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An Application of Fuzzy AHP Using Quadratic Mean Method: Case Study of ENC Preparation Process for Intended Voyages

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Abstract

Effective management of the electronic nautical charts (ENCs) preparation process using the electronic chart display and information system (ECDIS) is crucial to ensure the safety of ships. Delays or failures in this process can prevent the creation of a safe voyage plan and result in delays or maritime accidents, which may damage a company's reputation. To identify risk factors causing such issues, the quadratic mean method-based Fuzzy Analytical Hierarchy Process was used to weigh and determine the most prominent ones. Additionally, the study proposes specific solutions to eliminate each risk factor. The study's outputs are expected to improve the management of ENC preparation, which is a frequent task for ships using electronic navigation.

Keywords: Risk assessment, ECDIS, ENC, Fuzzy analytic hierarchy process, Quadratic mean method

1. Introduction

Technological developments have revolutionized navigation, with merchant ships increasingly relying on electronic chart display and information systems (ECDIS) for navigation using electronic nautical charts (ENCs). The ENCs are official navigation charts in digital form, produced by national hydrographic centers [1]. Two types of ENCs are widely used: raster and vector-based [1,2]. Raster navigational charts are digitalized versions of official paper nautical charts [2], whereas electronic navigational charts with vector chart format record digitized data for all charted features needed for safe navigation [3]. The introduction of ECDIS/ENCs on board ships has drastically changed classical navigation practices [4]. Particularly, they are critical in reducing the workload involved in the paper chart-based voyage plan preparation process [4] and improving marine safety [4,5].

Although, earlier, ECDIS/ENC utilization on ships was voluntary [6], now, it has become mandatory navigational equipment under certain conditions [4,6-8]. This obligation has imposed new critical process management responsibilities on ship owners, managers, captains, and navigation officers to ensure marine safety. Among these responsibilities, the ENC preparation process for the intended voyage is a critical process that requires careful management, including obtaining the necessary ENCs, uploading them to the ECDIS, and keeping them updated for safe navigation. Failure in this process may result in operational setbacks that could endanger navigational safety, leading to fatal maritime accidents. Furthermore, failure in the ENC preparation process can cause delays in ship voyages, resulting in economic and reputational losses for companies. Therefore, academic studies aim to identify and eliminate operational errors in this process, enhance marine safety and prevent possible voyage delays.

In this study, we aim to determine potential risk factors that cause delays or failures in the ENC preparation process for the intended voyage and prioritize them using the Fuzzy Analytical Hierarchy Process (FAHP) method with the participation of experts. The study is organized as follows: Section 1 provides concise information on ECDIS/ENC and the transition to paperless navigation on board ships.

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Section 2 summarizes the literature review of ECDIS/ENC. Section 3 introduces the techniques used in this study. Chapter 4 assigns weights to the risk factors identified by experts as causing delays or failures in the ENC preparation process for the intended voyage. Section 5 evaluates the research findings. Section 6 concludes the study and offers recommendations for future studies.

2. Literature Review

The literature contains numerous studies on various topics related to ECDIS/ENC. One such topic is ECDIS training. For instance, Brčić et al. [4] surveyed personnel in diverse positions within the maritime transportation sector to develop a new training model for ECDIS and enhance nautical training processes. In another study, Øvergård and Smit [9] examined the effects of participants' sea experience and computer-use skill levels on ECDIS training, using the outputs of ECDIS training courses. Navigation using ECDIS has different characteristics than traditional paper chart-based navigation. In this context, Car et al. [10] classified the potential differences between conventional navigation using paper charts and navigation with ECDIS. Similarly, Weintrit and Stawicki [11] investigated the changes in the bridge work processes for ships navigating using ECDIS. Furthermore, Brčić and Žuškin [12] surveyed officers on the watch to determine the contribution of ECDIS as a primary navigational tool to marine safety and the effects of the gradual shift from conventional navigation to electronic navigation.

The literature contains various studies on integrating ECDIS with other electronic bridge equipment. Koshevyy and Shyshkin [13] proposed updating the existing software used in ECDIS and creating an interface between digital selective calling (DSC) equipment to establish a more efficient structure for navigation and communication. Similarly, Jincan and Maoyan [14] suggested creating a collision avoidance warning system using ECDIS and an automatic identification system (AIS) and tested the proposed model through simulation studies. Tsou [15] proposed a decision support system that uses AIS, ECDIS devices, and a geographic information system module to prevent collision accidents on ships. Improper use of ECDIS has been linked to various maritime accidents [16-19], prompting numerous risk analysis studies. For example, Turna and Öztürk [20] analyzed 22 grounding accidents related to ECDIS/ENC using the 4M Overturned Pyramid model and identified the factors that led to the incidents. Brčić et al. [21] surveyed seafarers in various ranks to determine the importance and necessity of using a secondary positioning resource in ECDIS.

