A New Hybrid Approach for Determining Sector-Specific Risk Factors in Turkish Straits: Fuzzy AHP-PRAT Technique

Fatih TONOĞLU[a], Fuat ATALAR[b], İbrahim Burak BAŞKAN[c], Serdar YILDIZ[d], Özkan UĞURLU[e] and Jin WANG[f]

[a]Maritime Transportation and Management Engineering Department, Ordu University, Ordu, Turkey, fatihtonoglu@odu.edu.tr

[b]Directorate General of Coastal Safety, Ministry of Transport and Infrastructure, Çanakkale, Turkey, Fuat.Atalar@kiyiemniyeti.gov.tr

[c]Maritime Transportation and Management Engineering Department, Ordu University, Ordu, Turkey, ibrahimburakbaskan@odu.edu.tr

[d]World Maritime University, Malmö, Sweden, sy@wmu.se

[e]Maritime Transportation and Management Engineering Department, Ordu University, Ordu, Turkey, ougurlu@odu.edu.tr, ozkanugurlu24@hotmail.com (corresponding author)

[f]Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Faculty of Engineering and Technology, Liverpool John Moores University, Liverpool, UK, j.wang@ljmu.ac.uk

ABSTRACT

In this study, a hybrid approach that combines the Fuzzy Analytical Hierarchy Process (FAHP) and Proportional Risk Assessment Technique (PRAT) methods was developed for use within the scope of risk analysis. Using a hybrid approach for risk assessment enables researchers to overcome the disadvantages and limitations of a single method. The approach proposed in this study provides an opportunity to eliminate misconceptions that may arise from subjective judgments based only on expert opinions and inconsistencies that may occur from insufficient data. With the proposed approach, realistic analysis results were obtained by combining expert opinions and statistical data. The Turkish Straits System was chosen as a case study application area. One of the most important results of the study is that ships passing through the Turkish Straits face different risks in each Vessel Traffic Services (VTS) sector. The results proved that the proposed method could effectively be used as a consistent and accurate risk assessment tool. The study can contribute to safe strait passages by defining sector-specific risks that ships passing through the strait may encounter.

Key Words: Turkish Straits System; Istanbul Strait; Fuzzy AHP; PRAT; marine accident; risk analysis.

Abbreviations	
AHP	Analytical Hierarchy Process
CFP	Combined FAHP-PRAT
COLREG	International Regulations for Preventing Collisions at Sea
DM	Decision Maker
F	Frequency Factor
FAHP	Fuzzy Analytical Hierarchy Process
GT	Gross Tonnage
LTSS	Local Traffic Separation Scheme
MTFTS	Marine Traffic Fast Time Simulation
P	Probability Factor
PRAT	Proportional Risk Assessment Technique
R	Risk Value
S	Severity Factor
ST	Severity Type
SWOT	Strengths-Weaknesses-Opportunities-Threats
TS	Total Score
TSS	Traffic Separation Schemes
TSVTS	Turkish Straits Vessel Traffic Services
VTS	Vessel Traffic Services
WE	Weight of Expert

1. Introduction

Maritime transport is one of the main modes of transportation that takes the pulse of the global economy (Chan et al., 2016). Maritime safety closely affects the efficiency and profitability of maritime trade (Yildiz et al., 2021). In particular, the sustainability of the safe navigation of ships in restricted waters, which are called the nodal points of maritime trade, has been the focus of attention of maritime authorities for many years (Li et al., 2012). Ships navigating restricted waters usually follow a predetermined route. However, due to factors such as crossing, overtaking, local traffic, sharp turns, current, and wind, ships have to change their speed frequently and deviate from their predetermined route. Accident risks are also high in narrow waters where ships navigating at different speeds and routes are concentrated.

It is essential to understand the existing risks in order to increase maritime safety in restricted waters and be prepared for possible accidents (Kujala et al., 2009). Environmental factors play an active role in the occurrence of accidents in restricted waters. Narrow channel structures, heavy weather-sea conditions, strong surface currents, heavy traffic, visibility restriction, and shallow areas are the main environmental factors that play a role in accident formation (Goerlandt and Kujala, 2011; Zhang et al., 2013). In the study by Goerlandt and Kujala (2011) evaluating the risk of accidents in the Gulf of Finland, it was seen that the risk of collision is high in regions with high traffic density. Zhang et al. (2013) concluded that bad weather conditions and narrow channel structures in the Yangtze River significantly increased accident risk. In addition to environmental factors, human error is another important factor that causes accidents in restricted waters. COLREG (International Regulations for Preventing

Collisions at Sea) violation, crossing situation, unsafe speed, inaccurate plotting of ship position, and manoeuvring error are the most common human errors in restricted waters (Squire, 2003; Kujala et al., 2009; Qu et al., 2011; Şenol et al., 2013; Zaman et al., 2014). Squire (2003) revealed that COLREG violation caused collision accidents in the Dover Strait. Zaman et al. (2014) determined that most of the collision accidents in the Strait of Malacca were caused by crossing situations. Qu et al. (2011) stated that ships exceeding the speed limits set in the Singapore Strait pose a considerable risk for collision accidents.

The Turkish Straits where approximately 40 accidents occur in every 100,000 passages are narrow waterways with high risk (Ince and Topuz, 2004). Accidents in the Turkish Straits may cause delays in the passage of the vessels not only involved in the accident but also other vessels that intend to pass through the area. All parties of the transport are adversely affected by this delay. The accident that occurred in the Suez Canal in March 2021 is a perfect example of this. For this reason, determining the factors that threaten the safety of navigation in restricted waters is an important issue that closely concerns coastal states and all other stakeholders of maritime affairs (Oei, 2003). Therefore, determining the region-specific risk factors that play a role in accidents in restricted waters is crucial to prevent these accidents from happening again in the future. In this study, the factors that play a significant role in accidents in the Turkish Straits are analysed in a sector-specific manner. As a result, the risk factors that play a role in the occurrence of accidents for each sector have been estimated and listed in order of their priority.

The remainder of the study is organized as follows. In Section 2, there is explanatory information about the Turkish Straits System and sectors. While Section 3 includes the literature review, Section 4 explains the structure of the study and the methods used under the title of materials and methods. The application of the proposed method and the explanation of the criteria in the study are given in Section 5. Section 6 contains results and discussion, and Section 7 concludes the study.

2. Turkish Straits

The Turkish Straits, which separate the Asian and European continents, connect the Black Sea and the surrounding seas. The Turkish Straits are 164 nautical miles long and resemble a bagpipe (Kaptan et al., 2020). The Turkish Straits System, which consists of three parts, includes the Istanbul Strait, the Sea of Marmara and the Canakkale Strait. Figure 1 illustrates the Turkish Straits Vessel Traffic Services Area (TSVTS).

Figure 1. Turkish Straits Vessel Traffic Services area (DGCS, 2020)

2.1. Istanbul Strait

The Istanbul Strait covers the area between the Anadolu Feneri-Türkeli Lighthouse line in the north and Ahırkapı Lighthouse - İnciburnu Lighthouse in the south. The length of the Istanbul Strait, which has an average depth of 35 meters, is approximately 16.6 nautical miles. It includes 3 sectors: Türkeli, Kandilli and Kadıköy.

