}(B) \end{cases}$$

If the following situation is provided, alternative A is no different from alternative B.

$$\phi^{+}(A) = \phi^{+}(B) \quad \text{and} \quad \phi^{-}(A) = \phi^{-}(B)$$

If any of the following situations are provided, alternative A cannot be confused with alternative B.

$$\begin{cases} \phi^{+}(A) > \phi^{+}(B) & \text{and} & \phi^{-}(A) > \phi^{-}(B) \\ & \text{or} & \\ \phi^{+}(A) < \phi^{+}(B) & \text{and} & \phi^{-}(A) < \phi^{-}(B) \end{cases}$$

Step 7: The priorities for alternatives with PROMETHEE II are calculated according to Equation 15, given below. With the calculated net priority value, the exact ranking covering all alternatives is determined by evaluating all the alternatives in the alternative set in the same plane.

$$\varphi = \varphi^{+}(a) - \varphi^{-}(a) \qquad (15)$$

The decisions given below are taken depending on the net priority value calculated when there are two alternatives in the alternative sets a and B.

$\phi(A) = \phi(B)$ if a is the alternative, it is superior.

$\phi(A) > \phi(B)$ alternatives A and B are no different.

4. Case Study

SEDEF Shipyard, which is the largest private shipyard in Turkey in terms of area and capacity, has a total of 270,000

Table 3. *Representation of the data matrix*

f_1		Criteria				
		f_2	f_3	---	f_k	
Alternatives	A	$f_1(A)$	$f_2(A)$	$f_3(A)$	---	$f_k(A)$
	B	$f_1(B)$	$f_2(B)$	$f_3(B)$	---	$f_k(B)$
	C	$f_1(C)$	$f_2(C)$	$f_3(C)$	---	$f_k(C)$
	---	---	---	---	---	---
	Z	$f_1(Z)$	$f_2(Z)$	$f_3(Z)$	---	$f_k(Z)$
Weights		v1	v2	v3	---	vk

m² of shipbuilding area, with a Tuzla campus of 194,000 m² of which 51,000 m² is closed-area, and a 76.000 m² Orhanlı support area of 12.000 m² closed-area. SEDEF Shipyard, in terms of competence and equipment; provides services in the fields of military and commercial new shipbuilding, ship conversion projects, special steel constructions, and industrial projects. With nearly fifty years of knowledge and equipment, SEDEF Shipyard is a pioneer in the sector with the projects it has realized [56]. Other project partners are software and hardware companies that develop and prepare the necessary software and hardware for the IPS and the SEDEF shipyard, whose main field of activity is shipbuilding. In addition, the coordination and consultancy of the project are academics from different universities. In this study, all the necessary information, expert judgments, and evaluations were made by these stakeholders according to expert opinions. Stakeholders whose expert opinions were sought are as follows: SEDEF shipyard R&D department, IT department and senior managers and staff, Systematic OTVT company experts who developed the software, Experts from SADE Technology Company, which develops IoT hardware, and academics from Sakarya University and Yaşar University. In this context, both IPS technologies, evaluation criteria, and all judgments were determined through regular and repeated meetings.

The SEDEF shipyard, which is the subject of this study, faces a decision-making problem in choosing IPS. The SEDEF shipyard should select the technologies that are most suitable for its goals and prioritize them following its criteria. It is possible to classify the options to be evaluated by the shipyard under the following different headings. These;

1. Wi-Fi
2. Bluetooth
3. RFID
4. ZigBee
5. UWB

Seven main criteria stand out in the selection of IPS for the SEDEF Shipyard. These;

1. Accuracy
2. Coverage Area
3. Energy consumption
4. Cost
5. Scalability
6. Response Time
7. Robustness

IPS technologies have been implemented using the "Expert Choice" and "Visual PROMETHEE" software using the combined model described in detail above.

4.1. Calculation of Criterion Weights Using the Expert Choice

Seven main criteria have been determined by experts among many criteria when evaluating technologies that will be subjected to evaluation by the SEDEF Shipyard. The weights of these criteria were determined by AHP. The AHP, as described above, is based on the pairwise comparison. The weights of the criteria were determined using the "Expert Choice" software. Figure 3 shows the criterion weights formed as a result of the calculation performed.

The weights of the criteria used in the selection of IPS are ordered from largest to smallest as shown in Figure 3: "Energy consumption, Accuracy, Coverage Area, Cost, Scalability, Response Time, Robustness." In addition, the consistency of the matrix was checked and the inconsistency ratio was calculated to be less than 0.1, that is, Overall Inconsistency=0.02.

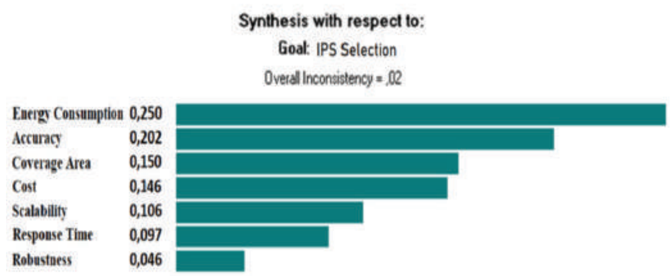

Figure 3. *The weights of the criteria used in the selection of IPS*

After calculating the weights of the criteria, we can now proceed to the outranking of IPS technologies using the PROMETHHE method.

4.2. Evaluation of alternatives using the Visual PROMETHEE

The "Visual PROMETHEE" software was used to perform the IP selection process. Five technologies have been evaluated for the best IPS selection. These have been compared based on seven criteria, and the data used in the selection of IPS is given in Figure 4. As shown in Figure 4, the evaluation table containing the determined alternatives, criteria, weights of the criteria, and data collected from the alternatives about the relevant criteria were created in Visual PROMETHEE software. For all the criteria, Preference functions were determined. The evaluation was made with the V-Shape function was used to evaluate Accuracy, Energy consumption, and Robustness, linear function for Coverage, Level function for Cost, Guassian function for Scalability, and Response Time function. The functions and parameters used are also given.

Visual PROMETHEE Demo - IPS-SELECTION-SEDEF.vpg (saved)

File Edit Model Control PROMETHEE-GAIA GDSS GIS Custom Assistants Snapshots Options Help

Indoor-Positioning-...	Accuracy	Response-Time	Energy-Cons...	Cost	Scalability	Coverage-Area	Robustness
Unit	5-point	ms	Kw	impact	Tags	m	impact
Cluster/Group							
Preferences							
Min/Max	max	max	min	min	max	max	max
Weight	20,08	9,64	24,91	14,90	10,53	14,93	5,00
Preference Fn.	V-shape	Linear	V-shape	Level	Gaussian	Usual	V-shape
Thresholds	absolute	absolute	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	n/a	5	n/a	1,0	n/a	n/a	n/a
- P: Preference	15	30	2,0	2,5	n/a	n/a	2,0
- S: Gaussian	n/a	n/a	n/a	n/a	3	n/a	n/a
Statistics							
Minimum	3	10	1,0	1,0	150	5	3,0
Maximum	5	200	5,0	5,0	1000	150	5,0
Average	4	102	3,0	3,0	510	75	4,0
Standard Dev.	1	60	1,4	1,4	317	54	0,6
Evaluations							
Wi-Fi	good	200	very high	low	150	100	high
Bluetooth	average	100	very low	very low	1000	20	moderate
RFID	good	10	moderate	high	700	5	high
ZigBee	average	100	low	moderate	200	100	high
UWB	very good	100	high	very high	500	150	very high

All | Indoor-Positioning-Systems

Actions: 5 (5 active) Criteria: 7 (7 active) Scenarios: 1 (1 active) Locale: USA [$/,] Saved

Figure 4. *Data used during the selection of the best IPS*

Considering the preference functions, pairwise comparisons of the alternatives were made for each criterion, and common preference functions were calculated based on this. While making this evaluation, minimization and maximization were taken into account. Preference indices for alternatives were determined by using common preference functions. As shown in Figure 5, positive Phi (ϕ+) and negative Phi (ϕ-) values were determined for each alternative.

PROMETHEE Flow Table

Rank	IPS	Phi	Phi+	Phi-
1	Bluetooth	0,2971	0,4778	0,1807
2	ZigBee	0,0958	0,3056	0,2098
3	UWB	-0,0170	0,3085	0,3256
4	Wi-Fi	-0,1303	0,2399	0,3702
5	RFID	-0,2456	0,1853	0,4309

Figure 5. *Positive, Negative and Net superiority values*

The partial ranking is done. The results obtained as a result of partial ranking by the POMETHEE I method are given in Figure 6. Based on this result, it is seen that the positive superiority value of Bluetooth is the biggest (best) and the negative superiority value is the lowest (again, the best).

As shown in Figure 7, the results obtained according to the full ranking were the most suitable option. Then ZigBee, RFID, UWB, Wi-Fi, and RFID are listed. The ranking of the alternatives and the Phi (Φnet) value is given in Figure 7.

4.3. GAIA Plane Analysis

The geometric plane showing the distribution of the criteria according to the values of the options is shown in Figure 8. It can be easily seen that the criteria are distributed on the side of the options that are leading in the ranking. After obtaining partial and complete rankings, the result values can be displayed geometrically in the GAIA plane, where the alternatives are represented by squares and the criteria are represented by vectors. While the vectors

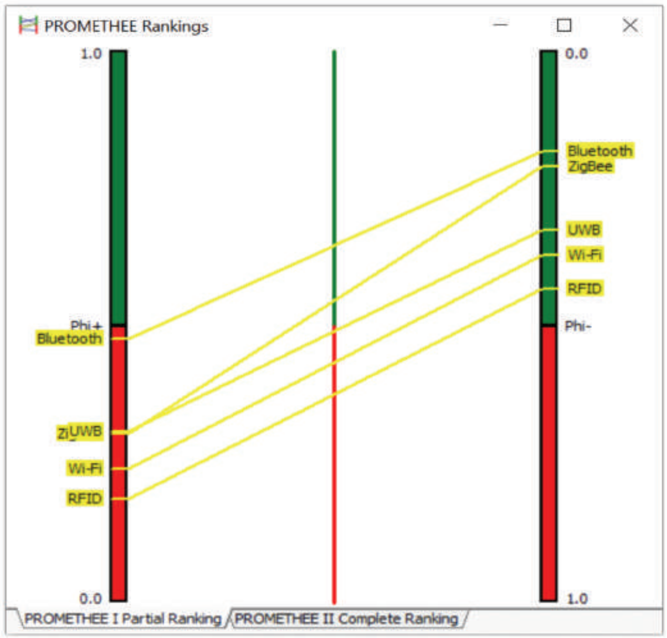

Figure 6. *Partial ranking by PROMETHEE I result*

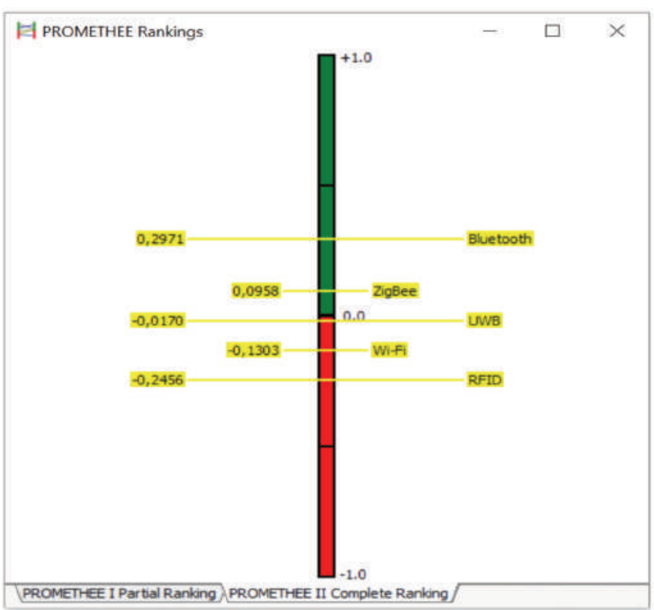

Figure 7. *Full ranking results as a result of PROMETHEE II*

representing the criteria showing similar preferences on the data are in the same direction, the vectors belonging to the conflicting criteria show different directions. In addition, the length of the vector belonging to a criterion shows the effect of that criterion on alternative IPS. The obtained GAIA plane also shows the quality value, which is 93% for this case. This quality value indicates the accuracy of the calculated values. As this value approaches 100%, the accuracy of the analysis increases. The GAIA plane is given in Figure 8; accordingly, Bluetooth has been successful in terms of "Energy consumption" and "Cost." RFID has been successful in "Scalability." UWB, on the other hand, has been successful in terms of "Accuracy," "Robustness" and "Coverage Area."