The literature includes various specific studies on ENCs used in ECDIS. For instance, Weintrit [22] has classified existing electronic chart systems by considering factors such as international standards, databases used, and updating methods. Similarly, he compared various electronic chart systems, highlighted differences, and evaluated them in terms of international hydrographic organization (IHO) standards and requirements [23]. In another study, Kang et al. [24] indicated that sounding information in ENCs is obtained from hydrographic surveys and tested the compliance of the data obtained after the soundings with the sounding compilation guideline using the Delaunay triangulation method. Additionally, Palikaris and Mavraeidopoulos [25] recommended selecting the most suitable projections to depict ENCs used in ECDIS and examined the factors that should be considered in the selection process.

Upon examining the studies on ECDIS/ENC in the literature, it is clear that the focus is typically on ECDIS training, comparisons between paperless and paper chart-based navigati various ECDIS integration models, and ENC systems features. In contrast, this study uses the FAHP method to identify the prominent risk factors that cause delays or failures in the ENC preparation process for the intended voyage. Therefore, it distinguishes itself from other literature. Moreover, this study is the first to quantitatively analyze the risk factors encountered during this frequently conducted operational process on ships that navigate with ECDIS. Thus, this study is expected to contribute to the literature and provide valuable insights to designated persons ashore, operational managers, masters, and navigation officers on efficient management of the ENC preparation process for the intended voyages.

3. Materials and Methodology

This study includes a comprehensive numerical risk analysis using fuzzy set theory, AHP, and quadratic mean method to assess risk factors encountered during preparation processes for ENCs required for voyages on ships that navigate with ECDIS. This section explains the steps used to apply the methods utilized in the study.

3.1. Fuzzy Set Theory

Fuzzy set theory is used in this study to reduce uncertainties that often arise in decision-making processes, providing an effective means to conduct these processes [26]. This theory assigns real numbers between 0 and 1 to represent the membership degrees of each element x in a fuzzy subset, denoted by its membership function $\mu(x)$ [26-28]. Although membership functions can vary significantly in their morphological characteristics and associated fuzzy numbers, triangular and trapezoidal characters are the most commonly used in academic studies [29-32]. Therefore, this study employs triangular fuzzy numbers (TFN). A TFN, denoted by Q = (α, β, Ω), is defined by α and Ω as the lower and upper limit values of Q, respectively, and β as the center value. The membership function of Q, shown as $\mu_Q(x)$:R → [0, 1], can be represented mathematically by the expression in Equation 1 [28,33]:

$$\mu_Q(x)= \begin{cases} 0, x < \alpha \\ \frac{x - \alpha}{\beta - \alpha'} & \alpha \le x \le \beta \\ \frac{\Omega - x}{\Omega - \beta'} & \beta \le x \le \Omega \\ 0, & x > \Omega \end{cases} \quad (1)$$

Additionally, suppose $Q_1 = (\alpha_1, \beta_1, \Omega_1)$ and $Q_2 = (\alpha_2, \beta_2, \Omega_2)$ are two different TFNs. In this context, Equations 2 and 3 below show the addition and multiplication operations performed with two TFNs, respectively, while Equation 4 shows the reciprocal of a TFN [28, 33]:

$$(\alpha_1, \beta_1, \Omega_1) + (\alpha_2, \beta_2, \Omega_2) = (\alpha_1 + \alpha_2, \beta_1 + \beta_2, \Omega_1 + \Omega_2) \quad (2)$$

$$(\alpha_1, \beta_1, \Omega_1) * (\alpha_2, \beta_2, \Omega_2) = (\alpha_1\alpha_2, \beta_1\beta_2, \Omega_1\Omega_2) \quad (3)$$

$$(\alpha_1, \beta_1, \Omega_1)^{-1} = (1/\Omega_1, 1/\beta_1, 1/\alpha_1) \quad (4)$$

3.2. Analytic Hierarchy Process

AHP is an approach developed by Thomas Saaty in 1980 [34] to address multi-criteria problems in a hierarchical order [35]. This hierarchy usually comprises three basic levels; at the top level, there is a target goal; at the level below it, there are the main criteria associated with the established objective; and at the third level, sub-criteria are defined for each of the main criteria [31]. Furthermore, if the study aims to make an optimal choice from predetermined alternatives, these alternatives are placed at the bottom of the hierarchy [36]. This approach involves pairwise comparisons of main and sub-criteria by a designated group of experts [37], resulting in weight values for each evaluated criterion and establishing a priority order based on these values. Due to its significant role in guiding decision-makers, the AHP approach is widely used in various fields [38], such as the maritime industry [36,39].