One of the most critical risk factors that threaten the safety of navigation in the Istanbul Strait is the variable current regime. There are three different current regimes in the Istanbul Strait, formed by water level, density difference, salinity and wind. The first is the southerly surface current caused by the water level difference between the Black Sea and the Sea of Marmara. With this surface current, the waters of the Black Sea are carried to the Sea of Marmara. While the surface current comes from the north at a speed of 0.5-1 knots, it accelerates towards the middle of the Istanbul Strait. The fastest currents are Beylerbeyi with 4-5 knots, Akıntıburnu, Kandilli and Sarayburnu with 3-4 knots. In the bays to the south of these capes, vortexes are formed by the effect of the current. The speed of the surface current can reach up to 7-8 knots when the water level of the Black Sea is fed by the river waters and the northerly winds increase. In this state, the Istanbul Strait almost resembles a raging river. Also, an undercurrent occurs in the Istanbul Strait due to the difference in salinity and density between the two seas. The waters of the Black Sea are less salty and of lower density. In contrast, the less dense waters flow from the top towards the Marmara Sea, the denser waters of the Marmara flow towards the Black Sea. These water movements create an undercurrent in the Istanbul Strait. The speed of the bottom current is between 0.5 and 2 knots. Particularly vessels with deep draught are affected by this current in regions where the depth of the Istanbul Strait decreases (Taşlıgil, 2004). The undercurrent may come to a standstill by getting stuck on the mounds on the seafloor during periods when the upper current accelerates. In weather conditions with continuous and robust winds, the upper flow may slow down enough to stop. Once or twice a year, during periods of south-westerly winds named Lodos, the lower current intensifies and overcomes the upper current. In such cases, an upper current flowing from south to north is observed in the Istanbul Strait. This current, which can even cause a change in the salinity balance, is called “Orkoz” (Topakoğlu, 2004). Current movements in the Istanbul Strait may pose a severe threat to the masters who do not sufficiently know the dynamics of the area.

Sector Türkeli**:** The borders of Sector Türkeli, which is the northern entrance of the Turkish Straits System, start from the Black Sea and extend to the Anadolu Kavağı-Dikilikaya

Lighthouse line (DGCS, 2020). Its approximate length is 3.55 nautical miles. There are two shipwrecks in it that do not hinder navigation. The narrowest part of the separation line is on the Dikilikaya line, with a width of 453 meters. There are Poyraz, Büyük Liman, Acar and Dikilikaya Banks in the sector (Cömert, 2013). The shallowest place in the separation line is in front of Cape Kazandibi, with a depth of 17.1 meters. The current strength is 1-1.5 knots in this area, where northern winds are effective since it is at the entrance of the Black Sea (Akten, 2004). Heavy weather and sea conditions, especially in winter, pose a severe threat to ships at anchor.

***Sector Kandilli*:** The sector is between the southern border of Türkeli and the "15 Temmuz Sehitler" Bridge (DGCS, 2020). Its approximate length is 9.6 nautical miles. The Kandilli-Bebek line, the narrowest part of the Turkish Straits System with a width of 700 meters, is in this sector (Akten, 2003). Especially with the narrow channel structure of the Istanbul Strait, vortexes created by strong and complex currents are one of the most critical risk factors in this region (Cömert, 2013). The speed of the current in the area can reach up to 7-8 knots. Sector Kandilli is a region where visibility is limited due to its narrow structure, excess blind spots caused by sharp turns and intense coastal lighting (Akten, 2004). There are seven tricky turns in Sector Kandilli. The sharpest ones are the 83-degree Yeniköy and 73-degree Büyükdere turns. There are 12 banks throughout the sector, including the Umur Bank and Büyükdere Bank (Cömert, 2013). The shallowest place in the separation is in front of Beykoz Shipyard, with a depth of 12.5 meters. It has the highest number of fishing ports in the Istanbul Strait (Öztürk et al., 2006).

***Sector Kadıköy*:** The northern border of the sector is on the "15 Temmuz Sehitler" Bridge, and the southern border is in the Marmara Sea (DGCS, 2020). Its approximate length is 3.45 nautical miles. There are three shipwrecks in the sector. The narrowest part of the separation line is the "15 Temmuz Sehitler" Bridge with a width of 575 meters. Sector Kadıköy, located at the southern entrance of the Istanbul Strait, is the region with the highest local traffic (Aydogdu et al., 2012). Within the sector, there are Ahırkapı, Sarayburnu, Kız Kulesi and Ortakoy Banks (Cömert, 2013). The shallowest place in the separation is at the outbound of Haydarpaşa breakwater with a depth of 18 meters (Cömert, 2016). With a 51-degree turn, the Kız Kulesi is the sharpest turning point in the sector.

2.2. The Marmara Sea

Sector Marmara**:** The sector is bounded by the Sector Kadıköy in the north, Sector Gelibolu in the west, and the longitude of the Dereboynu Cape in the east (DGCS, 2020). Its approximate length is 28.97 nautical miles. There are no turns and shallow waters along the separation line.

2.3. Canakkale Strait

The Canakkale Strait is the region between the longitude of the Zincirbozan Lighthouse in the north and the Mehmetçik Burnu Lighthouse-Kumkale Lighthouse line in the south. With an average depth of 55-60 meters, the total length of the Canakkale Strait is 37.8 nautical miles.

Sector Gelibolu**:** While the northern border of the sector is in the Marmara Sea, the southern border is on the Kanarya Capeline (DGCS, 2020). The length of the sector is approximately 7.4 nautical miles. The shallowest place in the separation is in front of Kanarya Cape with 40 meters. In the region, which is under the influence of northeast winds throughout the year, currents and vortexes are effective around the Gelibolu Harbor (ASD, 2019). In the section from the northern entrance of the Canakkale Strait to Nara Cape, the current speed is 0.5-1 knot. In addition to the ships crossing the Canakkale Strait, there are reciprocal ferries between Gelibolu and Lapseki in Sector Gelibolu. Therefore, careful navigation is required in this sector (Cömert, 2013).

Sector Nara**:** The southern border of the sector is the Kanlıdere Cape-Karanfil Capeline, and the northern border is the south border of Sector Gelibolu (DGCS, 2020). Its approximate length is 21.9 nautical miles. The shallowest place in the separation is in front of Çoraklık Point with a depth of 22.5 meters. The narrowest part of the separation line is the Kilitbahir-Canakkale line with 798 meters. In the sector with four turns, the sharpest turn is the Nara Cape turn with 76 degrees. The Nara turn and the variable currents in the Canakkale Harbor area create vortexes in these areas and make the sharp turn at Nara Cape more challenging (Cömert, 2013). The region with the highest local traffic in the Canakkale Strait is Sector Nara. There are local traffic lines of Gelibolu-Lapseki, Canakkale-Gökçeada, Kilitbahir-Canakkale and Eceabat-Canakkale.