4.4. Sensitivity Analysis

It is often difficult to determine a solid conclusion because of the variability in the relative importance of a given criterion. In response to this problem, an interactive tool called "walking weights" is used to control the precision of the result. The Walking Weights window allows you to change the weights of the criteria and see their effect on the analysis. The window is divided into two parts: At the top is a bar chart showing the full ranking. The bottom part is a bar chart showing the weights of the criteria. For example, if the relative importance of any criterion is increased by a certain %, how this will be reflected in the result is easily done in Figure 9. In this context, several sensitivity analyses were performed.

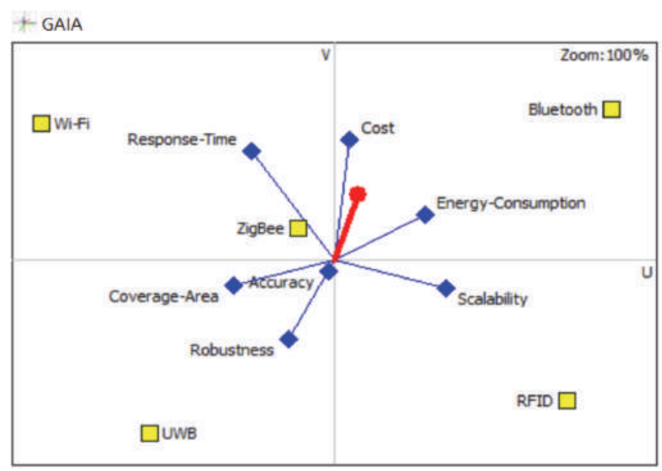

Figure 8. *Distribution of criteria and options in the geometric plane of values*

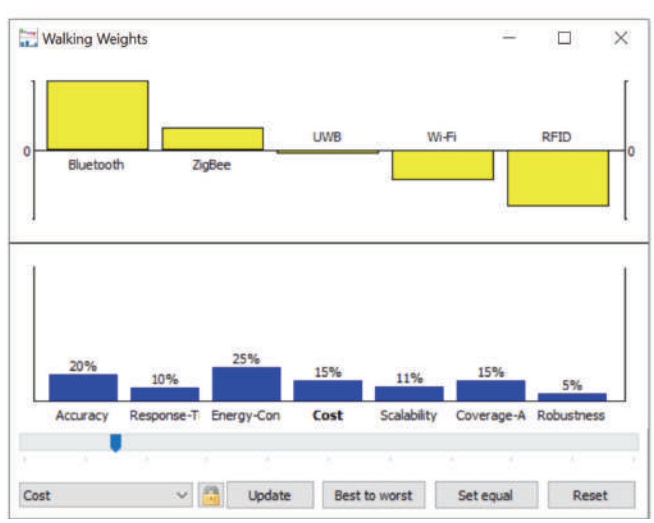

Figure 9. *Performing sensitivity analysis in the window of the walking weight*

5. Conclusion

Two of these scientific methods, AHP and PROMETHEE, were used together in this study to select and rank the IPS for the SEDEF shipyard. In the literature review, it is shown that these two methods are used separately or together to solve problems in many fields. However, there has not been a study in which these two methods are used together for the IPS selection problem. With this feature, this study has an important contribution to the field. The AHP and PROMOTHEE method was used to determine which IPS is more suitable for the SEDEF Shipyard from several alternatives used in this study. Based on the developed model, the definition of the problem and the determination of the weights of the criteria were made with AHP. For the final ranking, the PROMETHEE method was used. The main reason why we use a combined structure, as mentioned in this article, is to make the most of the superior aspects of both methods and minimize errors caused by their weaknesses. For example, the PROMETHEE method for determining the problem structure and criterion weights has not yet produced a scientific proposal. The process of determining the weights of the criteria is completely left to the personal interpretation of specialists. There are criteria in the AHP method as a result of pairwise comparisons based on the opinions of experts. However, it can be checked whether it is consistent or not, and pairwise comparisons of the criteria can be expressed and seen very clearly due to the scale used. Since it is allowed to define the preference function based on each criterion in the PROMETHEE method, it is possible to make the alternatives that meet the criteria stand out a little more. In addition, the ranking of alternatives was even more meaningful because the PROMETHEE method avoided "compromising." With PROMETEE I, the advantages and weaknesses of the options to each other can be seen and analyzed without the problem of compromise. The results of the PROMETHEE method, thanks to the analysis tools, the strengths of the featured alternatives, the main criteria that make them stand out, and how the preference functions affect the results, have been analyzed very easily. Whether there is a contradiction between the criteria has been evaluated by experts using the GAIA plane. Again, these results were examined from different aspects, such as changing the weights and changing the conditions of the preference functions, and a very good parametric analysis was performed.

Expert Choice Software, which is very useful, was used to determine the criterion weights. The weight of each criterion is arranged graphically from the largest to the smallest, and visuality is provided. Visual PROMETHEE software is also very useful software for visualizing the computation process, which is a valuable tool for PROMETHEE analysis. The biggest advantage is that they allow the use of scenarios and all kinds of changes during the evaluation phase. Another advantage is that they provide eye-pleasing decision support with colorful graphics.

The following conclusions were reached by a comparative evaluation of the IPS considered here. Although the coverage area is very wide when positioning on the Wi-Fi network, the sensitivity is very low. Wi-Fi is a low-cost solution as it doesn't require extra devices. Variable signal strength may occur due to signal reflection and dynamic network structure in shipyard environments due to poor performance in multi-floor and very dense areas. On the other hand, the UWB has a wide range and high sensitivity. However, due to its high cost, it is suitable for applications where the location must be very precise. For closer distances, RFID, which is slightly different from these, can be preferred and is more suitable for use in stock counting door entry/exit applications. RFID is not easy to integrate into other systems. Low coverage and the inability of signals to pass through metal materials can cause problems in shipyard areas. ZigBee technology is widely preferred in applications that can be performed with small-scale data exchange because of its low cost, minimum power consumption principle, and easy and flexible installation. Thanks to this technology, it is possible to establish complex network structures, expand them, and enable these structures to communicate with other technologies. The disadvantage is that it cannot provide large data streams like Wi-Fi or Bluetooth. This means that ZigBee is mostly used in applications with small data flows. Compared in terms of power consumption, Bluetooth systems have the highest battery life and perform well in terms of energy use. Although the range is lower in Bluetooth technologies, positioning accuracy that can fall below 1 m can be achieved. Compared to other systems, Bluetooth has been seen as a good choice for reliable indoor positioning applications due to its higher sensitivity, lower cost, and ease of implementation. Bluetooth systems use the received signal strength indication technique, which is based on measuring the incoming signal strength among positioning techniques so that the farther the signal comes from, the weaker it will be.

This study's implementation is a case study for a single shipyard in the shipbuilding industry. Shipyard digitalization is still in the development stage. For this reason, the results obtained are only from an application-based study carried out at the SEDEF shipyard. As a result, the application results to be realized in other shipyards may not be the same as the evaluation results to be obtained with the approach implemented here. Similar applications can be made at other shipyards to make a more general recommendation for the sector, and more accurate decision support can be provided for the sector. Future researchers could focus on how the proposed integrated AHP and PROMETHEE method can be applied to the selection and evaluation of IPS technologies in other shipyards. The proposed integrated AHP and PROMETHEE method can be applied in the selection and evaluation of IPS technologies in other sectors other than shipyards. Furthermore, future studies can be conducted on the use of IPS technologies together.

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Authorship Contributions

Concept design: I. Cil, F. Arisoy, E. Özgürbüz, Data Collection or Processing: F. Arisoy, E. Özgürbüz, H. Kılınç, Analysis or Interpretation İ. Cil, E. Özgürbüz, A. Y. Cil, H. Kılınç, Literature Review: İ. Cil, E. Özgürbüz, A. Y. Cil, Writing, Reviewing and Editing: I. Cil, A. Y. Cil, H. Kılınç.

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Ship-to-ship Dialogs Using A Finite State Machine

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Abstract

Collision Avoidance Systems require correct and unambiguous application of the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs). Ship-to-ship dialogs, aimed at sharing encounter data to comply with COLREGs and reaching maneuvering agreements, would help to reduce the risk of collision. Finite State Machine (FSM) is a mathematical model for describing the sequential behavior of a control program. Sequential function chart (SFC) based on FSM, is a graphical programming language for Programmable Logic Controllers, defined by the international standard IEC 61131-3. In this work, SFC language is used to model and program the set of states and transitions involved in the ship-to-ship dialogs initiated when one of them detects a risky situation. SFC facilitates the development, verification, and maintenance of the control program. The implemented ship-to-ship communications to share data will help in eliminating differences in decision-making and achieving safer encounters. An example of a risky encounter illustrates this assertion, not contemplated in the related studies consulted. The implemented dialogs will enable sharing information on the encounter characteristics and reaching agreements on the maneuvers to be performed, or maintaining a record about disagreements.

Keywords: Collision risk, COLREGs, Inter-ship communications, Discrete event systems

1. Introduction

According to the statistics on marine casualties [1,2], ship collisions remain high on the list of maritime accidents with the most serious consequences, with human actions being the first accident events. Reportedly, incorrect decisions by the Officers in charge of the Navigational Watch (OONW), misunderstandings in oral communication between them, and failure to take early actions are some main contributing factors in ship collisions.

A modern ship is equipped with devices and systems that provide information to the OONW about herself and nearby ships (targets), for e.g., static and dynamic values received via an Automatic Identification System (AIS). From these values, the Programmable Electronic System (PES) in each ship connected to her AIS can calculate the distance, bearing, Closest Point of Approach (CPA), and time to CPA (TCPA) for each target, as well as the manuevers to be performed based on the COLREGs. The PESs of the ships involved in the encounter can communicate to compare their information and display it in a way facilitating the decision-making by their OONWs.

Thus, ship-to-ship dialogs, sharing encounter data to comply with COLREGs and reaching maneuvering agreements between the two OONWs can help mitigate the collision risk.

This paper describes how these dialogs can be implemented.

• Section 2 presents an example of a close quarters situation illustrating some benefits of the inter-ship dialogs.

• Section 3 outlines the basic aspects of discrete event system (DES) models and languages. The associated state transition graph features facilitate the development of programs to implement the dialogs.

• Section 4 describes the structure of states and transitions in the developed program and the possible evolutions through the graph.

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• Section 5 explains how the program is tested and shows an example of the obtained results.

• Section 6 presents the main conclusions.

2. Ship-to-ship Dialogs as A Requirement to Reduce the Risk of Collision

In encounters between manual, semi-autonomous, and autonomous vessels, sharing data would be a fundamental navigational aid for correct decision-making.

As an illustrative example of this statement and to discuss its benefit, a ship-to-ship encounter case is shown (Figure 1) along with the possible ship responses with or without the reported communications between them.

Crossing situation (COLREG Rule 15): BLUE should keep out of the way and avoid crossing ahead of PINK.

RULE 16 Action by give-way vessel

Every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to keep well clear.

What distance corresponds to "so far as possible"?

Let us consider this Give-way distance as dPrealert. Thus, dPrealert can be defined as the distance to start maneuvering if the ship is a give-way vessel or a vessel that must not impede the passage or safe passage of another vessel.

RULE 17 Action by Stand-on Vessel

(a)

(i) Where one of two vessels is to keep out of the way the other shall keep her course and speed.

(ii) The latter vessel may however take action to avoid collision by her maneuver alone, as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules.

(b) When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision.

(c) A power-driven vessel which takes action in a crossing situation in accordance with subparagraph (a)(ii) of this Rule to avoid collision with another power-driven vessel shall, if the circumstances of the case admit, not alter course to port for a vessel on her own port side.

(d) This Rule does not relieve the give-way vessel of her obligation to keep out of the way.

What distance corresponds to "as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules"?

To determine when the stand-on vessel should act, we consider a distance (combination of time and speed), called dAlert. Thus, dAlert can be defined as the distance to start maneuvering if the ship is a stand-on vessel or a vessel whose passage must not be impeded, according to Rules 17 a) ii) and 17 b).

Let us quantify other terms:

• LRS. From Rule 7 (b): *Proper use shall be made of radar equipment if fitted and operational, including long-range scanning to obtain early warning of risk of collision*.