3.3. Integrated Methodology: Fuzzy Analytic Hierarchy Process

The FAHP is a technique that integrates fuzzy set theory and the classical AHP method, which has gained significant use in solving multi-criteria problems. Various FAHP application examples exist in the literature, including the pioneering work of Van Laarhoven and Pedrycz [40], which used triangle fuzzy numbers in pairwise comparisons as one of the first examples of this technique. The technique was further developed by Buckley [41] and Chang [42], with different perspectives on its application. The extent analysis model developed by Chang [42] has gained wide acceptance in the literature due to its simple implementation, adherence to classical AHP steps, and requiring fewer computational processes [43]. However, when weighted with Chang's extent analysis model, some criteria may weigh zero, thus preventing the precise observation of each criterion weight. To address this, Göksu and Güngör [44] introduced the quadratic mean method, which eliminates the possibility of criterion weights being zero and provides an opportunity for more accurate measurements of the determined criteria. This method significantly reduces the computational load in obtaining criterion weights compared to other approaches used in decision-making processes, such as the Technique for Order of Preference by Similarity to Ideal Solution and Vlsekriterijumska Optimizacija I Kompromisno Resenje. In this study, the potential risk factors encountered in ENC preparation processes are weighted by applying FAHP based on the quadratic mean method. Figure 1 illustrates the conceptual framework developed specifically for this study.

In the following section, we will explain the application stages of the method step by step.

3.3.1. Implementation phases of the FAHP

In this section, we will provide a detailed explanation of the implementation phases of FAHP, in order.

Phase 1. Building the hierarchical structure

Initially, the goal of the study, i.e., to identify risk factors that cause delays or failures in ENC preparation processes for the intended voyage, was determined. Next, a hierarchical structure was constructed by defining the main and sub-criteria associated with the identified goal.

Phase 2. Obtaining linguistic assessments for each criterion

The binary comparison matrices were created to determine the superiority of the main criteria and sub-criteria. The linguistic assessments provided by the experts were then converted into corresponding TFNs. Table 1 shows the

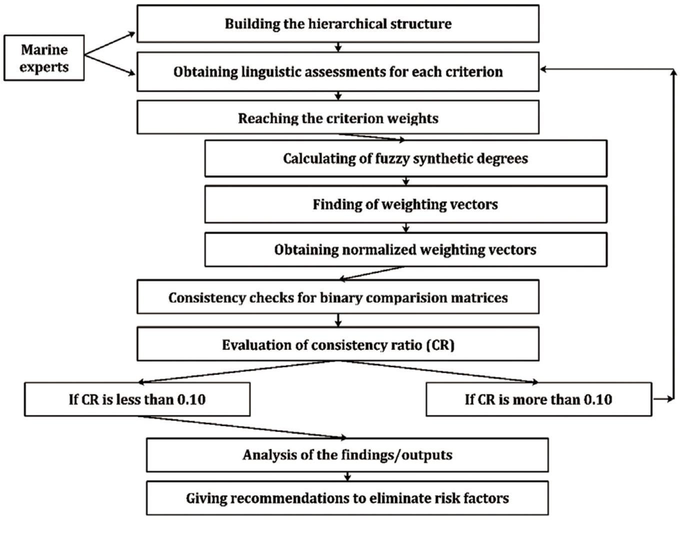

Figure 1. *Conceptual framework designated for the study*

evaluation scale used in the study and the corresponding TFNs for each scale point.

Phase 3. Reaching the criterion weights

Table 1. *Linguistic assessment scale used for the FAHP [45,46]*

Linguistic evaluation expressions as to the importance level	Equivalent TFNs	Reverses of each TFNs
Equal (E)	(1,1,1)	(1, 1, 1)
Weak (W)	(1,2,3)	(1/3, 1/2, 1)
Moderate (M)	(2,3,4)	(1/4, 1/3, 1/2)
Moderate plus (MP)	(3,4,5)	(1/5, 1/4, 1/3)
Strong (S)	(4,5,6)	(1/6, 1/5, 1/4)
Strong plus (SP)	(5,6,7)	(1/7, 1/6, 1/5)
Demonstrated (D)	(6,7,8)	(1/8, 1/7, 1/6)
Very, very strong (VVS)	(7,8,9)	(1/9, 1/8, 1/7)
Extremely (Ex)	(8,9,9)	(1/9, 1/9, 1/8)

At this stage, a numerical relationship is established between the goal (g)and the objects (X)X [47]. Assume that there are n sets of objects X_k ($k = 1, 2, 3, 4, \ldots, n$) and m sets of goals g_j ($j = 1, 2, 3, 4, \ldots, m$) determined [42]. In this approach, it is assumed that each X must achieve a g [42]. Therefore, a total of m extent analysis values are obtained for each X, as shown in Equation 5 .