Sector Kumkale**:** The southern border of the sector is in the Aegean Sea, and the northern border is the Kanlıdere Cape-Karanfil Capeline, which is the south border of Sector Nara (DGCS, 2020). The length of this part of the strait is approximately 9.1 nautical miles. The narrowest part of the separation line is the southern entrance of the strait with a width of 2,000 meters. The shallowest place in the separation is around Karanlık Bay with a depth of 22.5

meters. Within the sector, there is a large eddy system extending from Kumkale Cape to Kepez Bay. The current with a speed of 4 knots from Kilitbahir towards the south is more robust, especially on the northern shores of the strait. Ships navigating close to Kanlıdere Cape to avoid the current force run the risk of being stranded on Kepez Bank (ASD, 2019).

3. Literature Review

The Turkish Straits are one of the regions that have been studied from different perspectives. In particular, studies on the causes of accidents in the straits have an important place in the literature. Akten (2004) made a spatial analysis of 461 marine accidents that occurred in the İstanbul Strait between 1953 and 2002. According to the results of the study, the most important factors playing a role in the occurrence of accidents in the İstanbul Strait, where 55% of the accidents are grounding, were current, sharp turns and darkness. It has been stated that Umur Bank, Yeniköy, Bebek and Kandilli are the riskiest areas in terms of grounding while Beşiktaş, Bebek, Kandilli, Kanlıca, Yeniköy, Beykoz and Sarıyer are the riskiest areas in terms of collision/contact.

Arslan and Turan (2009) used a combination of Strengths-Weaknesses-Opportunities-Threats (SWOT) and Analytic Hierarchy Process (AHP) models for the analysis of accidents in the İstanbul Strait. While determining the factors that affect the accidents with SWOT, it has prioritized these factors with AHP. The results of the study show that negative factors are more effective than positive factors in the İstanbul Strait. While human factors were the most critical weakness in the occurrence of accidents, the most dominant threats were identified as Orkoz, local traffic and night.

Aydogdu et al. (2012) proposed a Local Traffic Separation Scheme (LTSS) to reduce the risk caused by heavy local traffic at the southern entrance of the İstanbul Strait. The study area was divided into 3 regions and the current local traffic was simulated. As a result of the simulation, three different LTSSs have been proposed to reduce the risk in high-risk areas. The study revealed that in scenarios where a LTSS is applied, the risk can be reduced and navigational safety can be increased in the region.

Aydogdu (2014) analysed 232 accidents in the İstanbul Strait between 2000 and 2011. In the study, the İstanbul Strait was divided into 3 regions from north to south as A1, A2, A3, and experts were asked to evaluate the risks in these regions. The evaluations of the experts were analysed with the Generic Fuzzy AHP method and the results were compared with the statistics of the accidents that occurred in the region. As a result of the study, the ranking of the risky regions according to the statistics was A1>A2>A3, while the ranking of the experts was

A2>A3>A1. Thus, a difference between the risk perception of the experts and the statistics was revealed.

Istikbal (2020) examined the relationship between the accidents and the left-hand traffic order applied in the İstanbul Strait between 1934 and 1982. For this purpose, the author analysed three major marine accidents that occurred under the left-hand traffic order. In the study, it has been determined that the common point of all three accidents is the head-on situation. In the head-on situation, the manoeuvre to be made according to the left traffic order and the manoeuvre recommended in the COLREG rules contradict. In the study, it was stated that this situation played a role in the occurrence of accidents by creating confusion for the captains.

When the literature studies are evaluated together, it is understood that the accident analysis studies on the Turkish Straits aim to determine the general causes of the accidents. However, no study highlights the sectors in the Straits and analyses them in detail with a sector focus. Therefore, this study aims to fill the relevant gap in the literature by examining the causes of accidents in the Turkish Straits based on individual sectors. When the accident analysis studies conducted using statistical data and expert opinions in the literature are examined, it is seen that different results can be reached. One of the main reasons for this is that risk estimation, which requires two approaches, qualitative and quantitative, is done using a single method. When a single method is used, the results may be faulty if the statistical data is not sufficient or incomplete. Similarly, in studies based on expert opinions using a single method, if there is any uncertainty in expert opinions, this may negatively affect the result. Therefore, method selection is vitally important in accident analysis studies. Hollnagel (2002) divided accident analysis methods into three categories according to their perspective on accidents. These are sequential methods, epidemiological methods, and systemic methods. Sequential methods describe accidents as a series of cause-effect relationships. They are easy to implement, but they do not take into account the hidden factors that play a role in the occurrence of accidents. Epidemiological methods take into account the hidden factors that play a role in accidents and consider that accidents occur as a result of deficiencies/errors occurring simultaneously in different safety layers. However, these methods do not identify interactions between different factors. Systemic methods argue that accidents occur as a result of the interaction of different factors in the entire system. Although these methods have the potential to reveal all the factors that play a role in the occurrence of accidents and to offer suggestions to prevent similar accidents in the future, they are quite laborious (Hollnagel, 2002; 2004; Hollnagel and Goteman, 2004). Apart from these, hybrid methods that are frequently used in the literature have emerged in recent years. These hybrid methods integrate and use more than one method to achieve the result (Table 1). The hybrid method applied in this study integrates two easy-to-apply methods.

Table 1. Comparison of methods used in accident analysis

4. MATERIAL AND METHODS

In this study, a sectoral analysis of the factors that play a role in the occurrence of accidents in the Turkish Straits has been conducted. The study area covers the Turkish Straits Vessel Traffic Services (TSVTS) area (Figure 1). The accidents in the study are limited to collision, contact, grounding and sinking accidents involving ships over 500 GT in this region. The study aims to help reduce future accidents in the area by estimating major risk factors in the Turkish Straits on sectoral focus.

In studies conducted over a large and wide area, a single method may be insufficient to provide a realistic forecasting model or a risk assessment process. For this reason, robust analysis approaches should be used together by the data set and purpose of the studies (Marhavilas, 2015; Sarıalioğlu et al., 2020). For this purpose, Fuzzy AHP, a versatile analysis approach, and the PRAT approach, which is frequently used in the literature to assess safety risks, were used in a hybrid way in this study (Marhavilas and Koulouriotis, 2008; Koulinas, 2019a). The combined FAHP-PRAT approach used in the study provides the risk manager with a tool that can produce results by combining actual accident data and the subjective judgments of the decision-maker (Koulinas, 2019b). The study consists of 5 steps presented in Figure 2 and is explained in detail below.