	BLUE	PINK
LAT (N,S):	N	N
degrees (0 .. 89) :	37	37
minutes (0 .. 59) :	0	3
seconds (0 .. 59) :	0	30
LON (E,W):	E	E
degrees (0 .. 179) :	0	0
minutes (0 .. 59) :	0	5
seconds (0 .. 59) :	0	30
Ini Course(0.0 .. 359.9):	0.0	310.0
Length (m):	100.0	300.0
Nav. status (0..15):	0	0
Angle ord.:	0.0	0.0
Speed ord.:	15.0	13.4
Visibility:	GOOD	GOOD
Radar detection:	YES	YES

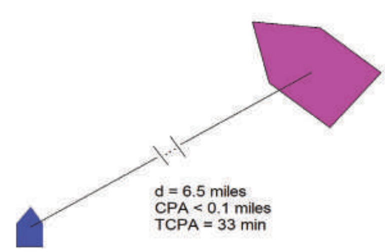

Figure 1. *Crossing situation, vessels in sight*

Crossing situation (COLREG Rule 15): BLUE should keep out of the way and avoid crossing ahead of PINK

• CPASafe. Minimum CPA, limit between safe distance and close quarters.

• TCPASafe. Minimum value for TCPA to avoid collision, if CPA < CPASafe.

And four logical terms:

• Safe distance: CPA ≥ CPASafe.

• Close quarters/Risk of Collision: CPA < CPASafe.

• Prealert condition: (CPA < CPASafe) AND [(distance ≤ dPrealert) OR (TCPA < TCPASafe)].

• Alert condition: Prealert condition AND (distance ≤ dAlert).

Evidently, these distances (dPrealert, dAlert, CPASafe) and time (TCPASafe) must be quantified (especially for autonomous ships) depending on the ship dynamics and her maneuvering parameters [3]. Each ship will have her own specific values for these distances and times; thus, the values will differ if the ships involved in the encounter have different characteristics.

Figure 2 collects and illustrates an example of values for the encounter shown in Figure 1. dPrealert and dAlert are approximately 20 and 9 times the lengths of the ships, respectively.

Parameter	Ship BLUE	Ship PINK
LRS (miles)	12.0	12.0
CPASafe (miles)	0.3	0.5
Length (m)	100	300
TCPASafe (min)	6.0	12.0
dPrealert (miles)	1.0	3.2
dAlert (miles)	0.5	1.5

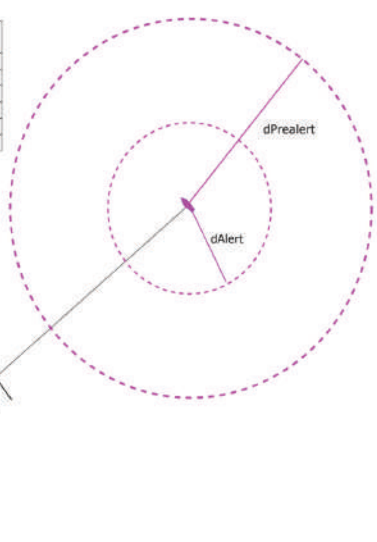

Figure 2. *dPrealert and dAlert distances for both ships*

In this case, ship PINK is the Stand-on vessel, and ship BLUE is the give-way vessel. For the given values, BLUE will detect prealert condition (and must maneuver) when distance ≤1.0 miles or when TCPA <6 min, whichever occurs first.

However, before this situation, PINK enters in alert when distance ≤1.5 miles, so she is forced to maneuver (Figure 3a), according to Rule 17 (a)(ii).

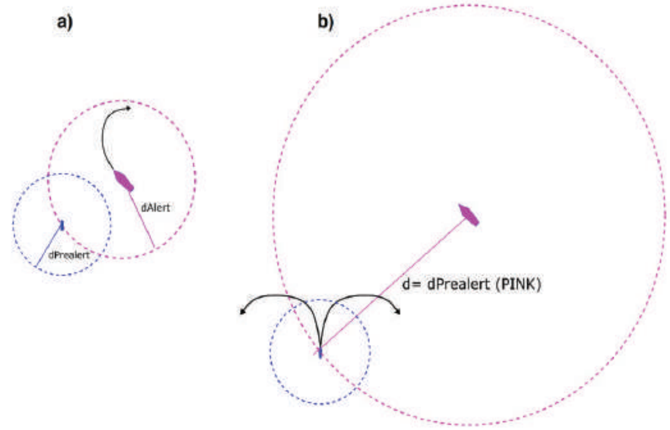

Figure 3. *Possible maneuvers: a) without dialogs; b) with dialogs*

What should BLUE ship do then? Her subsequent behavior is not contemplated by COLREGs, which will increase the risk of the encounter.

If both ships share their information about prealert and alert situations, BLUE will know that she shall keep out of the way when she enters in PINK dPrealert and will share her agreement (or disagreement) with the prescribed maneuver. This maneuver is shown in Figure 3b.

This encounter, without communications, can also generate different maneuvering decisions if the OONW of one of the ships considers that the vessels are in sight and applies Rule 15 (BLUE should maneuver) and the other considers that they are in a restricted visibility scenario, where both ships must maneuver (Rule 19).

The agreement for maneuvering can be achieved as follows: the PES on each ship receives dynamic data about own and target ships (position, heading, speed, ...) from the onboard equipment, calculates distance, bearing, CPA, and TCPA and determines the type of situation and the Rules to be applied for each encounter. In detecting a prealert condition, it will inform the OONW and exchange messages with the PES in the target ship.

An implementation of such communications is presented in Argüelles et al. [4], using Programmable Logic Controllers (PLCs) as the PES and AIS for data acquisition and communications.

3. Sequential Function Charts

A PLC is a robust and reliable programmable electronic device with proven use in the control of industrial processes. Its architecture and programming are defined in the IEC 61131 standard. The PLC structure mainly consists of the processing unit, memory, Input/Output modules, and communication interfaces. PLC executes its tasks in a cyclic mode (scan cycle), which consists of the following four steps:

(1) read the inputs from the periphery to the memory,

(2) execute the user program that reads and modifies the memory contents,

(3) write the values to the output periphery and

(4) perform internal tasks, such as checking for errors and storing the duration of the scan cycle.

Sequential function chart, SFC, is one of the five languages defined by the IEC 61131-3 standard. It is a graphical programming language that allows specifying the sequential control logic of a DES in an intuitive way. A brief introduction to this language is given below.

A DES is an event-driven system of discrete states, i.e., its state evolution depends on the occurrence of asynchronous discrete events in time [5]. Since the middle of the last century, several DES modeling approaches have been proposed, including Finite State Machines (FSM) and Petri Nets (PN) formalisms based on states and transitions.

Figure 4a shows a simple FSM an oriented graph that describes the DES. It consists of discrete states represented by circles and the transitions between them represented by arrowed lines. PNs enable modeling and analyzing more complex and concurrent systems. Figure 4b illustrates a graphical representation of a PN with places (states), transitions, and oriented arcs [6,7].

These state transition models, as graphical tools, represent the behavior of sequential systems graphically, facilitating the development of control logic and verification operations (through exhaustive testing) of requirement specifications. In addition, as mathematical tools, FSM and PN models are the basis for formal verification techniques to ensure the correctness of the safety-critical software [8,9].

GRAFCET (GRAphe Fonctionnel de Commande Etape Transition) is a specification language related to PN [10]. It was defined in 1977 and subsequently standardized as IEC 60848 [11] for the functional description of the behavior of the sequential part of a control system. This specification language is independent of any specific technology of implementation. SFC language defined in IEC 61131-3 [12], is based on IEC 60848 and is a specific programming language for PLCs.

In the IEC 61131 standard, the term Program Organizational Unit (POU) is used for all programming objects: PRoGrams (PRG), Function Blocks (FB), and Functions (FU), used to create a controller application.

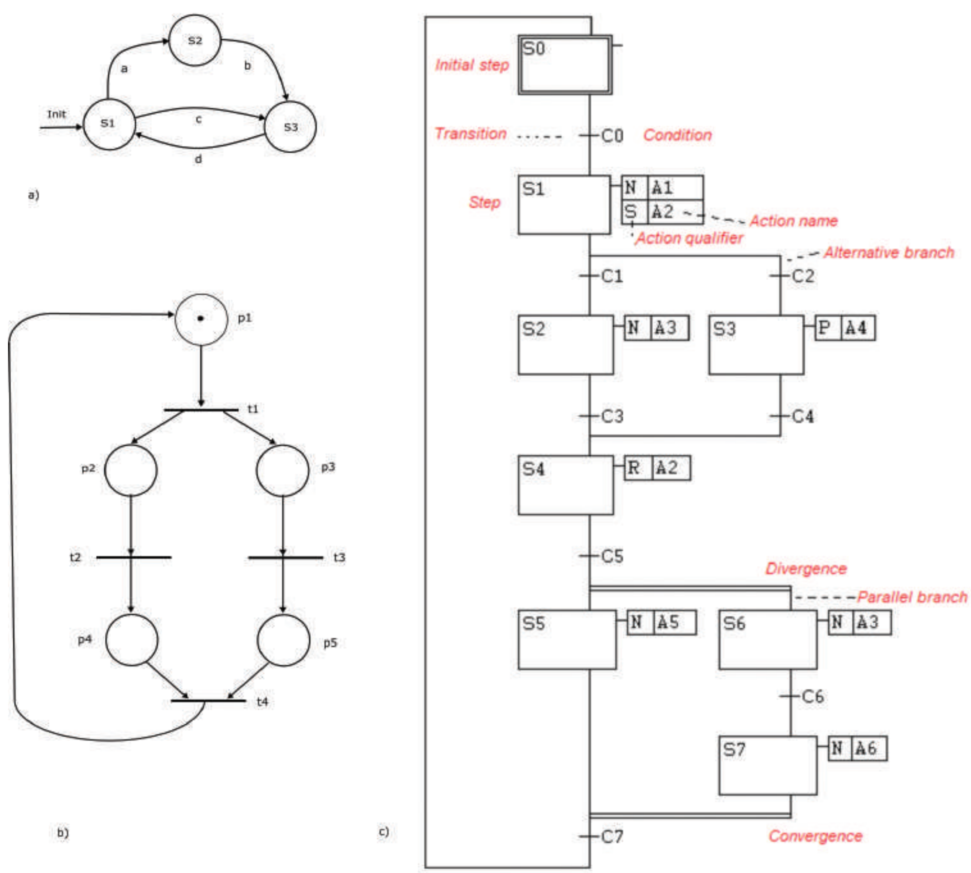

Figure 4. *Discrete event models: a) FSM; b) PN; c) SFC language*

FSM: Finite State Machine, PN: Petri Nets, SFC: Sequential function chart

A POU written in SFC consists of steps (states) and transitions. It has one initial step, and each transition is labeled with an associated condition. Zero, one, or more actions may be associated with each step. Figure 4c shows an example of an SFC.

Actions in the SFC include a qualifier, specifying the duration of the action, and a name, identifying the programmed instructions. Some qualifiers:

• N (Non-stored): The action is active as long as the step is active.

• P (Pulse): The action is executed just once if the step is active.

• R (Reset): The action is deactivated.

• S (Set): The action is activated and remains so until a Reset.

There are different types of transitions:

• simple transitions between two steps,

• alternative branching, i.e., the choice among several transitions,

• parallel branching with divergence from one step into a set of parallel steps and ulterior convergence into a single step.

In the first scan cycle of a SFC POU, the initial step becomes active, and the associated actions (if any) are executed. Then, at each cycle, all conditions on transitions starting at active steps are evaluated, and if true, the corresponding transition is enabled, changing the set of active steps.

4. SFC Implementation of Ship-to-ship Dialogs

SFC is used in this work to model and program the set of states and transitions involved in the ship-to-ship dialogs initiated when one of them detects a risky situation.

The controller application executed on the PLC of each ship includes a number (N) of FBs written in SFC, one for each target; 0 ≤ N ≤ Max, where Max: maximum number of targets.

When the PLC application running on a ship detects a target, it activates the initial step of an associated SFC (Figure 5).