$$M^1_{gi}, M^2_{gi}, \ldots M^m_{gi}, i = 1,2,3,4, \ldots, n \quad (5)$$

Here, the values denoted by M^j_{gi} $\left(j = 1, 2, 3, 4, \ldots, m\right)$ are represented as TFNs. The calculation of fuzzy synthetic degrees for each object is made. These calculation processes are detailed in the following steps [42,43,47]:

1. Calculating fuzzy synthetic degrees

The value of the fuzzy synthetic degrees for object i (S_i) is obtained using the following Equation 6:

$$S_{i=} \sum_{j=1}^{m} M^j_{gi} \times \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M^j_{gi}\right]^{-1} \quad (6)$$

To calculate the value of $\sum_{j=1}^{m} M^j_{gi}$ in the multiplication above, the fuzzy addition process defined by Equation 7 is utilized.

$$\sum_{j=1=1}^{m} M^j_{gi} = \left(\sum_{j=1=1}^{m} \alpha_j, \sum_{j=1=1}^{m} \beta_j, \sum_{j=1=1}^{m} \Omega_j\right) \quad (7)$$

To obtain the inverse of the second vector $\left[\sum_{i=1=1}^{n}\sum_{j=1=1}^{m} M^j_{gi}\right]$ defined in Equation 6, Equation 8 is utilized.

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M^j_{gi}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n}\Omega_i}, \frac{1}{\sum_{i=1}^{n}\beta_i}, \frac{1}{\sum_{i=1}^{n}\alpha_i}\right) \quad (8)$$

The synthetic degree values obtained from the TFNs (α, β, Ω) [43] required an approach to estimate the weights of each criterion in the hierarchical structure. The quadratic mean method developed by Göksu and Güngör [44] is utilized in this estimation process to obtain criterion weight vectors. The next step will explain the application steps of the method.

2. Finding of weight vectors (W') sing the quadratic mean method

When determining the criterion weight vectors, as suggested by Chang [42], discovering some criterion weights of zero can create uncertainty in evaluating the criteria. This study employs the quadratic mean method to establish the criterion weight vectors to address this [44]. If there are n TFNs, represented by $M_i = (\alpha_i, \beta_i, \Omega_i)$ (i = 1, 2, 3,..., n.), then the weight vector's n^{th} value can be determined using Equation 9 [44].

$$C(M_n) = \sqrt{\frac{\alpha_n^2 + \beta_n^2 + \Omega_n^2}{3}} \quad (9)$$

The value of the n^{th} TFN in the weight vector is denoted by $C(M\,n)$. Subsequently, each obtained $C(M)$ value is sorted, and a criterion weight vector is created [44, 47]. The mathematical expression for the criterion weight vector is given in Equation 10.

$$W' = \left(C(M_1), C(M_2), \ldots, C(M_n)\right)^T \quad (10)$$

3. Obtaining normalized weight vector (W)

Normalization is applied to the obtained weight vector (W') resulting in the normalized weight vector (W). Each value in this vector represents the priority weight of the corresponding criterion. These values can be used to evaluate the criteria's weights.

3.3.2. Consistency checks for binary comparison matrices

Defuzzification is used to convert a TFN expressed as M= (x, y, z) to a crisp number. Equation 11, provided below [27], is used for this conversion:

$$Crisp\ (M) = \frac{4y + x + z}{6} \quad (11)$$

The consistency of each pairwise comparison matrices was verified using the consistency check steps suggested by Saaty [48]. To accomplish this, the following equations are used in the order provided below: Equation 12-15 [27,31,48]:

$$E_i = \frac{d_i}{w_i} \quad (12)$$

Criterion weights are represented by w_i, while E_i and d_i can be regarded as intermediate values during the calculation process.

$$\lambda_m = \frac{\sum_{i=1}^{n} E_i}{n} \tag{13}$$

λ_m represents the largest eigenvalue of the designed matrix, where n denotes the size of the matrix.

$$CI = \frac{\lambda_m - n}{n - 1} \tag{14}$$

Herein, CI represents the consistency index.

$$CR = \frac{CI}{RI} \tag{15}$$

Here, CR denotes the consistency ratio, while *RI* symbolizes the random consistency index. The CR value varies depending on the matrix size, as specified in Table 2. The consistency of the matrices generated from expert evaluations depends on the CR value is less than 10% [27,48].

Table 2. *Random consistency indexes (RI) based on matrix size (n) [49]*

n value	Equivalent RI	n value	Equivalent RI
1	0.0	6	1.24
2	0.0	7	1.32
3	0.58	8	1.41
4	0.90	9	1.45
5	1.12	10	1.49

4. Quantitative Risk Analysis for the ENC Preparation Process

This study used the FAHP method to identify potential risk factors that could cause delays or failures in the ENC preparation process for the intended voyages. The study successfully identified prominent risk factors.