Figure 2. Flow chart of the methodology followed in the study

4.1. Determining the Appropriate Analysis Method

In risk assessment, past accident reports are often considered as one of the most reliable data. In addition, the opinions of experienced domain experts, who know the region closely, are frequently consulted in determining the risk factors/hazards in an area. Fuzzy AHP, a multi-criteria decision-making method based on pairwise comparisons, is one of the well-known methods frequently used in the literature to benefit from expert knowledge. In the study, Chang's (1996) Fuzzy AHP method was preferred to rank the factors (criteria) that play a role in accidents. This method can be applied more quickly than other Fuzzy AHP methods and requires relatively less time and calculation efforts (Bozbura et al., 2007; Wang et al., 2008; Çelik et al., 2009; Xu and Liao, 2013). On the other hand, the PRAT method is a quantitative technique that enables risk assessment based on accident data, taking into account probability, severity, and frequency ~~factors~~. The PRAT method can be easily combined with other analysis methods to obtain more objective and consistent results (Koulinas, 2019b). In the scientific literature, it is necessary to take into account three factors to define the risk level quantitatively: Severity, Probability and Frequency (Høj and Kröger, 2002). PRAT can provide a quantitative risk assessment by combining these three factors with a proportional formula (Marhavilas, 2015). In addition, this technique has significant advantages such as ease of application and production of relatively "reliable" results since it is based on historical accident data (Koulinas, 2019a). Therefore, in this study, Fuzzy AHP and PRAT techniques were used in a combined way to determine the risk factors (criteria) in the Turkish Straits accurately and consistently. With the hybrid approach, a rating was made for the risk factors within each sector.

4.1.1. Fuzzy Analytical Hierarchy Process (FAHP)

The Analytic Hierarchical Process (AHP) was developed by Saaty (1980). This method is suitable for solving problems with criteria and sub-criteria in the hierarchical scheme. Although AHP is primarily used in multi-criteria decision-making problems, its main disadvantage is that it uses a one-to-nine scale for comparing attributes, which cannot often handle uncertain decisions. In particular, real numbers used to compare qualitative factors pose great challenges for decision-makers (Deng, 1999; Karsak and Tolga, 2001; Ding and Liang, 2005; Kulak and Kahraman, 2005; Kilincci and Onal, 2011). Therefore, since this method is not fully suitable for decision-making in case of uncertainty, the Fuzzy Analytical Hierarchical Process has been revealed by combining fuzzy logic with AHP (Göksu, 2008). There are various Fuzzy AHP methods practiced and recommended by many scientists. These methods systematically approach alternative selection and justification problems using fuzzy set theory and hierarchically structural analysis. However, decision-makers generally believe that it is more reliable to make intermittent judgments rather than expressing their judgments as fixed values (Erensal et al., 2006) because there is complexity and uncertainty in real-world decision problems (Wang et al., 2008).

There are a wide variety of fuzzy AHP methods introduced by researchers in the literature. The first studies on fuzzy AHP were put forward by Van Laarhoven and Pedrycz (1983), Buckley (1985), Boender et al. (1989), Chang (1996) and Cheng (1997). All these Fuzzy AHP versions are developed to deal with uncertain or poorly-defined situations. In Chang's approach, pairwise comparisons are represented by fuzzy triangular numbers. With the use of fuzzy numbers, the disadvantages arising from the estimations are tried to be eliminated. In Chang's method, each criterion is taken, and extent analysis is applied for each target. Therefore, there are m extent analysis values for each criterion: $M_{gi}^{1}, M_{gi}^{2}, \dots\dots\dots\dots, M_{gi}^{m},\ i = 1,2,\dots\dots\dots, n$. All $M_{g_i}^{j}$ values $(j = 1,2,\dots, m)$ above are fuzzy triangular numbers. Triangular fuzzy numbers and their verbal equivalents are shown in Table 2. A fuzzy number is represented by a symbol with "~" on it. The triangular fuzzy number $\tilde{A}$ is simply denoted as (l, m, u). Here, the (l, m, u) parameters indicate the smallest possible value, the most promising value, and the largest possible value describing a fuzzy event (Figure 3). The membership function ($\mu_{\tilde{A}}(x)$) can be defined in Equation (1).

$$\mu_{\tilde{A}}(x) = \left\{\begin{matrix} 0, & x < l \\ (x-l)/(m-l), & l \leq x < m \\ 1, & x = m \\ (u-x)/(u-m), & m < x \leq u \\ 0, & u < x \end{matrix}\right\} \tag{1}$$

Figure 3. An example of a triangular membership function

Table 2. Fuzzy Numbers

The foundations of Chang's FAHP are defined in four phases (Chang, 1996). First, after the hierarchical structure is established, an $n\times n$ dimensional square comparison matrix is created as shown in Equation (2).

$$A = (a_{ij})_{nxn} = \begin{bmatrix} (1,1,1) & \cdots & (l_{1j}, m_{1j}, u_{1j}) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ \cdots & \cdots & \vdots & \cdots & \vdots \\ (l_{1j}, m_{1j}, u_{1j})^{-1} & \cdots & (1,1,1) & \cdots & (l_{in}, m_{in}, u_{in}) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ (l_{1n}, m_{1n}, u_{1n})^{-1} & \vdots & (l_{in}, m_{in}, u_{in})^{-1} & \cdots & (1,1,1) \end{bmatrix} \tag{2}$$

n = Number of criteria to be evaluated

(a_{ij}) = importance of criterion i compared to criterion j

If $i=j$ in the comparison matrix, the value will be $(1,1,1)$ because in this case, the relevant criterion is compared with itself.

If $a_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right)$, then, $a_{ij}^{-1} = (l_{ij}, m_{ij}, u_{ij})^{-1}; \, for \; (\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}})$; *i, j=1,…n* and *i≠j*

Let X = {$x_1, x_2, \ldots, x_n$} represent the elements of the alternatives and U = {$u_1, u_2, \ldots, u_m$} as the target set for the selection criteria. According to Chang's (1996) extended analysis method, each object should be taken, and extent analysis should be performed for each target g_i respectively. Therefore, m extent analysis values for each object can be obtained by $M_{gi}^1, M_{gi}^2, \ldots \ldots \ldots \ldots, M_{gi}^m, \; i = 1,2, \ldots \ldots \ldots, n$.

The steps of Chang's extended analysis can be presented as follows:

Step-1:

The fuzzy synthetic extent (S_i) value according to the object is defined in Equation (3).

$$S_i = \sum_{j=1}^{m} M_{g_i}^j \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j\right]^{-1} \qquad i = 1, 2, \ldots, n \qquad j = 1,2, \ldots, m \tag{3}$$

To obtain $\sum_{j=1}^{m} M_{g_i}^j$, fuzzy aggregation of m fuzzy synthetic extent analysis values for a given matrix is performed according to Equation (4).

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{4}$$

To obtain $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j\right]^{-1}$, the fuzzy aggregation of $M_{g_i}^j (j = 1,2, \ldots, m)$ values is performed with Equation (5) as follows.

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \tag{5}$$

Then, the inverse of the vector in the equation is calculated using Equation (6).

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{6}$$

Step-2:

The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as:

$$V(M_2 \geq M_1) = \sup_{y \geq x} \left[min \left(\mu_{M_1}(x), \mu_{M_2}(y) \right) \right] \tag{7}$$

and Equation (7) can be expressed equivalently as Equation (8).

$$V(M_2 \geq M_1) = \text{hgt}(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1, & if\ m_2 \geq m_1, \\ 0, & if\ l_1 \geq u_2, \\ \frac{(l1-u2)}{(m2-u2)-(m1-l1)}, & otherwise \end{cases} \tag{8}$$

Here d is the ordinate of the highest intersection point between μ_{M_1} and μ_{M_2} (Figure 4).