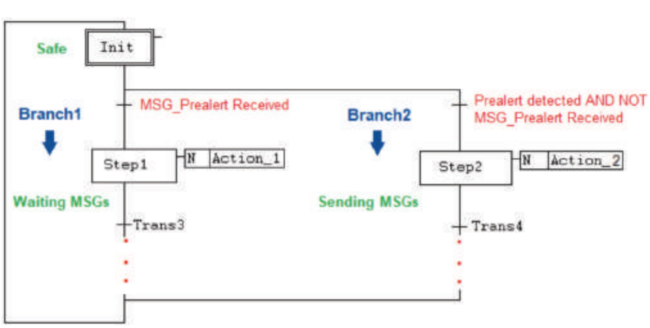

Figure 5. *Basic SFC for Ship-to-ship dialogs*

SFC: Sequential function chart

SFC starts from a safe state (safe situation), which is exited for one of two following reasons:

- A prealert message (*MSG_prealert*) is received from the target (branch1). While progressing through this branch, the target takes the initiative of the communication. The own ship's PLC waits for the messages and then responds (Figure 6).

- Prealert condition is detected (branch2). In this branch, the ship's own PLC takes the initiative. It sends messages and waits for replies from the target (Figure 7).

To avoid a possible simultaneous activation of both branches, in case both ships detect prealert at the same time, their initial conditions cannot be simultaneously true.

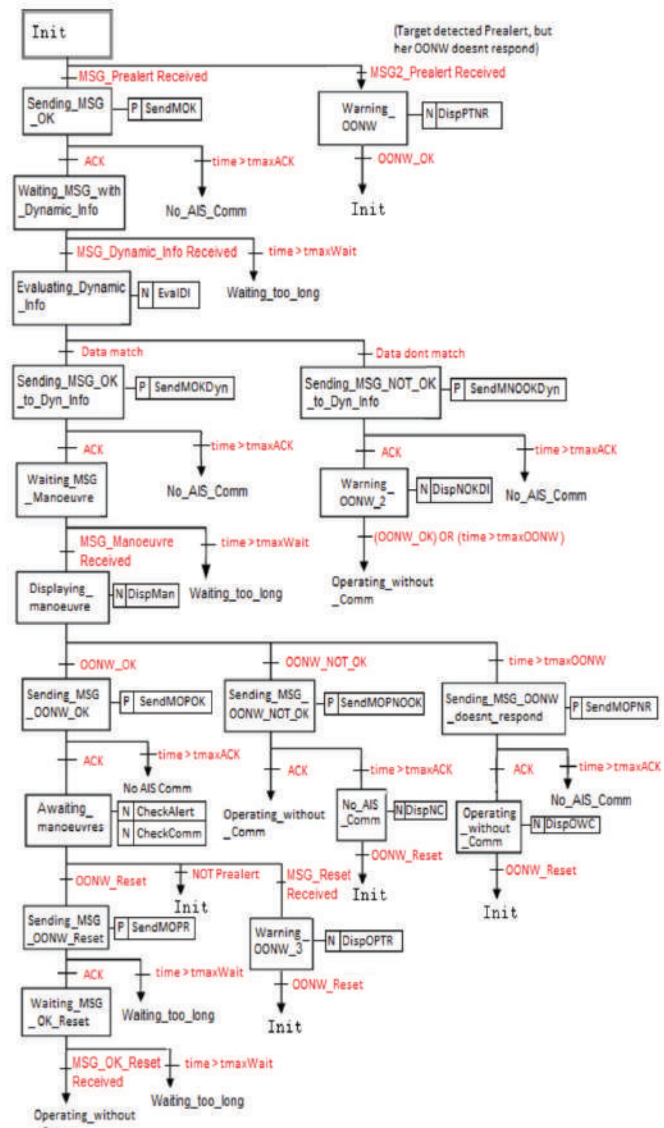

Figure 6. *SFC Branch1*

SFC: Sequential function chart

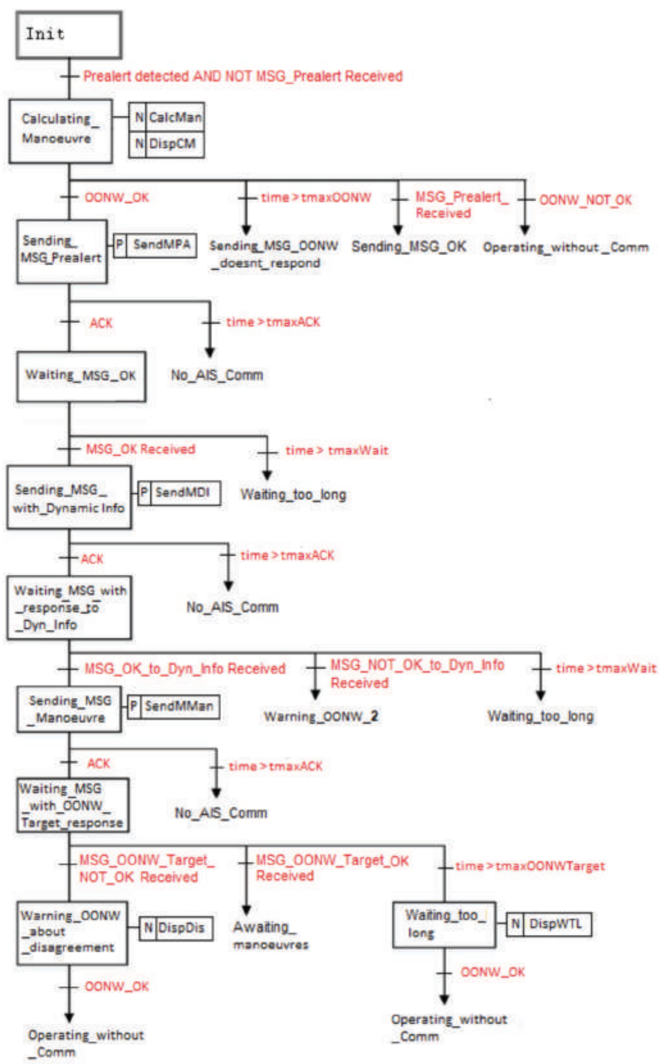

Figure 7. *SFC Branch2*

SFC: Sequential function chart

To this end, a priority is given to Branch1, including in the following initial condition of Branch2: *Prealert* detected AND NOT *MSG_Prealert* Received.

A feasible channel of communication between the PLCs of the ships can be achieved through their AIS stations, using standard messages 6 and 7 [13].

After sending a message, it is necessary to wait for the reception of the ACK issued by the AIS in the target, indicating that the message has been transmitted. If more time than expected (*tmaxACK*) elapses without receiving the ACK, it is understood that there has been a communication failure between the AIS stations, and the SFC moves to a *NO_AIS_Comm* step, wherein the operator is informed of the communication failure.

Other maximum waiting times associated with transitions should be established, as listed below:

- PLC communication message waiting time (*tmaxWait*).
- Waiting time for the OONW to respond to a received MSG (*tmaxOONW*).
- Waiting time for the target OONW to respond to the maneuvering proposal sent by own ship (*tmaxOONWTarget*).

The names of the actions in Figures 6 and 7 have been shortened to avoid overloading the images. Main assignments of the action POUs are as follows:

- *Send**: Generate the corresponding binary message and send it to the target.
- *Disp**: Display the corresponding text to inform the OONW.
- *EvalDI*: Compare the dynamic information sent by the target with the information available about it to check whether it is consistent. This dynamic information is included as parameters in the received message comprising visibility, navigational status, prealert and alert defined values, distance, bearing, CPA, TCPA, heading, speed, and the calculated situation according to COLREGs.
- *CalcMan*: With the dynamic data received from own and target ships, the calculated bearing, distance, CPA, TCPA, and situation, this POU determines what possible maneuver must be performed.
- *CheckAlert*, *CheckComm*: The step *Awaiting_maneuvers* is active if there is agreement between the OONWs of both ships about the maneuver to leave the prealert condition. While in this state, waiting for the agreed maneuver to be performed, *CheckAlert* determines if there is an alert condition. In that case, a warning is displayed, indicating that both ships must maneuver. *CheckComm* conducts periodic checking of the communication between the PLCs.

5. Results

The crossing situation described previously is used as an example for checking the operation of the developed POUs. These software tests require the simulation of the ship movements and the AIS messages for data acquisition and communications. The development of the models for the simulation of a ship movement follows the standard ISO 11674-A [14]. AIS messages have been simulated using OPC communications. All values to transmit are transformed into bit strings according to the standard approved by the International Telecommunication Union [15]. Each PLC acts as an OPC server to share the memory area reserved for messages. An application acting as an OPC client is responsible for reading the message string from the source PLC and writing it to the destination PLC.

The simulation starts with the data given in Figure 1. In our example, the PLCs in both ships, PINK and BLUE have an enabled SFC with the initial state active. At 3.2 miles (see Figure 2), PINK PLC detects prealert and activates its branch2 (see Figure 5). Then, it initiates the dialog with BLUE PLC. On receiving the message, the SFC running on BLUE progresses through its branch1.

Figure 8 shows the information visualized by each OONW with the data in the PLC of BLUE (PLC1) and PLC of PINK

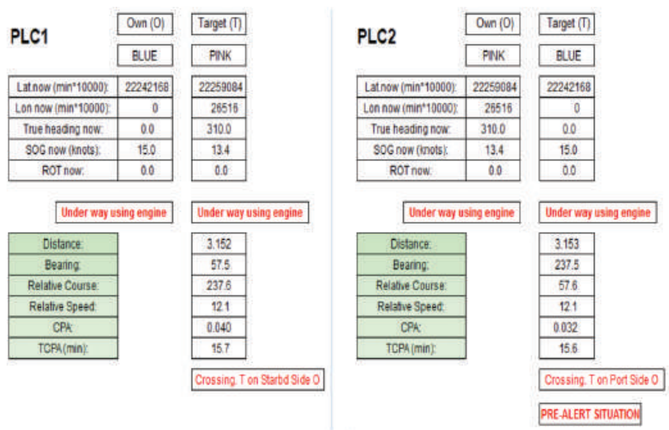

Figure 8. *Received and calculated data, PINK on prealert*

(PLC2), when PLC2 detects the prealert condition. In addition to the information received from the AIS on positions, headings, speed over ground, rate of turn, and the calculated data (distance, bearing, relative course and speed, CPA, and TCPA), BLUE OONW sees that both ships are Under way using engine (navigational status 0, from their AIS dynamic data) and the situation is crossing. T is on the Starbd Side O (crossing, PINK on BLUE's starboard side). PINK OONW sees that both ships are under way using engine, and the situation is crossing. T is on port side O (crossing, BLUE on PINK's port side) and the prealert SITUATION warning.

When PLC2 detects the prealert, and the evolutions through the SFCs start. Figure 9 shows the sequence of communications between PLCs and the messages displayed by the OONWs. First, PLC2 calculates the maneuver according to COLREGs and warns its OONW. If she/he agrees, it sends the message with the prealert to PLC1, waits for the reception of MSG OK, and later sends the message with the associated dynamic data to PLC1. PLC1 compares them with its own data and if they match, it sends MSG_OKDyn to PLC2. Then, PLC2 sends the MSG with the information about the maneuver and advises its OONW that it is waiting for an answer from BLUE OONW. PLC1 displays the received information, and if its OONW says OK, both PLCs inform about the agreement.