4.1. ENC Preparation Process for the Intended Voyage

Before sailing, the required ENCs for a voyage are determined using specialized software installed on a computer onboard the ship, provided by the ENC service provider. This software includes a digital chart catalog (DCC), which allows the selection of specific ENC cells. A request file is sent via the ship's mail system to the authorized ENC provider, according to company policies and processes, to obtain the chosen ENCs. The communication process may vary based on company policies and procedures. While the communication between the ship and the authorized ENC provider may suffice to obtain the required ENCs, sometimes, the connection between the seafarer, the company, and the approved ENC provider may be necessary. Once the ship's ENC request is approved, the relevant ENC access files, also known as permit files [50], are received via e-mail. The permit files are uploaded and displayed in the ECDIS based on the steps submitted by the authorized ENC chart provider. It is mandatory for ECDIS-equipped ships to use the latest version of relevant ENCs and to keep them up-to-date to meet the chart-carrying requirements stipulated under International Convention for the Safety of Life at Sea (SOLAS) [6,8]. Consequently, the ENCs in the ECDIS and inventory, DCC, and backup devices are updated.

4.2. Potential Risk Factors Encountered in ENC Preparation Process for the Intended Voyage

Several risk factors can contribute to failures or delays in preparing ENCs for voyages on ECDIS-equipped ships. Communication-related factors (C) are particularly relevant and must be managed effectively to ensure successful preparation. These factors include a lack of communication between the ship's master and navigation officer (C1), between the ship and ENC provider (C2), between the seafarer and the company (C3), and disconnections in the ship's communication systems (C4).

Furthermore, a lack of knowledge (D) also poses an obstacle to managing this process successfully, which can manifest as a lack of knowledge on the steps required to requisition ENC charts (D1), a lack of knowledge on how to use the DCC (D2), a lack of knowledge on the steps required to upload ENCs to ECDIS (D3), and a lack of information on how to update backup navigation devices (D4).

The software, hardware, and power supplies used in the ENC preparation process for the intended voyage are crucial. The lack of planned maintenance (E) on these components poses a risk to the successful completion of the process. Such hazards or risks include software malfunctions in ECDIS (E1), hardware malfunctions in ECDIS (E2) [50], power supply failures (E3), and emergency power supply failures, including uninterruptible power supplies *(*UPS) (E4).

Procedures (F) are also essential and crucial to avoid undesired delays or failures in the ENC preparation processes. One such risk factor is the lack of procedures (F1). Another is incompatible procedures (F2) that fail to consider the characteristics of the systems used onboard ships. Additionally, complex procedures (F3) and procedures with limited information (F4) are other risk factors that can delay the completion of the process or lead to failure.

4.3. Application of the Methodology: FAHP

The study identified potential risk factors by examining various electronic chart usage circulars [50,51] and consulting expert opinions. The identified risk factors that can cause delays or failures in the ENC preparation process for the intended voyage are presented in Table 3.

Furthermore, Figure 2 shows the hierarchical structure constructed for the study.

The study used the perspective of marine experts, who not only assisted in designing the study's hierarchical structure

Table 3. *Identified risk factors for the ENC preparation process for an intended voyage*

Abbreviation	Definition
GOAL	Risk factors that cause failure/delay in the ENC preparation process for the intended voyage
C (Main criteria)	Communication-related risk factors
C1 (Sub-criteria)	Lack of communication between the ship's master and the navigation officer
C2 (Sub-criteria)	Lack of communication between the ship and ENC provider
C3 (Sub-criteria)	Lack of communication between the ship the and company
C4 (Sub-criteria)	Disconnections in the ship's communication systems
D (Main criteria)	Risk factors due to lack of knowledge
D1 (Sub-criteria)	Lack of knowledge of ENC requisition steps
D2 (Sub-criteria)	Lack of knowledge on using the digital chart catalog (DCC)
D3 (Sub-criteria)	Lack of knowledge on steps to upload ENCs to ECDIS
D4 (Sub-criteria)	Lack of knowledge about update steps of backup navigation devices
E (Main criteria)	Risk factors related to lack of planned maintenance
E1 (Sub-criteria)	Malfunctions occurring in the software of the ECDIS.
E2 (Sub-criteria)	Malfunctions occurring in the hardware of the ECDIS.
E3 (Sub-criteria)	Power supply failures
E4 (Sub-criteria)	Emergency power supply failures, including UPSs
F (Main criteria)	Risk factors related to procedures
F1 (Sub-criteria)	Lack of procedures
F2 (Sub-criteria)	Incompatible procedures
F3 (Sub-criteria)	Complex procedures
F4 (Sub-criteria)	Procedures with limited information

but also in evaluating the pairwise comparison matrices developed for both the primary and sub-criteria. Table 4 provides detailed profile information for the seven experts who participated in the study.