Figure 4. The intersection between M_1 and M_2 (Chang, 1996)

To compare M_1 and M_2 values, it is necessary to obtain $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$ values.

Step-3:

The degree of possibility for a convex fuzzy number to be greater than a specific number (k) of convex fuzzy numbers can be defined by Equation (9):

$$V(M_i \geq M_1, M_2, .. M_k) \quad i, k = 1, 2, \dots, n;\ i \neq k \tag{9}$$

Applying Equation (10) de-fuzzifies the weight vector by finding the minimum values within each comparison (min $V(M_i \geq M_k)$, which is calculated by Equations (8) and (9).

$$d'(A_i) = \min V\ (S_i \geq S_k) \quad for \quad i, k = 1, 2, \dots n;\ i \neq k \tag{10}$$

Therefore, the weight vector becomes Equation (11):

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_i)) \quad i = 1, 2, \dots, n \tag{11}$$

where $d'(A_i)$ is the minimum value of each decision element, which is obtained from comparison of fuzzy number pairs and represents the de-fuzzified weight of each criterion. W' represents the set of de-fuzzified weights.

While each $d'(A_i)$ is not a fuzzy number, they do need to be normalized, utilizing Equation (12):

$$d(A_i) = \frac{d'(A_i)}{\sum_{i=1}^{n} d'(A_i)} \quad i = 1, 2, \dots, n \tag{12}$$

$$W = (d(A_1), d(A_2), \dots, d(A_n)) \tag{13}$$

W in Equation (13) represents the normalized weights of the specified criteria.

4.1.2. Combination of FAHP and PRAT (CFP)

PRAT is a risk assessment method based on the studies of Fine and Kinney (1971) and Hammer (1972). This method uses a formula to calculate the risk proportionally (Marhavilas, 2009; Marhavilas et al., 2011; Marhavilas and Koulouriotis, 2008, 2012; Supciller and Abali, 2015). The Risk Value (R) is calculated with Equation (14).

$$R = P \times F \times S \tag{14}$$

where P (Probability Factor) is a measure of the probability of a hazardous situation occurring over a period of time; F (Frequency Factor) is the number of times a dangerous situation occurs in a specific time period; and S (Severity Factor) represents the magnitude of the damage to humans, the environment, or property as a result of the dangerous situation. This formula is used to determine the priority levels of criteria to be considered in dangerous situations (Marhavilas and Koulouriotis, 2008). Combined FAHP-PRAT (CFP value) consists of priority values (A%) calculated with FAHP and risk values (R%) calculated with PRAT (Koulinas et al., 2019a). Koulinas et al. (2019a) hybridized PRAT and FAHP methods in their study. In the study, it was assumed that both methods were of equal importance and their averages were taken to obtain the result. Similarly, in the study of Koulinas et al. (2019b), when PRAT and TOPSIS models were hybridized, it was assumed that the models had equal importance and the results were obtained by averaging the model results. In this study, as in the studies of Koulinas et al. (2019a, 2019b), it is assumed that the hybridized models have equal importance.

Therefore, the arithmetic average of the results obtained from both models was taken while calculating the final results. The CFP value can be obtained by Equation (15).

$$CFP = 0.5\times(A\%) + 0.5\times(R\%) \tag{15}$$

4.2. Determining the Criteria and Establishing the Hierarchical Structure

To determine the assessment criteria, firstly, previous studies in the literature on the analysis of marine accidents in restricted waterways were reviewed. Through these studies, a list of factors that play a role in the occurrence of accidents in restricted waterways was created. In the second stage, the listed risk factors were evaluated by experts with sufficient domain knowledge and experience on the Turkish Straits. The final criteria for the study need to meet two prerequisites: a risk specific to restricted waterways; variation regionally. As a result of expert evaluations, 16 factors were determined as the final criteria of the study. The 16 criteria determined were grouped under 3 main criteria in line with the opinions of the experts. Thus, the hierarchical structure of the study was established. Since the aim of the study is to define the risks sector-based, VTS sectors in the Turkish Straits were taken as alternatives. The hierarchical structure is shown in Figure 5.

Figure 5. Hierarchical structure of the study

4.3. Application of Fuzzy AHP Method

The experts prioritized the criteria and sub-criteria that play a role in accidents in the Turkish Straits with a pairwise comparison approach. The expert group in the study has sufficient experience and knowledge about the Turkish Straits; the group consists of 20 people, including 5 Oceangoing Masters, 7 VTS Operators and 8 Pilots. As a result of the calculations, the priorities of the criteria and alternatives were determined for each expert. Since pairwise comparisons are based on subjective judgments, it was thought that each expert's influence on the result within their experience would contribute positively. For this reason, a weight was determined for each expert. Information used for expert weighting includes professional position, length of service and the number of passages through the straits.

4.4. Analysis of Previous Accident Data using PRAT

Maritime accidents in the Turkish Straits System last decade, registered in the Transport Safety Investigation Center database, were used (KAIK, 2018). A total of 525 maritime accident records in this data set contain information about the "Name of the ship, Flag, Ship type, Tonnage, Accident type, Position, Date, Time, accident severity, Result of the accident and Causes of the accident". The accidents outside the Turkish Straits VTS area and the accidents within the port were extracted by examining this data set. The remaining 311 maritime accidents were analysed using the PRAT technique.

4.5. Calculation of Combined FAHP-PRAT (CFP) Values

At this stage, the priority values obtained from FAHP and the risk values obtained as a result of PRAT analysis were combined. The new figure, expressed as CFP, gives the risk manager the priorities of the factors that need attention in dangerous situations. The main aim of this study is the ranking of the priority values of the risks for each sector.

5. APPLICATION OF PROPOSED METHOD

5.1. Criteria and Sub-criteria

The criteria and sub-criteria in this study were determined by taking the previous studies in the literature as a reference and in the presence of expert opinions. Table 3 shows the list of reference studies. Table 4 presents the studies on which each criterion/ sub-criterion is based. The expert group, whose opinions were consulted in the study, has sufficient experience with the Turkish Straits. Qualifications of experts are listed in Table 5. In the study, 3 main criteria and 16 sub-criteria related to them were determined. Descriptive information about the criteria is presented below.

Table 3. Reference studies to identify criteria and sub-criteria

Table 4. Reference studies for each sub-criteria

Table 5. Qualifications of experts

5.1.1. Human Factors

It covers all the errors, violations, mistakes made by the team members commanding the ship or the service personnel related to the navigation outside the ship due to ignorance, carelessness and incompetence (Macrae, 2009).

Faulty Manoeuvre: This unsafe action occurs because the bridge team members do not perform the manoeuvre that needs to be done in the present situation, timely or correctly (Kaptan et al., 2021). Typical examples include: not starting the turn at the appropriate time considering the current, ship length, speed and manoeuvrability in sharp turn (Cömert, 2013); failure to use the rudder effectively and efficiently to eliminate the bank effect and keep the ship on the planned route (Cömert and Sağ, 2016).