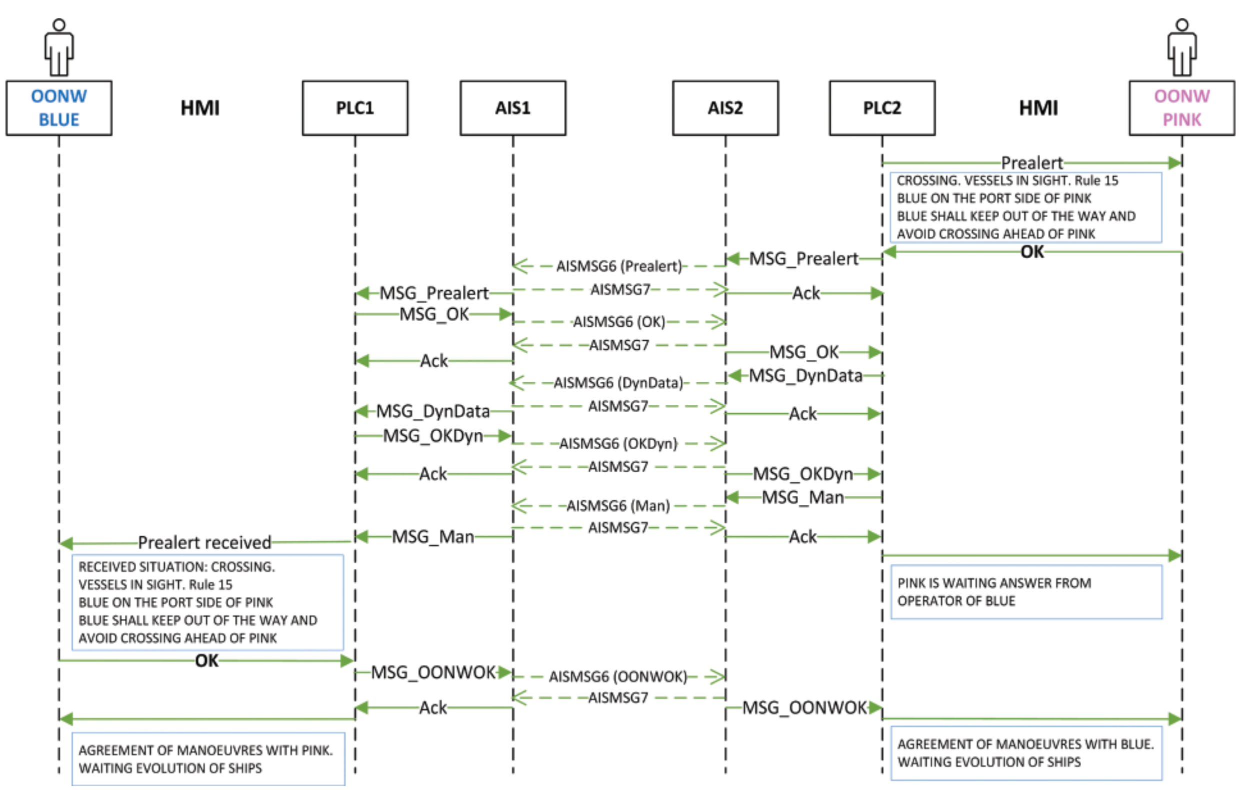

Figure 9. *Sequence of messages, in case of agreement between OONWs*

OONW: Officers in charge of the Navigational Watch

The same situation, but assuming a difference in the visibility criteria (PINK OONW considers that they are in a restricted visibility scenario and BLUE OONW that vessels are in sight) produces a sequence of messages shown in Figure 10.

The system informs both OONWs that PINK has entered in prealert, but that there is a difference in visibility considerations, and therefore, possible differences in maneuvering decisions. In this example, messages for OONWs in Figure 10 show the following:

• PINK OONW, after agreeing to apply COLREG Rule 19 sees that the target (BLUE) info is vessels IN SIGHT crossing starboard side (i.e., PINK is crossing on BLUE's starboard side). Therefore, PINK OONW infers that BLUE OONW will act according to this information and will apply COLREG Rule 15.

• BLUE OONW, considering that vessels are in sight, receives the message depicting that PINK is in prealert, and her info is vessels NOT IN SIGHT WITH RADAR, T FWD PSD O, O FWD T (BLUE forward on PINK's portside, PINK forward BLUE). Therefore, BLUE OONW infers that PINK OONW will act according to this information and will apply COLREG Rule 19.

Thus, both OONWs are aware that their maneuvering decisions may differ.

The graphical character of the language facilitates the design, verification, and validation of the software. It allows to visualize and check whether all possible states that the system can go through are considered, without probing how the actions are implemented. This makes it easier to understand how the system works for the potential users of the system.

The visualization of the program execution during software testing, showing which step is active at any given moment, makes it possible to check and verify all possible transitions.

6. Conclusions

A functional safety model has been developed for the prevention of ship-to-ship collisions, aimed at reducing the probability of occurrence of two dangerous factors among the main causes of these accidents:

• Errors in the detection of critical situations, and

• Errors in the decision-making on collision avoidance maneuvers.

For this purpose, the defined system is responsible for detecting and identifying the type of dangerous encounter, checking that both are handling the same information to suggest the manuever to be performed in compliance with COLREGs and to ensure that the operators of the vessels involved are aware of and accept (or not) the suggested maneuver.

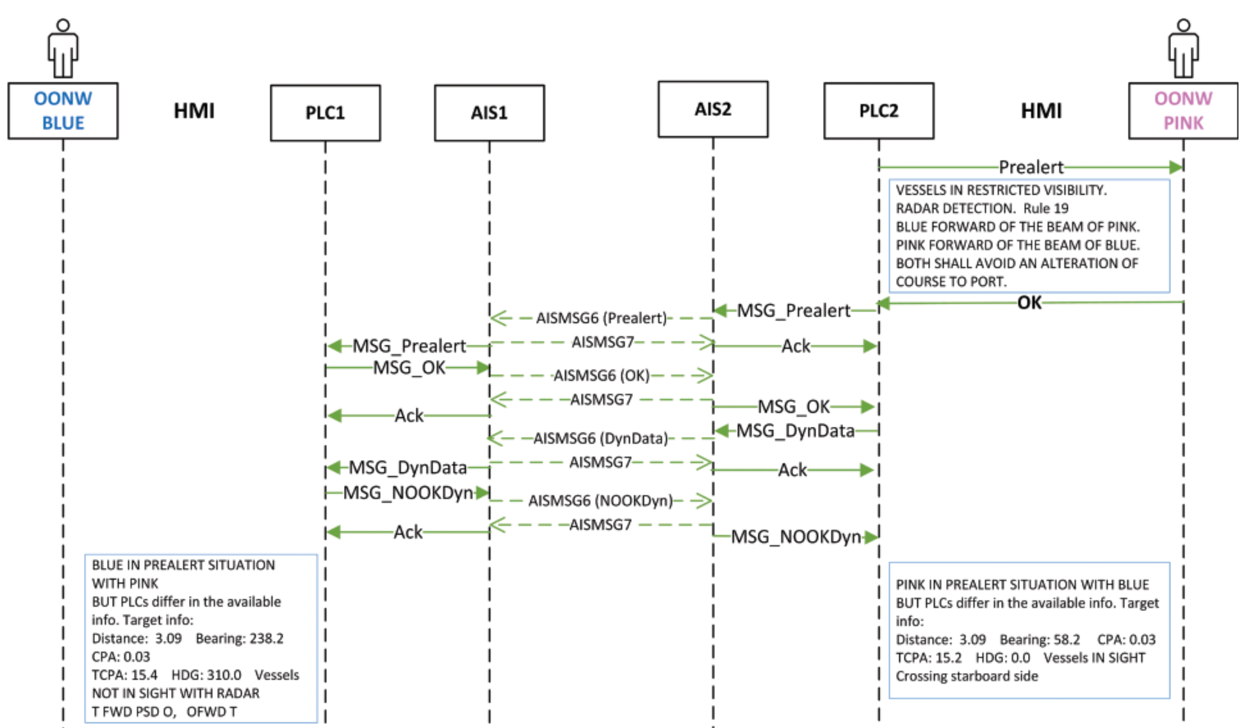

Figure 10. *Sequence of messages, in case of disagreement between data*

OONW: Officers in charge of the Navigational Watch

To reach these decision agreements, the system establishes a communication between the two ships. SFC, a finite state machine-based language, is used to model and program the set of states and transitions involved in the ship-to-ship dialogs initiated when one of them detects a risky situation. This language facilitates the development, verification, and maintenance of the program.

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Probability Theory Analysis of Maritime Piracy and the Implications for Maritime Security Governance

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Abstract

The objective of this study was to determine the empirical probability coefficients of pirate attacks on ships in various sea regions, individual ship types, and the occurrence probability scores of trauma associated with hostage-taking, injury, death, kidnap for ransom, missing, and threats to the lives of crew members effected by pirate attacks on ships. Secondary data on the frequency of pirate attacks on ships trading in various regions of the world were obtained from the International Maritime Bureau. The data covered 10 years, that is, between 2011 and 2020, and were analyzed using the empirical probability statistical method implemented with the MATLAB software. Results showed that Southeast Asian and African waters have the highest empirical probability coefficients of 0.40 and 0.39, respectively, and are most prone to pirate attacks on ships. Trauma associated with hostage-taking of the ship's crew has the highest probability coefficient and likelihood of occurrence of 0.76 compared with other effects of piracy affecting the ship's crew. Kidnap for ransom is second with an occurrence probability of 0.15. Chemical and product tankers have the highest likelihood of a pirate attack, with an occurrence probability of 0.26, followed by bulk carriers, crude oil tankers, container vessels, general cargo ships, LPG tankers, and trawler fishing vessels, with empirical probabilities of 0.24, 0.11, 0.11, 0.06, 0.04, and 0.02, respectively. The implications for maritime security governance were discussed.

Keywords: Maritime, security, governance, piracy, ship types, ship's crew

1. Introduction

Insecurity in the maritime domains of coastal states manifests in the form of piracy, terrorism, and armed robbery attacks on ships involved in seaborne trade over the years and has a negative impact on the development potential of the blue economy subsectors of the affected coastal states. For example, reports from the International Maritime Bureau (IMB) [1] revealed a sharp increase in attacks on ships and maritime insecurity in the African trade routes, such as the coast of the Horn of Africa and the Gulf of Aden (GOA), the east coast of Africa and the Gulf of Guinea (GOG), and the west coast of Africa. This increase in attacks has a direct disruptive effect on maritime logistics, supply chain, and trade flows, which subsequently threaten the African shipping trade and commerce with the rest of the world. The situation is similar in major sea routes and maritime regions of the world. Between 2011 and 2020, the IMB [2] reported an aggregate of 2,513 pirate attacks on ships trading in all sea regions of the world, that is, an average of 251 attacks per annum. However, the report noted that not all such attacks over the period were recorded. Table 1 shows the regional spread of global attacks on ships involved in seaborne trade globally.

Table 1 shows that maritime insecurity has affected major global maritime trade routes and regions, necessitating the need for the development and deployment of serious strategies for maritime security governance. Moreover, maritime security across global sea regions and shipping routes, particularly the Southeast Asian and African regions, is seriously threatened. Furthermore, the efficient and effective flow of shipping trade and seamless supply chain operations is threatened and disrupted. The consequence

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is cost-push inflation on the prices of import and export commodities [3]. From Asia to Africa and other regions, maritime trade, logistics, and supply chain networks face security risks and are threatened by the incessant scourge of maritime insecurity that has led to increased piracy-related insurance for ships transiting through piracy hotspots and increased and unstable freight and charter rates. Martínez-Zarzoso and Bensassi [4] estimated the annual cost expenditure for combating piracy and promoting maritime security globally at between $7 billion per annum and $12 billion per annum. Table 2 shows the disaggregated cost of pirate attacks on ships involved in maritime trade.

Apart from economic consequences, maritime piracy has a set of social and health implications and effects suffered by both ship's crew and passengers affected, which include the risk cum probability of injury and/or death, kidnapping for ransom, trauma associated with hostage-taking and torture, threats to life, and assault. Reports from the IMB [2] indicate that, between 2011 and 2020, the global injury burden suffered by ship's crew affected by pirate attacks in all sea regions is 156 injured persons, whereas the death burden representing the number of crew members killed by pirates over the same period is 24 persons (Table 3).

These findings underscore the fact that the socioeconomic effects of maritime insecurity are multifarious, thus the inevitable need for anti-maritime piracy measures to remedy the spate of insecurity in global waters and limit the socioeconomic impacts.

Table 1. *Regional spread of pirate attacks on ships involved in seaborne trade globally*

Sea region/zones	(i) Aggregate attacks 2011-2020	(ii) Regional attacks as a % of global attacks	(iii) Average attack per annum
Southeast Asian region	1.016	40.4%	101.6
Far East Asian region	118	4.7%	11.8
India subregion	183	7.28%	18.2
South America	212	8.4%	21.2
Africa	974	38.8%	97.4
Middle East as well as the rest of the world	10	0.39%	1.0
Global aggregate	2,513	100%	251.3
Source: (i) was aggregated from the IMB [2]. (ii) and (iii) were calculated by the authors			

Table 2. *Total estimated disaggregated cost of piracy in 2010*

Cost type	Cost ($)
Ransoms	$148 million
Insurance premiums	$460 million to $3.2 billion
Rerouting ships	$2.4 to $3 billion
Security equipment	$367 million to $ 2.5 billion
Naval forces	$2 billion
Prosecutions	$31 billion
Anti-piracy organizations	$19.5 billion
Cost to regional economies	$1.25 billion
Total estimated cost	$7 to $12 billion per year
Adapted from [4]	

Table 3. *Effects of pirate attacks suffered by seafarers between 2011 and 2020*

Outcome/risk type	Aggregate number of crew affected in all sea regions	Average per annum
Injury burden/seriously injured	156	15.6
Killed/death	24	2.4
Kidnapped for ransom	588	58.8
Source: IMB [2] Note: Authors' calculation		

Although many coastal states and the global shipping community have over the years responded to the scourge of maritime insecurity by promoting maritime security governance through the implementation of several anti-piracy measures, including direct combative measures such as the militarization of the waterways by deploying the navies and the implementation of anti-piracy regulations/legislations, vessel rerouting strategies, the International Ship and Port Facility Security (ISPS) code, and regional collaborative strategies. The implementation of various anti-piracy measures and the promotion of maritime security governance seem to have led to a declining trend in attacks on ships in some regions; however, maritime insecurity persists in some other regions, and the rate of decline in attacks in most regions seen to be rather insignificant [5-7].