The study involved creating five binary comparison matrices that included primary and sub-criteria groups for expert evaluation. To provide their evaluations, experts used the linguistic assessment scale shown in Table 1. Based on the feedback from the experts, these linguistic expressions were converted into equivalent TFNs. Table 5 presents the resulting fuzzy pairwise comparison matrices.

Subsequently, the process of calculating fuzzy synthetic degrees for each criterion began, using Equations (6-8) as per the methodology. Table 6 presents the resulting fuzzy synthetic degrees obtained for each criterion.

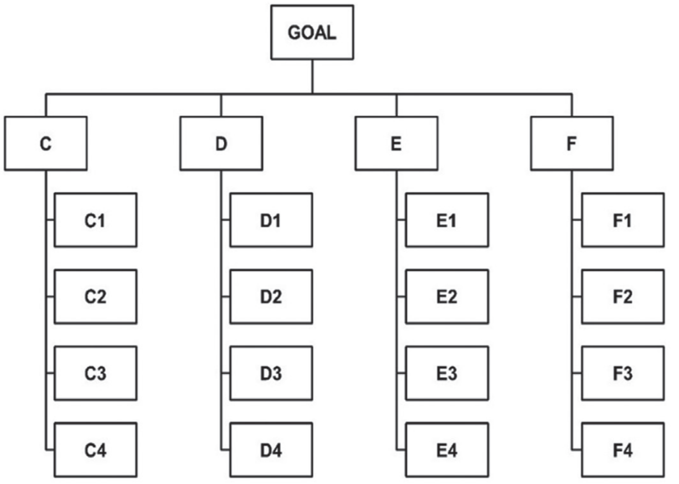

Figure 2. *Hierarchical structure constructed*

The process of determining weight vectors was initiated by creating the weight values of each criterion using Equation (9). Both primary and sub-criteria weight vectors (W') were obtained through this process. However, these weight vectors could not be used for criterion evaluation. A normalization process was used to determine the priority weight values for each criterion and create normalized weight vectors (W). Table 7 presents the obtained weight vectors (W') and normalized weight vectors (W).

A consistency test was performed for each paired comparison matrix using Equations (11-15) in sequential order to establish a consistent comparison process and minimize the impact of any potential errors in expert evaluations. Table 8 shows the consistency analysis results obtained for each pairwise comparison matrix.

5. Results and Discussion

The consistency tests for all paired comparison matrices designed within the scope of the study resulted in CR values less than 0.10, indicating that the obtained results were consistent [27,48].

The study's analysis of the primary criteria indicated that the most critical risk factor causing delay or failure in the ENC preparation process for the intended voyage was the lack of knowledge (D), with a priority weight of 0.55, followed by communication-related risk factors (C: 0.25), lack of planned maintenance (E: 0.14), and risk factors related to procedures (F: 0.06). As such, specific recommendations as targets to eradicate these risk factors, particularly D and C, are crucial for reducing the risk of delay or failure in this process.

Table 4. *Profile details of the experts*

Exp.	Professional position	Total sea service (years)	Experiences in navigation with ECDIS/ENC (years)	Competency
1	Master	12	7	Oceangoing Master
2	Master	11	7	Oceangoing Master
3	Master	9	6	Oceangoing Master
4	Master	8	6	Oceangoing Master
5	Navigation Officer	8	5	Oceangoing Watchkeeping Officer
6	Navigation Officer	6	5	Oceangoing Watchkeeping Officer
7	Navigation Officer	5	5	Oceangoing Watchkeeping Officer

Table 5. *Fuzzy binary comparison matrices created within the scope of the study*