Violation of COLREG Rule 16 (Unsafe Speed): Such a violation indicates that the ship is not cruising at a speed that complies with COLREG, local rules and the current situation and conditions. Under normal conditions, the navigation speed is determined as 10 miles per hour in the passage through the Turkish Straits (DGCS, 2020). Due to the narrow and shallow structure of the Turkish Straits, there are a narrow water effect and a shallow water effect. Both effects increase with speed (Cömert and Sağ, 2008).

***Violation of COLREG Rule 15 (Crossing Situation)*:** It is the situation in which one of the two ships approaches each other by crossing, one showing the starboard and the other showing the port side of the ship (Kaptan et al., 2021). All vessels in local traffic making reciprocal voyages in the Turkish Straits cross the separation line in the shortest way (Official Gazette, 2019). Since there is no institution regulating the local traffic in the straits, these crossings are at the initiative of the ferry captains. During these crossings, unauthorised crossings may cause accidents (Aydogdu et al., 2012). In addition, the crossing situation at anchorage areas of both the Istanbul Strait and Canakkale Strait is a serious threat that ships constantly face.

***Violation of COLREG Rule 10 (TSS)*:** Navigating outside the safe navigation line is a violation of COLREG Rule 10. As a rule, ships must comply with the local traffic separation scheme and COLREG. Due to the narrow and curved structure of the strait, large ships often cannot fully follow their traffic lane. At specific points in the restricted waters, violation of separation may naturally occur in sharp turns due to the geographical structure (Akten, 2003).

***Violation of COLREG Rule 13 (Overtaking)*:** According to the Turkish Straits Maritime Traffic Regulations, ships will cruise at a distance of at least 0.8 nautical miles between each other and will not overtake unless it is necessary and permitted. There will be no overtake between Vaniköy and Kanlıca in the Istanbul Strait and between Nara and Kilitbahir Cape in the Canakkale Strait. Overtaking can be made while ships are proceeding on a straight route leg

(Official Gazette, 2019). Overtaking is not allowed when approaching turning points or at the time of route alteration. Violation of COLREG Rule 13 means violation of these rules.

***Lack of Communication and Coordination*:** It means that internal and external communication is not done effectively and efficiently. Studies have revealed that the basis of communication-related errors is commonly misunderstanding and refraining from communication between them. Underneath these are the lack of awareness of the situation, the assumption that other people in the environment are aware of the situation, the lack of proficiency in English or a common language, and avoiding using the radio (McCallum et al., 2000).

5.1.2. External Environmental Factors

It covers the non-ship factors affecting the accident that occurred in the environment where the ship is navigating.

***Heavy Weather and Sea Conditions*:** If refers to the adverse atmospheric and meteorological conditions in the area where the ship is navigating. There are continuous winds from the north and northeast from June to September in the Istanbul and Canakkale Straits, and from the southeast and west from October to March (Cömert and Sağ, 2006). In the Istanbul Strait, the winds blow from the northeast about 75% of the year. In winter, strong winds turn into storms 3-4 days a month. Although strong winds and storms are mainly from the north, they can sometimes come from the south in winter (Akten, 2002). In the Marmara Sea, the wind usually blows from the northeast (Cömert and Sağ, 2008).

***Current*:** The strong and variable currents in the Turkish Straits can make it difficult to control the ship and cause accidents (Akten, 2004). Currents and winds in the Turkish Straits can adversely affect the movement of ships, especially in winter, when southerly and northerly winds are strong (Akten, 2002, 2003). The surface current, which is strengthened by the winds, can adversely affect the manoeuvrability of large ships (Birpınar et al., 2009). The strong currents at the turns of Kandilli and Yeniköy in the Istanbul Strait may drag the vessel ashore, increasing the risk of stranding (Yazıcı and Otay, 2009). In the Canakkale Strait, strong currents may increase the risk of stranding at the Nara Cape and Kilitbahir turns.

***Dense Traffic*:** It refers to the negativities arising from local traffic, transit traffic and port traffic that ships face during their transit passage. In the 10 years between 2010 and 2019, an average of 45,000 ships transits through the Turkish Straits annually. Today, more than 2000 ferry trips are made every day to sustain local transportation services in Istanbul, home to a population of over 15 million. In the Canakkale Strait, there are hundreds of ferry trips per day to provide local transportation. This situation proves that the local traffic is heavy in both straits.

Night**:** At night, it is more difficult to notice changes in speed, distance, and environment than during the day. Light pollution from restaurants, vehicles, houses and street lighting reduces the visibility of navigational aids (Akten, 2002). Ships navigating at night should take extra care because of lights restricting vision, backlighting to confuse, reduced visibility of navigation lights, and the presence of unlit navigating hazards (Akten, 2004).

Sharp Turn**:** In restricted waters, the safe fairway is restricted. With the effect of negative factors such as current and wind, it becomes difficult to keep the ship in the desired route and position in large turns of more than 30 degrees. Especially for the low speed or the large tonnage ships, this risk is higher than the others. There are 12 sharp turns in the Istanbul Strait (Akten, 2004). The sharpest ones are in Yeniköy with 80 degrees, Umur Yeri with 70 degrees and Kandilli with 45 degrees. There are several critical course changes from Ortaköy, the narrowest part of the Istanbul Strait, to Emirgan (Akten, 2003). Similarly, in the Canakkale Strait, ships have to make at least 10-course changes. Of these, the Nara Cape turn and the Kilitbahir turn are the sharpest turning points with 70 degrees and 50 degrees, respectively (Kılıç and Sanal, 2015).

Narrow Channel**:** Both the Istanbul and the Canakkale Straits can be named as narrow areas with a lot of shallow water for the ships passing through (Cömert and Sağ, 2006). The bank effect may occur in restricted waters. Many places in the straits should be passed near shore lines, including Cape Nara, Kilitbahir, Cape Kandilli, Cape Akıntı and Cape Aşiyan. While the bank effect pushes the ship's head in these regions, it tries to pull the stern towards the shore (Cömert and Sağ, 2016). While this situation negatively affects the ship's movement, if it is not taken into account by the bridge team members, it prepares the ground for accidents.

Shallow Water**:** The squat effect causes the ship to be more submerged in shallow waters (Cömert and Sağ, 2006). This situation, also known as the shallow water effect, starts to show its impact at depths of 2.5 times the ship's draft or less (Cömert, 2013). Furthermore, the shallow water effect increases with ship draft (Cömert and Sağ, 2008). Previous studies have shown that the risk of stranding is high in Umur Bank, Yeniköy, Bebek and Kandilli in the Istanbul Strait (Akten, 2004). In the Canakkale Strait, the risk of being stranded may be high between the Sehitler Abidesi-Kumale, Gelibolu-Zincirbozan, Kilitbahir-Karanfil Lighthouse, and Nara-Kilitbahir (Kılıç and Sanal, 2015).