The achievement of a secure maritime environment demands the eradication and suppression of acts of piracy and armed robbery against ships, which can be realized by maritime security governance through the deployment of knowledge-based security intelligence, technology, and legislation. The probability scores indicating the likelihood of occurrence of pirate attacks on individual ship types and in individual sea regions are an important example of a knowledge-based security intelligence needed to support current anti-piracy measures and promote maritime security governance to eradicate maritime piracy. To help the shipping industry, particularly ship operators and crew, acquire knowledge on and develop the capacity to understand the risk levels and likelihood of pirate attacks on individual ship types and the associated risks of kidnap for ransom, death, injury, torture, and hostage-taking, the empirical probability coefficients of pirate attacks on individual ships types and the coefficients of the empirical probability of risks of death, kidnap for ransom, injury, assault, torture, and hostage-taking associated with the attacks cum the probability coefficients of the likelihood of pirate attacks in various sea regions and trade routes need to be determined.

1.1. Objectives of this Study

The objectives of this study are:

(i) To determine the empirical probability coefficients of pirate attacks in Southeast Asia, the Far East, South America, Africa, the Indian subcontinent, and the Middle East as well as the rest of the world's maritime zones.

(ii) To measure the occurrence probabilities of death, kidnap for ransom, trauma associated with hostage-taking of crew members, assault, missing seafarers, and threats to the lives of seafarers following pirate attacks in global waters.

(iii) To estimate the empirical probability coefficient cum likelihood of pirate attacks on individual ship types in global sea routes.

The following constitute the research questions to be addressed in this study:

(i) What are the empirical probability coefficients of the likelihood of pirate attacks in Southeast Asia, the Far East, South America, Africa, the Indian subcontinent, and the Middle East as well as the rest of the world's maritime zones?

(ii) What are the occurrence probabilities of death, kidnap for ransom, trauma associated with hostage-taking of crew members, assault, missing seafarers, and threats to the lives of seafarers following pirate attacks in global waters?

(iii) What are the empirical probability coefficients cum likelihood of pirate attacks on individual ship types in global sea routes?

2. Literature Review

Several empirical studies have been conducted in an attempt to analyze the challenges of maritime insecurity caused by pirate attacks on ships involved in seaborne trade across global waters. For example, Ahmadi [8] reviewed the international legal regime of maritime piracy over the years to identify lacunas to legislations and legal frameworks as anti-piracy operations and policies in maritime states and used exploratory research approaches. Moreover, Ahmadi [8] recommended that dealing with maritime piracy involves coordinated and orchestrated efforts at different levels, including domestic, regional, and international. Furthermore, Ahmadi [8] noted that, although anti-maritime piracy operations have been successful in controlling and reducing piratical activities, for example, attacks on merchant vessels off the coast of Somalia have considerably reduced, the legal issues and the gaps in the international maritime piracy legal regime need to be identified. However, although the trend of attacks in most maritime domains, such as the Somali zone and the GOG, follows a decreasing trend, the rate of decrease is still insignificant and the economic impact on maritime trade and businesses is still significant [5,9]. One of the ways to accelerate the achievement of the current anti-piracy policies and further decrease the rate of attacks on ships is the determination of the ship types that are most prone to attacks, as well as the zones of most attacks and the probability and risk of attacks facing each ship type in various maritime zones and regions. This is a fact that the work presented in Ahmadi [8] did not address.

Mbekeani and Ncube [9], in a study for the African Development Bank, investigated the economic cost of maritime piracy, particularly in the African region, and determined that incidents of ship attacks in the waters of Africa are creating a challenge to maritime trade and other maritime economic opportunities. According to Mbekeani and Ncube [9], pirate attacks in the GOA have necessitated the adoption of the rerouting strategy by tanker operators to the Cape of Good Hope, which is approximately $3.5 billion in annual fuel costs. Mbekeani and Ncube [9] also noted that, although the fishery subsector is seriously hit economically by pirate attacks across the waters of Africa, in Seychelles alone, the cost of piracy is approximately 4% of the gross domestic product. The cost of piracy has increased the insurance costs and affected the development of the tourism potential of most coastal regions [9,10].

Ece and Kurt [7] analyzed maritime piracy in global waters using a quantitative approach and employed both primary data from surveys and secondary data from the IMB between 2015 and 2020 to analyze the attacks on ships in major global sea routes and regions and the frequency distribution method to examine the obtained data. The results of the study indicated that most piracy attacks occurred in 2015 (20.9%) and in March, April, and May (30.2%), with the prevalent time of attacks between 24:00 and 04:00 (29.2%). The results also indicated that most attacks occurred in Southeast Asian (42.6%) waters and the attackers in the majority of the attacks (79.1%) boarded the attacked vessels. Bulk carriers (BC) suffered the most attacks (28.6), and Marshall-Island-flagged ships were the most attacked (17.1%).

Hasan and Hasan [11] evaluated the effectiveness of the current regimes to combat piracy in the GOG. The study aimed to assess the application and shortcomings of the current arrangements in addressing the problem of piracy in the region. By employing data obtained from both secondary and primary sources, the study determined that the current anti-piracy strategies in the regions that focus more on the militarization of the waters in the regions have achieved minimal success as attacks continue over the years [11,12]. The findings support the propositions of the frustration-aggression theory and demand that the multifaceted approach requires the involvement of ship operators, coastal communities, navies of coastal states, and representatives of the government. Part of the approaches should be the economic emancipation of the youthful population in the coastal zones via meaningful employment opportunities. The involvement of the ship operators in the form of risk analysis and identification of piracy-prone zones, ship types, and information-sharing strategies is also important.

Nwokedi et al. [13] estimated the economic cost of output losses as a result of death and injury caused by maritime piracy and armed robbery in the ocean trawler fishery subsector of Nigeria and the global maritime industry and as economic justification for investment in remedial measures and policies against attacks in the subsector. The study used an ex post facto design approach where secondary data were obtained and analyzed using the gross output and empirical probability models to determine the output losses due to death and injuries to human capital caused by pirate attacks in the maritime industry [13]. The study developed a model for the estimation of output losses due to death and injury based on the relationship between the empirical probability coefficients of each risk type, the per capita output of the economy, and the number of maritime workers exposed to pirate attacks in any given economy [13].

Knyazeva and Korobeev [14], in the study entitled "Maritime Terrorism and Piracy: The Threat to Maritime Security," established the distinctive features of piracy and maritime terrorism. By employing secondary data from the databases of the International Maritime Organization and IMB, the study determined the maritime regions prone to piracy and terrorist attacks. The authors opined that the anti-piracy approaches, policies, and measures cannot work in the case of combating maritime terrorism because available evidence indicates that the acts are committed with different intentions and motivated by different purposes [14,15].

Özdemir and Güneroğlu [16], in the study entitled "Quantitative Analysis of the World Sea Piracy using fuzzy AHP and fuzzy TOPSIS Methodologies," investigated the factors causing piracy incidents and the most significant practical and applicable solutions to the problem. The expert opinions on the criteria set were analyzed by applying fuzzy AHP and fuzzy TOPSIS techniques to determine the significance level and ranking of the alternatives. Among all criteria, economic insufficiency received the maximum score as the most effective cause of sea piracy, whereas the geographic location of the canals and straits that are in risky regions of the world was identified as the least effective factor.

In a different study, Livingstone et al. [17] examined global maritime piracy, its impact on seafaring, and the factors shaping confrontational outcomes of piracy. The objective of the study was to determine the factors that affect the crew members' attitude toward their job, including piracy, as well as the determinants of the success and failure of global maritime piracy, particularly the role of crew members. The study employed primary data obtained through surveys. The results of the study indicated that the fear of being captured (kidnapped) at sea by pirates significantly influence seafarers' decision to move from working onboard ships to landside jobs. The study recommended that shipping industry employers should conduct a thorough appraisal of the effects of maritime piracy on recruitment efforts and develop policies to mitigate these effects to ensure improvement in seafarers' productivity.

Finally, Helmick [18] assessed the key cost impacts of global piracy and armed robbery attacks on global supply chain operations and discussed strategies that can be employed to evade, deter, and mitigate this threat. The study identified the implications of piracy and armed robbery for supply chain partners to include seafarer abuse, injury, or death; the need for premium crew compensation; the payment of hostage ransoms; elevated insurance premiums; delayed cargo delivery; reduced cargo value; higher fuel costs; security equipment expenses; and the need for embarked security teams. Moreover, the study identified the implementation of best management practices as one of the strategies that can be used to address the threat of piracy to supply chain security without specific mention of particular best management strategies [18,19].

The current study overcame the gap of non-identification of specific empirically based anti-piracy strategies by developing occurrence probability coefficients of pirate attacks in specific regions and on individual ship types, which are important empirical information for evading and deterring pirate attacks, and the impacts on supply chain security.

The most important alternative to offering a solution to this problem was established as "providing support to local and regional authorities in risky regions", whereas the least important alternative was confirmed as "providing rehabilitation to individuals or groups whose actions tend to fuel pirate attacks".

The question of what constitutes in empirical terms the probability coefficients of pirate attacks on ship types (bulkers, tankers, general cargo vessels, passenger vessels, and cruise ships) involved in seaborne voyages in various sea regions seems currently lacking. Similarly, the available empirical literature has not tried to investigate what constitutes the occurrence probability coefficients and likelihood occurrence of death, kidnap for ransom, missing, trauma, assault, and threats to life associated with pirate attacks on crew members.

3. Data and Methods

The secondary data on the frequency of global pirate attacks on individual ship types between 2011 and 2020 was obtained from the IMB. The time series data on the spread of attacks on ships in global waters in various regions, such as the Southeast Asian region, Far East, Indian subcontinent, South America, Africa, and the Middle East as well as the rest of the world, covering 10 years, that is, between 2011 and 2020, were also obtained. Frequency data on the effects of the pirate attacks suffered by ship's crew, consisting of injury to crew, death/killed, kidnapped for ransom, assaulted, trauma/hostage, missing crew, and threats to life, covering the period between 2011 and 2020 were also obtained. Each category of the dataset was analyzed using the empirical probability statistical method implemented with the MATLAB software.

3.1. Empirical Probability

Probability theory deals with chance or stochastic processes. Empirical probability measures the likelihood that an event may occur based on historical data. The empirical probability coefficient is a numerical value or score that measures the likelihood that some events will occur based on past and/or historical data. Pirate attacks on ships are a stochastic occurrence, and pirate attacks on a given ship in the maritime zones, that is, Southeast Asia, Far East region, Indian subcontinent, South American region, Africa, and the Middle East as well as the rest of the world, are a mutually exclusive stochastic event [20]. Therefore, frequency data on global attacks spread across the identified piracy-prone maritime zones can be employed as the basis for estimating the empirical probability coefficients of pirate attacks in each zone. The empirical probability P_e of an event e is expressed as follows:

$$P_e = \frac{F}{N}, \tag{1}$$

where F is the frequency/number of successful occurrences in the past, N is the aggregate frequencies representing the number of possible outcomes, and P_e is the empirical probability coefficient showing the likelihood of occurrence of event e.

The IMB (2021) divided the global maritime zones prone to insecurity challenges into six regions consisting of Southeast Asia, the Far East region, the Indian subcontinent, the South American region, Africa, and the Middle East as well as the rest of the world. The empirical probability coefficient showing the likelihood that a vessel trading or on a voyage in each of the regions may be attacked by pirates can be estimated using Equation (1) modified as follows:

For example, the empirical probability P_e of pirate attacks in the Southeast Asia region is expressed as follows:

$$P_{e1} = \frac{FSEA}{N}, \tag{1a}$$

where $FSEA$ is the frequency of attacks in the waters within the Southeast Asian region between 2011 and 2020 and N is the aggregate global attacks on ships involved in seaborne trade between 2011 and 2020.