Fuzzy binary comparison matrix for the main criteria				
	C	D	E	F
C	1.00-1.00-1.00	0.23-0.31-0.44	1.33-2.38-3.44	2.38-3.45-4.35
D	2.27-3.22-4.35	1.00-1.00-1.00	4.35-5.26-6.25	6.25-7.14-8.33
E	0.29-0.42-0.75	0.16-0.19-0.23	1.00-1.00-1.00	1.33-2.38-3.45
F	0.23-0.29-0.42	0.12-0.14-0.16	0.29-0.42-0.75	1.00-1.00-1.00
Fuzzy binary comparison matrix for sub-criteria of communication-related risk factors				
	C1	C2	C3	C4
C1	1.00-1.00-1.00	0.31-0.44-0.82	0.14-0.16-0.19	1.22-2.22-3.22
C2	1.22-2.27-3.22	1.00-1.00-1.00	0.23-0.31-0.44	3.45-4.54-5.55
C3	5.26-6.25-7.14	2.27-3.22-4.35	1.00-1.00-1.00	7.69-8.33-9.00
C4	0.31-0.45-0.82	0.18-0.22-0.29	0.11-0.12-0.13	1.00-1.00-1.00
Fuzzy binary comparison matrix for sub-criteria of risk factors due to lack of knowledge				
	D1	D2	D3	D4
D1	1.00-1.00-1.00	2.00-3.00-4.00	4.76-5.88-6.66	7.69-8.33-9.00
D2	0.25-0.33-0.50	1.00-1.00-1.00	1.22-2.22-3.22	2.56-3.57-4.54
D3	0.15-0.17-0.21	0.31-0.45-0.82	1.00-1.00-1.00	1.33-2.38-3.45
D4	0.11-0.12-0.13	0.22-0.28-0.39	0.29-0.42-0.75	1.00-1.00-1.00
Fuzzy binary comparison matrix for sub-criteria of risk factors related to lack of planned maintenance				
	E1	E2	E3	E4
E1	1.00-1.00-1.00	1.43-2.49-3.57	5.26-6.25-7.14	7.69-8.33-8.95
E2	0.28-0.40-0.70	1.00-1.00-1.00	1.89-2.94-4.02	4.16-5.26-6.25
E3	0.14-0.16-0.19	0.25-0.34-0.53	1.00-1.00-1.00	1.33-2.38-3.45
E4	0.11-0.12-0.13	0.16-0.19-0.24	0.29-0.42-0.75	1.00-1.00-1.00
Fuzzy binary comparison matrix for sub-criteria of risk factors related to procedures				
	F1	F2	F3	F4
F1	1.00-1.00-1.00	0.31-0.44-0.82	0.12-0.13-0.15	0.14-0.17-0.20
F2	1.22-2.27-3.22	1.00-1.00-1.00	0.20-0.24-0.32	0.24-0.32-0.49
F3	6.67-7.69-8.33	3.12-4.17-5.00	1.00-1.00-1.00	1.10-2.13-3.12
F4	5.00-5.88-7.14	2.04-3.12-4.17	0.32-0.47-0.91	1.00-1.00-1.00

Among the communication-related risk factors (C) sub-criteria, the lack of communication between the ship and the company (C3) had the highest priority weight of 0.56, making it the most significant risk factor leading to delays or failures in the ENC preparation processes, followed by the lack of communication between the ship and the

ENC provider (C2: 0.25), lack of communication between the ship's master and navigation officer (C1: 0.13), and disconnections in the ship's communication systems (C4: 0.05). Effective communication must be established among all parties responsible, ensuring timely receipt and proper display of required ENCs on the ECDIS to prevent delays or failures in the ENC preparation process. A clear definition of responsibilities for all involved parties is essential to achieve this. Given the importance of communication technologies in ship operations [52], ship communication systems must function efficiently. The computers with e-mail systems, critical for ship communication, should be supported by UPSs to prevent disruption from potential power failures. Furthermore, to prevent computer viruses and cyber-attacks, antivirus software should be installed to protect the e-mail and internet systems onboard.

Table 6. *Calculated fuzzy synthetic degrees (S_i)*

Fuzzy synthetic degrees calculated for the main criteria	
S_C	0.13-0.24-0.40
S_D	0.37-0.56-0.86
S_E	0.07-0.13-0.23
S_F	0.04-0.06-0.10
Fuzzy synthetic degrees calculated for the sub-criteria of C	
S_{C1}	0.07-0.12-0.20
S_{C2}	0.15-0.25-0.39
S_{C3}	0.41-0.58-0.81
S_{C4}	0.04-0.05-0.08
Fuzzy synthetic degrees calculated for the sub-criteria of D	
S_{D1}	0.41-0.58-0.83
S_{D2}	0.13-0.23-0.37
S_{D3}	0.07-0.13-0.22
S_{D4}	0.04-0.06-0.09
Fuzzy synthetic degrees calculated for the sub-criteria of E	
S_{E1}	0.38-0.54-0.76
S_{E2}	0.18-0.29-0.44
S_{E3}	0.07-0.12-0.19
S_{E4}	0.04-0.05-0.08
Fuzzy synthetic degrees calculated for the sub-criteria of F	
S_{F1}	0.04-0.06-0.09
S_{F2}	0.07-0.12-0.20
S_{F3}	0.31-0.48-0.71
S_{F4}	0.22-0.34-0.54