5.1.3. Internal Environmental Factors

It expresses the effect of the factors related to the ship's design, structure, and equipment on the occurrence of the accident.

Failures Preventing Vessel's Motion**:** It covers the malfunctions/failures that occur in the ship's propulsion and steering systems such as rudders, generators, main engine, auxiliary engines (Uğurlu et al., 2018). When such malfunctions occur in the absence of situational awareness, they can lead to operators' unsafe actions. Therefore, technical and mechanical failures are critical causal factors that cause accidents in the Turkish Straits (Akten, 2002; Tozar and Güzel, 2012; Uğurlu et al., 2020).

Ship Size**:** According to the Turkish Straits Maritime Traffic Regulation, ships with an overall length of 200 meters or more are defined as large ships (Official Gazette, 2019). The increasing number of ships, sizes, and tonnages are pushing the limits of restricted waters, especially the Turkish Straits. (Cömert and Sağ, 2008). Decreased manoeuvrability with increasing ship length is an increasing risk, especially in straits (Chapman and Akten, 1998; Akten, 2004).

Low Speed Vessels**:** Ships with a service speed of fewer than 8 knots are not allowed to pass through the Turkish Straits without the assistance of a tugboat. When ships are at low speed, they are more affected by currents and winds, posing a threat to maritime safety, especially in sharp turns and in areas with heavy traffic.

5.2. FAHP Application

Step 1: Pairwise comparison of different criteria is made to create the fuzzy comparison matrix, and then the priority values of each criterion are calculated. While Table 6 gives the elements and abbreviations of the hierarchical structure, Table 7 shows the pairwise comparisons of the main criteria made by Expert-1 (DM1). A calculation example of pairwise comparisons made by Expert-1 for the main criteria is presented below.

Table 6. The elements of hierarchy and their abbreviations

Table 7. Fuzzy judgment matrix of criteria by DM1

Step 2: Equation (3) is used to find the fuzzy synthetic extent value of each criterion.

$S_{C1} = (2.40, 2.50, 2.67) \, X \, (8.80, 10.00, 11.33)^{-1} = (0.212, 0.250, 0.303)$

$S_{C2} = (2.40, 2.50, 2.67) \, X \, (8.80, 10.00, 11.33)^{-1} = (0.212, 0.250, 0.303)$

$S_{C3} = (4.00, 5.00, 6.00) X (8.80, 10.00, 11.33)^{-1} = (0.353, 0.500, 0.682)$

Step 3: Degree of possibility values are calculated by using Equation (8).

$V(S_{C1} \geq S_{C2}) = 1.00$, $V(S_{C2} \geq S_{C1}) = 1.00$, $V(S_{C1} \geq S_{C3}) = 0.00$, $V(S_{C3} \geq S_{C1}) = 1.00$, $V(S_{C3} \geq S_{C2}) = 1.00$, $V(S_{C2} \geq S_{C3}) = 0.00$

Step 4: By using Equation (10), the minimum degree of possibility is determined for each criterion.

$d'(C1) = min\ V(S_{C1} \geq S_{C2}, S_{C3}) = (1.00, 0.00) = 0.00$

$d'(C2) = min\ V(S_{C2} \geq S_{C1}, S_{C3}) = (1.00, 0.00) = 0.00$

$d'(C3) = min\ V(S_{C3} \geq S_{C1}, S_{C2}) = (1.00, 1.00) = 1.00$

Step 5: According to Equation (11), the weight vector of the criteria is created.

$W' = (0.00, 0.00, 1.00)^T$

With Equation (12), the normalization process is applied, and the normalized weight vector is calculated.

$W = (0.00, 0.00, 1.00)$

Step 6: Steps 1-5 are repeated to find normalised weight vectors of all sub-criteria according to the criteria and the normalized weight vectors of the alternatives according to the sub-criteria (Tables 8-9).

Table 8. Fuzzy judgement matrix of sub-criteria respect to criteria by DM1

Table 9. Fuzzy judgement matrix of alternatives with respect to sub-criteria by DM1

Step 7: Calculations were made by repeating Steps 1-6 for all experts. Interviews with 20 experts, consisting of Pilots, VTS Operators and Oceangoing Ship Captains, who are familiar with the Turkish Straits, were completed through face-to-face and remote access. In addition, all of the pilots and VTS operators who participated in this study have the Oceangoing Captain competency. The scale used for weighting the experts in the study is shown in Table 10.

Table 10. Expert weighting scale

Step 8: Weight of Expert (W_E), which determines the degree of influence of each expert on the outcome, was calculated using Equation (16) (Table 11).

$$W_{E_i} = \frac{TS_i}{\sum_{i=1}^{n} TS_i} \quad i = 1,2,\dots,n \tag{16}$$

Here n represents the number of experts; TS_i represents the total score of expert i.

Table 11. Weighting of decision-makers

Step 9: In Table 12 and Table 13, the normalized priorities and expert weights calculated as a result of the evaluations of each expert are shown together. To find the total priority values in the last column, the weight of each expert was first multiplied by the normalized priority values based on expert judgments. Then the values calculated for the 20 experts were summed up and accepted as final priorities. Thus, it was guaranteed that each expert would affect the result in proportion to their weight. Table 14 and Table 15 show the final weights and normalised FAHP results.

Table 12. Individual expert weights and de-fuzzified priorities of criteria and sub-criteria for each DM

Table 13. Individual expert weights and de-fuzzified priorities of alternatives for each DM

Table 14. Aggregated priorities

Table 15. Normalised FAHP results

5.3. Combined FAHP-PRAT (CFP) Application

In this study, real accident statistics were used to determine P, F and S. The data set used in the study is the accidents that occurred in the Turkish Straits VTS area over the last 10 years. Statistics for Sector Kadıköy are given in Table 16. The average time required for the accident to occur is considered for determining P. The P values corresponding to the frequency of events occurring are shown in Table 17.

Table 16. Accident statistics in Sector Kadıköy

Table 17. Scoring of the probability factor

F was determined according to the number of accidents in Table 16. The F values corresponding to the number of accidents are given in Table 18.

Table 18. Scoring of the frequency factor

The average severity scores in the last column of Table 19 were taken into account to determine S. Average severity scores were calculated using Equation (17).

$$Mean\ Severity\ Score = \frac{Total\ Severity\ Score}{Number\ of\ Accidents} \tag{17}$$

Table 19 and Table 20 were used to calculate the total severity scores.

Table 19. Severity statistics in Sector Kadıköy

Table 20. Scoring of the severity type

The S values corresponding to the average severity scores are shown in Table 21.

Table 21. Scoring of the severity factor

When the risk value (R) is calculated for each criterion, the sum of the risk values is defined as the total risk in the relevant sector (Table 22). For example, the total risk value in Sector Kadıköy is 554 (Table 23). By dividing the risk value of each criterion by the total risk, the normalized risk value (R%) of each criterion in the relevant sector is determined (Table 24).