The empirical probability coefficients showing the likelihood of pirate attacks in the remaining regions of the Far East region, Indian subcontinent, South American region, Africa, and the Middle East as well as the rest of the world are expressed as follows:

For the Far East region, the empirical probability:

$$P_{e2} = \frac{FFER}{N}, \tag{1b}$$

For the Indian subcontinent:

$$P_{e3} = \frac{FISC}{N}, \tag{1c}$$

For the South American region:

$$P_{e4} = \frac{FSAR}{N}, \tag{1d}$$

For African waters:

$$P_{e5} = \frac{FAFR}{N}, \tag{1e}$$

For the Middle East as well as the rest of the world:

$$P_{e6} = \frac{FMEW}{N}, \tag{1f}$$

where *FFER*, *FISC*, *FSAR*, *FAFR*, and *FMEW* denote the frequencies of attacks in the Far East, Indian subcontinent, South American region, Africa, and the Middle East as well as the rest of the world between 2011 and 2020.

Based on the rules of probability theory, the following expression can be derived:

$$\sum P_{e1} + P_{e2} + P_{e3} + P_{e4} + P_{e5} + P_{e6} = 1 .$$

Similarly, the IMB [2] indicated that the attacks are spread over a total of 28 ship types, which include accommodation barge (AB), BC, cement carriers (CC), container ships (CS), dredger (D), drilling rig (DR), Floating production storage and offloading (FPSO), general cargo ships (GCS), heavy lift vessel (HLV), ore carrier (OC), passenger ships (PS), pipe layer vessel (PLV), pleasure craft (PC), refrigerated cargo ship (RCS), research vessel (RV), supply ship (SS), support vessel (SV), tanker/asphalt/bitumen (TAB), RORO, tanker bunkering (TB), tanker/chemical/product (TCP), tanker-crude oil (TCO), LNG tanker, LPG tanker, trawler fishing vessel (TFV), tug/offshore tug, vehicle carrier (VC), and yachts [20].

We determined the empirical probability coefficients of pirate attacks on individual ship types (P_{st}) over the period by employing the frequency of attacks on each ship type between 2011 and 2020 and the aggregate attacks on all ship types, that is:

$$P_{st} = \frac{ST_f}{N}, \tag{2}$$

where ST_f is the frequency of attacks on a given ship type (*ST*) over the period and *N* is as defined previously.

For example, the empirical probability coefficient of pirate attacks on ABs P_{AB} over the period is expressed as:

$$P_{AB} = \frac{AB_f}{N}. \tag{3}$$

Based on the rules of probability theory, the aggregate empirical probably coefficients ($P_{staggregate}$) of global attacks on all 28 ship types must not be equal to 1 [20,21], that is:

$$P_{staggregate} = \frac{ST_{faggregate}}{N} = 1.$$

Therefore:

$$\sum \frac{AB_f}{N}_t + \frac{BC_f}{N} + \frac{CC_f}{N} + \frac{CS_f}{N} + \frac{D_f}{N} + \frac{DR_f}{N} + \frac{FPSO_f}{N} + \frac{GCS_f}{N} +$$

$$\frac{HLV_f}{N} + \frac{OC_f}{N} + \frac{PS_f}{N} + \frac{PLV_f}{N} + \frac{PC_f}{N} + + \frac{RCS_f}{N} + \frac{RV_f}{N} + \frac{SS_f}{N} +$$

$$\frac{SV_f}{N} + \frac{TAB_f}{N} + \frac{RORO_f}{N} + \frac{TB_f}{N} + \frac{TCP_f}{N} + \frac{TCO_f}{N} + \frac{LNG_f}{N} + \frac{LPG_f}{N} +$$

$$\frac{TFV_f}{N} + \frac{TUG_f}{N} + \frac{VC_f}{N} + \frac{YACHTS_f}{N} = 1,$$

where $\sum \frac{AB_f}{N}_t$ is the empirical probability coefficient of pirate attacks on AB ship types between 2011 and 2020 and

$\frac{BC_f}{N}, \frac{CC_f}{N}, \frac{CS_f}{N}, \frac{D_f}{N}, \frac{DR_f}{N}, \frac{FPSO_f}{N}, \frac{GCS_f}{N}, \frac{HLV_f}{N}, \frac{OC_f}{N}, \frac{PS_f}{N}, \frac{PLV_f}{N},$

$\frac{PC_f}{N}, \frac{RCS_f}{N}, \frac{RV_f}{N}, \frac{SS_f}{N}, \frac{SV_f}{N}, \frac{TAB_f}{N}, \frac{RORO_f}{N}, \frac{TB_f}{N}, \frac{TCP_f}{N}, \frac{TCO_f}{N},$

$\frac{LNG_f}{N}, \frac{LPG_f}{N}, \frac{TFV_f}{N}, \frac{TUG_f}{N}, \frac{VC_f}{N}, \frac{YACHTS_f}{N}$

are the respective empirical probability coefficients of pirate attacks on individual ship types, that is, BC, CC, CS, Ds, DRs, floating production, storage and off-loading ships, GCS, HLVs, OCs, PS, PLVs, PCs, RCSs, RVs, SSs, SVs, TAB, RORO vessels, TB, TCP, TCO, LNG tanker, LPG tanker, TFVs, tugs/offshore tugs boats, VCs, and yachts [20].

Using Equation (2) and the respective frequencies of pirate attacks on the identified individual ship types over the period, the study estimated the empirical probability coefficients of all individual ship types.

3.2. Limitations of the Study

The data used in this study was obtained from the IMB piracy reports. Some pirate attacks in the industry may go unreported according to general public opinion. Therefore, the accuracy of these estimations and findings of the study may be influenced to a large extent by the accuracy of the data used.

4. Results and Discussion

The results of this study presented in Table 4 indicate the empirical probability coefficients of pirate attacks in each of the six sea regions between 2011 and 2020. For example, the highest likelihood/probability of occurrence of pirate attacks on ships occurred in 2015 in Southeast Asian waters, with an empirical probability coefficient of 0.58. This finding indicates that the likelihood of pirate attacks on ships on Southeast Asian sea routes is highest in 2015, with an empirical probability score that is close to 1, indicating that it is approximately 58% likely that ships trading within that region in 2015 will experience attacks by pirates.

The results shown in Table 4 also provide answers to research question (i) identified in Section 1.1. The average empirical probability coefficient of pirate attacks between 2011 and 2020 in the sea routes in Southeast Asia, Far East Asia, Indian subcontinent, South America, Africa, and the Middle East as well as the rest of the world is 0.40, 0.05, 0.07, 0.08, 0.39, and 0.004, respectively. The Southeast Asian sea region has the highest probability (0.40) of global occurrence probability, the African sea routes have the second-highest occurrence probability of pirate attacks of 0.39, and the Middle East as well as the rest of the world has the least occurrence probability (0.004) of attacks on ships. Notably, the aggregate occurrence probability coefficients is 0.4+0.05+0.07+0.08+0.39+0.004=1, which indicates the non-violation of the probability rule of the sum of probabilities of a sample. The results also show that the likelihood/occurrence probability of pirate attacks on ships is $P_{e1} > P_{e5} > P_{e4} > P_{e3} > + P_{e2} > P_{e6}$. This finding indicates that the likelihood/occurrence probability of pirate attacks in Southeast Asian sea routes (P_{e1}) is the highest globally, followed by the occurrence probability in African routes (P_{e5}), South America (P_{e4}), the Indian subcontinent (P_{e3}), Far East, and the Middle East as well as the rest of the world (P_{e6}). The closer the probability score is to 1, the greater the certainty of the occurrence of attacks in the region. Meanwhile, the farther the coefficient of probability score of a region is to 1, the less the likelihood of pirate attacks in the region. For example, Southeast Asian sea routes with a probability coefficient of 0.40 are closer to those with 0.004, and the occurrence of pirate attacks on ships in the region is most likely than in the Middle East region with an occurrence probability coefficient of 0.004, which is far from 1. The implications for maritime security governance is that ship operators trading in the Southeast Asian and African sea regions with the highest occurrence probabilities should develop and deploy more sophisticated anti-piracy measures and shipboard security defense mechanisms than those operating in the less piracy-prone regions with negligible occurrence probabilities, such as the Middle East, Far East, and Indian subcontinent. Similar to the implementation strategy of the ISPS code maritime security instrument, the global sea regions identified are ranked in three orders or levels of maritime security based on the empirical probability coefficients and the likelihood of pirate attacks on ships over the years. The purpose of the ranking is to guide authorities on the prioritization of maritime security governance strategies and anti-piracy measures. The security levels can be used to determine the intensity of implementation of security and anti-piracy strategies and the level of sophistication of such strategies (Table 5).

Table 4. *Empirical probability coefficients of piracy in various sea regions between 2011 and 2020*

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average
Year	0.18	0.52	0.49	0.57	0.58	0.37	0.42	0.30	0.33	0.32	0.40
SE Asia = P_{e1}	0.05	0.02	0.05	0.03	0.13	0.08	0.02	0.04	0.03	0.02	0.05
Far East Asia = P_{e2}	0.04	0.05	0.09	0.14	0.09	0.09	0.08	0.09	0.03	0.05	0.07
Indian subcontinent = P_{e3}	0.06	0.04	0.07	0.02	0.03	0.14	0.13	0.14	0.18	0.16	0.08
S. America = P_{e4}	0.67	0.38	0.30	0.23	0.14	0.33	0.32	0.43	0.44	0.45	0.39
Africa = P_{e5}	0.005	-	-	0.01	0.004	0.01	0.02	-	-	-	0.004
Middle East (as well as the rest of the world) = P_{e6}	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Global aggregate											

Table 5. *Ranking the maritime zones in decreasing order of occurrence probability of pirate attacks*

Security level/ rank(s)	Sea regions	Empirical probability coefficient(s)	Remarks
Security level 1	Southeast Asia	0.04	Deploy the most intensified maritime security and anti-piracy measures
	Africa	0.39	
Security level 2	South America	0.08	Deploy more serious anti-piracy measures than is implemented in security level 3
	Indian subcontinent	0.07	
Security level 3	Far East	0.005	Deploy less sophisticated anti-piracy measures than needed in security levels 1 and 2
	Middle East as well as the rest of the world	0.004	
Source: Authors' calculation			

The occurrence probability scores show the proneness of ships to attacks in the regions between 2011 and 2020. The ships trading in the waters in Southeast Asia and Africa are far more prone to pirate attacks than in other regions. The findings of the study corroborate the findings of Özdemir and Güneroğlu [16] and Coggins [19] who agreed that the Southeast Asian region poses the greatest risk for piracy and armed attacks on ships involved in seaborne trade. However, their study approaches are different as they did not employ a probability approach such as that used in the current study and which present a novel and simple but empirically based approach toward analyzing the incidents of piracy in global maritime domains. The probability approach analysis is considered better because the spatial distribution of pirate attacks on ships is a stochastic occurrence.

The results shown in Table 6 provide answers to research question (ii) identified in Section 1.1. Notably, the probability scores of each pirate attack are associated with the effects and outcome types in each of the years covered in the study between 2011 and 2020. The occurrence probabilities indicate the respective likelihood of occurrence and risk of assault, trauma/hostage, injury, kidnap for ransom, death/killed, missing, and threats to life facing the ship's crew as a result of pirate attacks each year between 2011 and 2020. The results indicated that the average occurrence probability coefficient of assault, trauma associated with hostage-taking of crew members, injury to crew, kidnap for ransom, death/killed, missing crew members, and threats to the lives of crew members is 0.01, 0.76, 0.04, 0.15, 0.01, 0.001, and 0.03, respectively. The sum of the average probabilities is also 1, which indicates the non-violation of the probability rule of the sum of probabilities of a sample. This finding is similar to the findings of Nwokedi et al. [13] who reported that trauma associated with hostage-taking of crew members constitutes most of the outcomes of piracy attacks on ships suffered by crew members of fishing boats attacked in Nigerian waters.