Table 7. *The calculated weight vectors (W') normalized weight vectors (W)*

Designed Matrices	(W′)	(W)
C, D, E, F	$W' = (0.28,0.63,0.16,0.07)^T$	$W = (0.25,0.55,0.14,0.06)^T$
C1, C2, C3, C4	$W' = (0.14,0.28,0.62,0.06)^T$	$W = (0.13,0.25,0.56,0.05)^T$
D1, D2, D3, D4	$W' = (0.63,0.26,0.15,0.07)^T$	$W = (0.57,0.23,0.14,0.06)^T$
E1, E2, E3, E4	$W' = (0.58,0.32,0.13,0.06)^T$	$W = (0.53,0.29,0.12,0.06)^T$
F1, F2, F3, F4	$W' = (0.07,0.14,0.53,0.39)^T$	$W = (0.06,0.12,0.47,0.35)^T$

Among the risk factors resulting from the lack of knowledge (D), the risk factor with the most significant negative impact on the process was the lack of knowledge about the steps for ENC requisition (D1), with a priority weight of 0.57. The lack of knowledge about using the DCC (D2) was identified as the second most critical risk factor, with a priority weight of 0.23. These risk factors were followed by the lack of knowledge about procedures for uploading ENCs to ECDIS (D3: 0.14) and the lack of knowledge about the update steps of backup navigation devices (D4: 0.06). To mitigate these risks, the officer in charge of the navigational planning and the ship's master should receive computer-aided simulation training on the ENC preparation process before joining the seafarer. This training should consider the specific characteristics of the ECDIS and ENCs used onboard ships [10,53,54]. Additionally, to ensure the effective use and maintenance of ECDIS/ENCs on ships, it is recommended to increase the frequency of internal audits [55]. Furthermore, detailed information on this issue should also be shared during the duty handover onboard.

Another significant criterion that negatively affects the ENC preparation process is the risk factors arising from the lack of planned maintenance (E). Among these factors, malfunctions in the ECDIS software (E1) were identified as the most significant, with a priority weight of 0.53, causing delays or failures in the ENC preparation process.

Table 8. *The obtained consistency analysis results*

Designed matrices	λ_m	CI	RI	CR
C, D, E, F	4.10867	0.03622	0.90	0.04
C1, C2, C3, C4	4.08999	0.02999	0.90	0.03
D1, D2, D3, D4	4.08306	0.02768	0.90	0.03
E1, E2, E3, E4	4.08850	0.02950	0.90	0.03
F1, F2, F3, F4	4.09111	0.03037	0.90	0.03

Other critical risk factors in order of importance are malfunctions occurring in the hardware of the ECDIS (E2: 0.29), power supply failures (E3: 0.12), and emergency power supply failures, including UPSs (E4: 0.06). Thus, it is essential to establish a planned maintenance system for the software, hardware, and power sources involved in the ENC preparation process to mitigate these risk factors. This system should include regular updates of the ECDIS software by the manufacturer's instructions and routine checks on other hardware components such as fans, monitors, universal serial bus (USB) slots, and keyboards to prevent any deformation. Furthermore, it is crucial to integrate an adequate power supply as specified by the ECDIS, International Maritime Organization (IMO), and flag state; also, it is vital to replace UPS batteries before they reach their expiration date to ensure optimal performance [56]. To ensure compliance with these requirements onboard ships, ports, and flag state officers should conduct frequent audits.

The analysis of sub-criteria related to procedures (F) identified complex procedures (F3) as the primary risk factor with a priority weight of 0.47 that can disrupt the process. The other risk factors in the order of priority were procedures with limited information (F4: 0.35), incompatible procedures (F2: 0.12), and lack of procedures (F1: 0.06) that could cause delays or errors in the ENC preparation process for the intended voyage. To address these issues, the procedures created for this process should be easy to understand and apply, tailored to the unique characteristics of the systems used on the ships. A team with specialized knowledge and experience about the ECDIS installed on a seafarer should be established. If this is not feasible in the short term, assistance from an independent organization should be sought [57]. Furthermore, the prepared procedures should provide detailed instructions for handling emergencies such as ECDIS signal loss or ENC scale failure [20].

6. Conclusion

The study examined risk factors that can cause delays or failures in preparing ENC for planned voyages. A FAHP application based on the quadratic mean method, a novel criterion weighting approach [44], was used to identify prominent risk factors. The results indicated that the most significant risk factors hindering the successful management of the process are those arising from a lack of knowledge (D) and communication-related risks (C). Other identified risk factors were the lack of planned maintenance (E) and procedure-related risks (F) based on their priority weights. Consequently, the study emphasizes the necessity of regulatory and preventive measures such as training, effective communication, technological infrastructure development, and the publication of appropriate procedures to eliminate these risk factors. The study's findings increase seafarers' awareness of the risk factors that disrupt the operational process frequently performed on ECDIS-equipped ships. Further research exploring the effect of human factors on inappropriate ECDIS use could add value to the literature.

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