This finding indicates that the ship's crew faces trauma associated with hostage-taking of crew members as the highest risk suffered by the crew associated with pirate attacks on ships. With the empirical probability coefficients of 0.76>0.15>0.04>0.03>0.01>0.001, the likelihood of a ship's crew suffering trauma as a result of being taken hostage by pirates is far higher than being injured, killed, kidnapped for ransom, assaulted, threatened, and going missing. The probability of being kidnapped for ransom has

Table 6. *Occurrence probability of the outcomes/effects of pirate attacks suffered by crew*

Effect/outcome type/year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average
Assaulted	0.01	0.01	-	0.002	0.04	0.02	0.03	-	0.01	0.03	0.01
Trauma/hostage	0.89	0.88	0.82	0.92	0.81	0.64	0.48	0.59	0.28	0.18	0.76
Injured	0.05	0.04	0.05	0.03	0.04	0.03	0.03	0.03	0.03	0.05	0.04
Kidnap for ransom	0.01	0.04	0.09	0.02	0.06	0.26	0.39	0.34	0.64	0.70	0.15
Killed/death	0.01	0.01	0.003	0.01	0.003	-	0.02	-	0.01	-	0.01
Missing	-	-	-	0.002	0.003	-	-	-	-	-	0.001
Threatened	0.03	0.02	0.03	0.02	0.04	0.04	0.05	0.04	0.03	0.04	0.03
Aggregate	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Source: Authors' calculation											

Table 7. *Ranking the effects suffered by crew members affected by pirate attacks in decreasing order of occurrence probability*

Outcome types/ effects	Occurrence probability coefficient(s)	Levels/rank(s)	Remarks
Trauma/hostage	0.76	Rank 1	Most dominant effect of attack suffered by ship's crew between 2011 and 2020
Kidnap for ransom	0.15	Rank 2	Second-ranked outcome suffered by the crew
Injury	0.04	Rank 3	Third most outcome/effect of attacks on ships suffered by ship's crew
Threatened	0.03	Rank 4	-
Killed/death	0.01	Rank 5	
Assaulted	0.01		
Missing	0.001	Rank 6	Least effect suffered by the ship's crew
Source: Authors' calculation			

a coefficient of 0.15 and has the second-highest likelihood/probability of occurrence associated with pirate attacks on ships in global waters, followed by the occurrence probability of injury to crew members (0.04) and threats to life (0.03). Assault on crew members and death have the same occurrence probability coefficient of 0.01, whereas missing crew has the lowest occurrence probability of 0.001, indicating the least chance of occurrence. Based on the results shown in Table 6, we ranked the outcomes and effects of pirate attacks on ships affecting crew members in decreasing order of occurrence probability. This finding corroborates the findings of Livingstone et al. [17] that kidnapping a ship's crew for ransom significantly influences seafarers to change from onboard jobs to shore-based jobs. Even though the study did not proceed to estimate the occurrence probability of kidnapping for ransom, it is identified as a significant effect of pirate attacks on ships affecting crew members (Table 7).

The implication for maritime security governance is that the deployment of shipboard security measures and defense strategies should focus more on averting trauma associated with hostage-taking of crew members, kidnapping a ship's crew for ransom, and injury, which has the highest occurrence probability and likelihood.

Table 8 provides answers to research question (iii) identified in Section 1.1. The table shows the empirical probability coefficients of global pirate attacks on individual ship types between 2011 and 2022. The average empirical probability coefficient, which indicates the occurrence probability of

Table 8. *Empirical probability scores of pirate attacks on individual ship types between 2011 and 2020*

Ship type/year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average
Accommodation barge	-	0.02	-	-	-	0.005	-	-	-	0.005	0.003
Bulk carrier	0.23	0.15	0.20	0.23	0.35	0.27	0.21	0.29	0.29	0.26	0.24
Cement carrier	-	0.01	-	0.004	-	-	0.006	-	-	-	0.002
Container ship	0.14	0.11	0.11	0.08	0.12	0.05	0.13	0.09	0.12	0.12	0.11
Dredger	0.002	0.01	-	-	-	0.005	-	-	-	-	0.002
Drilling rig/ship	0.002	0.01	-	-	-	-	-	0.005	-	0.005	0.003
FPSO/FSO	-	0.01	-	-	0.008	-	-	-	-	0.005	0.003
General cargo	0.09	0.05	0.07	0.06	0.06	0.06	0.07	0.03	0.04	0.07	0.06
Heavy lift vessel	0.05	0.01	-	0.004	-	0.02	-	0.005	-	-	0.005
Ore carrier	-	0.01	-	-	0.004	0.005	-	0.005	-	-	0.003
Passenger ship	0.002	0.01	-	0.004	0.004	-	-	-	0.006	-	0.003
Pipe layer barge/vessel	-	0.01	-	-	0.004	0.02	-	-	-	0.01	0.005
Pleasure craft	0.002	0.01	-	-	-	-	-	-	0.006	-	0.002
Refrigerated cargo ship	0.009	0.02	0.008	-	0.01	0.005	0.01	0.03	-	0.02	0.01
Research ship	-	0.01	-	0.008	-	0.01	0.01	-	0.006	0.005	0.005
Supply ship	0.002	0.03	0.02	0.01	0.008	0.02	0.04	0.03	0.01	0.04	0.02
Support ship	-	0.01	-	0.004	-	0.005	0.01	0.01	0.006	0.02	0.006
Tanker/asphalt/bitumen	0.002	0.01	0.01	0.02	-	0.005	0.006	0.005	-	0.005	0.006
RORO	0.007	0.02	0.004	0.008	-	-	-	0.01	-	-	0.006
Tanker bunkering	-	0.02	-	0.008	0.004	0.005	0.006	-	-	0.005	0.005
Tanker/chemical/product	0.22	0.20	0.31	0.36	0.23	0.29	0.25	0.25	0.27	0.27	0.26
Tanker-crude oil	0.15	0.10	0.15	0.10	0.07	0.07	0.12	0.08	0.12	0.07	0.11
LNG tanker	-	0.02	-	0.004	-	0.005	0.02	0.02	0.01	0.005	0.007
LPG tanker	0.01	0.04	0.03	0.05	0.06	0.05	0.06	0.03	0.04	0.02	0.04
Trawler fishing	0.03	0.02	0.02	0.01	0.008	0.005	0.006	0.06	0.03	0.03	0.02
Tug/offshore tug	0.07	0.07	0.07	0.03	0.04	0.07	0.06	0.06	0.04	0.04	0.06
Vehicle carrier	0.02	0.01	-	0.008	0.004	0.01	-	0.005	0.01	-	0.008
Yacht	0.009	0.005	-	-	-	-	-	-	0.006	-	0.003
Aggregate probability	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Source: Authors' calculation

pirate attacks on individual ship types, shows that chemical and petroleum product tankers have the highest likelihood/occurrence probability of pirate attack with a coefficient of 0.26, followed by BC with an occurrence probability coefficient of 0.24. Crude oil tankers and CS each with a probability score of 0.11 have the third-highest likelihood of pirate attacks over the period. This finding indicates that chemical and product tankers, BC, crude oil tankers, and container vessels are the most pirate-targeted ship types. The implication for maritime security governance is that operators of ship types, such as chemical and product tankers, BC, crude oil tankers, container vessels, and general cargo vessels, with the most likelihood of pirate attacks should optimize the implementation of anti-piracy strategies needed to ensure the protection of the ship, trade, and crew against pirate attacks. The implementation of anti-piracy and maritime security measures for such ship types with a higher likelihood of pirate attacks should be intensified. Figure 1 shows the ranking of the individual ship types in decreasing order of likelihood of pirate attacks. The findings of the study are consistent with the findings of Helmick [18] who determined that pirate attacks on individual ship types disrupt supply chain security and could threaten the supply of the commodity types carried by affected ships in global markets.

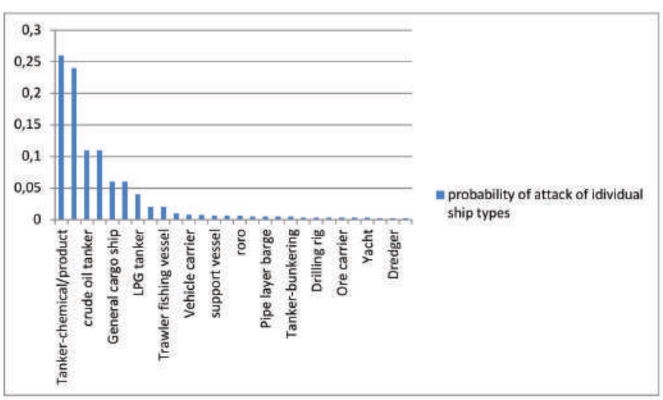

Figure 1. *Ranking of individual ship types in decreasing order of likelihood of pirate attacks*

5. Conclusion

The findings of this study indicate that the empirical probability coefficients of pirate attacks in various sea regions are disproportionate, with Southeast Asian and African waters having the highest occurrence probability scores and being most prone to pirate attacks on ships. Trauma associated with hostage-taking of the ship's crew has the highest occurrence probability coefficient than any other outcome/effect of pirate attacks suffered by the ship's crew, followed by kidnap for ransom with an occurrence probability of 0.15. For individual ship types, chemical and product tankers with an occurrence probability of 0.26 have the highest likelihood of pirate attacks, followed by BC, crude oil tankers, container vessels, GCS, LPG tankers, and TFVs with occurrence empirical probabilities of 0.24, 0.11, 0.11, 0.06, 0.04, and 0.02, respectively. Dredgers have the least likelihood of pirate attacks with an empirical probability of 0.002. The implications for maritime security governance are that sea regions, individual ship types, and outcomes/effects of pirate attacks on seafarers with higher occurrence probabilities should be prioritized when implementing anti-piracy measures. Moreover, the higher the occurrence probability coefficient of pirate attacks, the more the need for stricter implementation of anti-piracy measures in such regions, ship types, and the control of pirate attack outcome/effect types on the crew.

6. Recommendations

For maritime security governance, in the deployment of anti-piracy measures, the maritime zones and individual ship types having the highest occurrence probability scores should be prioritized and focused more upon. The ship's crew should also be trained to guard against the effects of pirate attacks suffered by crew members by prioritizing the deployment of shipboard security and defense mechanism against the outcome types with the most occurrence probabilities and likelihood such as trauma/hostage and kidnap for ransom.

7. Suggestions for Further Studies

Given the empirical probability coefficients determined, further studies must be conducted to forecast and extrapolate the numbers of likely attacks on ships in various regions, individual ship types, and the quantum of kidnapping for ransom, trauma, death of crew members, physical injury, and assault in the future. Further studies will provide information on the deployment of anti-piracy measures to proactively prevent the attacks and the associated effects.

Authorship Contributions

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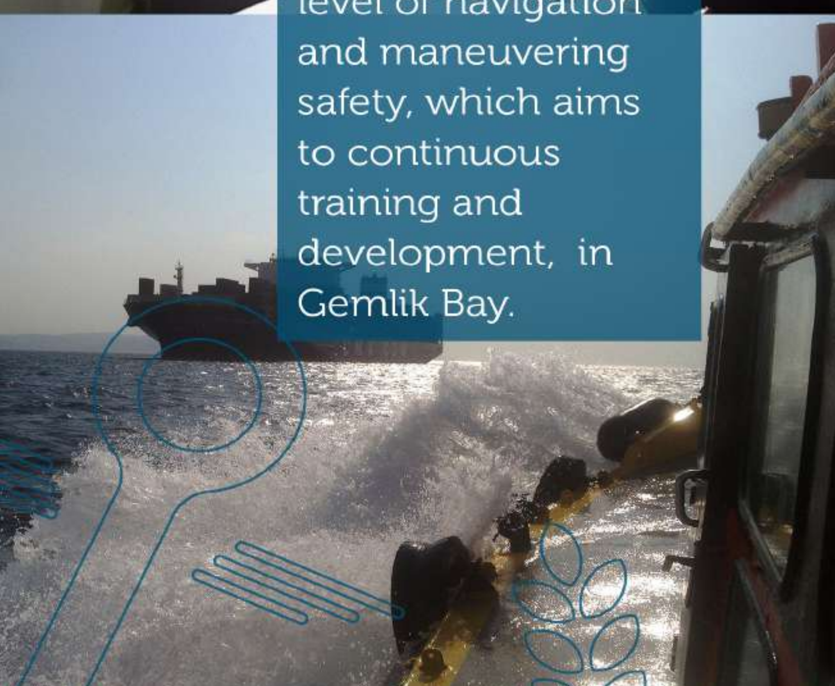

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