Table 22. Calculations of the risk value for each sub-criterion in Sector Kadıköy

Table 23. PRAT (R) risk value of each sub-criterion

Table 24. PRAT (R%) normalized risk value of each sub-criterion

Equation (15) is used to calculate CFP values. Table 25 shows the CFP results for Sector Kadıköy. These steps are repeated for all sectors. The final results of the study are given in Table 26 and Figure 6. This table estimates the priority criteria for accident occurrence for each sector.

Table 25. Combined FAHP-PRAT ranking for each sub-criterion in Sector Kadıköy

Table 26. Combined FAHP-PRAT (CFP) result

Figure 6: a. Istanbul Strait, b. Canakkale Strait Combined FAHP-PRAT results

6. Results and Discussion

In this study, an analysis of the factors that play a role in accidents in the Turkish Straits, at a sector-specific level, was conducted with a hybrid approach that combines FAHP and PRAT methods. This hybrid approach made it possible to break the misconceptions that may arise from subjective judgments based only on expert opinions. In addition, the hybrid approach combines expert opinions with statistical data, and eliminates inconsistencies arising from insufficient statistical data. In this way, it provides more accurate and consistent results. Using a hybrid method for risk assessment enables the assessment of potential risks from different aspects. Thus, it allows researchers to overcome the disadvantages and limitations of a single method.

As a result of the study, the sectors with the highest total risk in the Turkish Straits are Sector Kadıköy (43.59%), Sector Kandili (20.54%), Sector Gelibolu (9.28%), Sector Türkeli (8.65%), Sector Kumkale (8.50%) and Sector Nara (7.71%). In comparison, Sector Marmara (1.73%) had the lowest total risk (Table 23). In addition, the total risk value in the Istanbul Strait (72.78%) was found to be almost three times the total risk value in the Canakkale Strait (25.49%). These results explain why current studies mostly focus on the Istanbul Strait.

In the Istanbul Strait, respectively, human factors (40.76%), external environmental factors (37.35%), and internal environmental factors (21.89%) are effective. In the Canakkale Strait, respectively, human factors (44.66%), external environmental factors (32.02%) and internal environmental factors (23.32%) are effective (Table 26). While there is a 3.41% difference between human factors and external environmental factors for the Istanbul Strait, this difference is 12.64% for the Canakkale Strait. From this point of view, it can be concluded that the risks arising from external environmental factors in the Istanbul Strait are more than the ones in the Canakkale Strait. This result supports the statement, “One of the main causes of accidents in the Istanbul Strait is natural conditions”, as stated in the studies of Istikbal (2006) and Erol et al. (2018).

Another notable difference between the Istanbul and Canakkale Straits is the effect of the night factor on accidents. While the night has a high priority in the sectors in the Istanbul Strait; it is among the low priority factors in the sectors in the Canakkale Strait (Table 26). These results support the results of previous studies (Arslan and Turan, 2009) on the Istanbul Strait in the literature. In addition, according to the results obtained in the study, contrary to the studies of Ilgar (2015) and Bayazıt et al. (2020), it was determined that the sector with the lowest total risk in the Canakkale Strait was Sector Nara.

According to the sector-specific risks in the Istanbul Strait, 40.36% of the total risks in Sector Türkeli are caused by human error, 38.14% by external environmental factors, and 21.50% by internal environmental factors (Table 26). Among the 16 factors, the most effective risk factor in Sector Türkeli was night (17.02%) (Table 26, Figure 6). The night factor ranks first in the PRAT analysis (32.73%) in Sector Türkeli (Table 24). However, according to the FAHP results obtained from expert evaluations, the night factor was the lowest risk ratio (1.31%) (Table 15). This result proves that the combined approach used in the study gives more consistent and balanced results by minimizing the misconceptions caused by the results obtained with a single method.

In Sector Kandilli, 36.01% of the total risks are associated with human factors, 43.32% with external environmental factors, and 20.68% with internal environmental factors (Table 26). The top three risk factors in Sector Kandilli are: faulty manoeuvre (13.00%), failures preventing the vessel's motion (12.07%) and current (10.61%) (Table 26, Figure 6). The determination of strong currents in the Kandilli area as one of the most critical risk factors in the region supports the results of previous studies (Akten, 2004; Arslan and Turan, 2009). However, although Umur Yeri and Yeniköy, located in Sector Kandilli, were identified as the regions with the highest risk of stranding, in the studies of Akten (2002, 2003, 2004), shallow water (2.17%) was found to be one of the lowest risk factors in Sector Kandilli according to the results of this study. The shallow water location at Umur Yeri is well known to the experts who conducted the assessments in this study. For this reason, it can be said that more careful navigation was made while passing the area. It can be thought that this increase in attention reduces the risk of shallow water (1.28%). In addition to expert judgments, data-based PRAT analysis also showed that the shallow water factor had a low-risk priority (3.07%).

In the Sector Kadıköy, 45.91% of the total risks are associated with human error, 30.60% with external environmental factors, and 23.49% with internal environmental factors (Table 26). The top three risk factors in Sector Kadıköy are: failures preventing the vessel's motion (12.57%), lack of communication and coordination (11.28%) and faulty manoeuvre (11.24%) (Table 26, Figure 6). In contrast to these top three, Aydogdu conducted studies on the heavy traffic at the southern entrance of the Istanbul Strait and stated that this factor poses a high risk in the area (Aydogdu et al., 2012; Aydogdu, 2014). In addition, it has been stated in many studies that the night factor plays a role in the occurrence of accidents in the area due to the coastal lighting and the lights of the ships at the anchorage (Akten, 2004; Arslan and Turan, 2009; Cömert, 2013).

In Sector Marmara, 52.48% of the total risks are associated with human error, 26.09% with external environmental factors, and 21.43% with internal environmental factors (Table 26). Sector Marmara, the area with the lowest total risk, has the top three risk factors: lack of communication and coordination (13.66%), failures preventing the vessel's motion (12.61%), and violation of COLREG Rule 13 (9.71%) (Table 26, Figure 6). Here, it is thought that the high rates of crossing situation and overtaking factors have been affected by the ferries making reciprocal voyages in the Marmara Sea, which was shown in the study of Altan (2014).

According to the distribution of the risks in the Canakkale Strait based on the sectors, 54.59% of the total risks in Sector Gelibolu are caused by human error, 22.39% by external environmental factors, and 23.02% by internal environmental factors. Sector Gelibolu draws attention as the sector where the external environmental factors have the most negligible impact in the Turkish Straits. The top three risk factors in Sector Gelibolu are: lack of communication and coordination (15.27%), faulty manoeuvre (11.94%) and violation of COLREG Rule 13 (11.69%), respectively (Table 26, Figure 6).

In Sector Nara, 34.10% of the total risks are associated with human factors, 43.20% with external environmental factors, and 22.70% with internal environmental factors (Table 26). Although the top three risk factors for Sector Nara are the same as Sector Kandilli, failures preventing the vessel's motion (12.77%) are in the first place, while faulty manoeuvre (12.07%) is in the second place (Table 26, Figure 6). Sector Nara and Sector Kandilli are the narrowest areas of the Turkish Straits with sharp turns. Their common characteristics have made the two sectors similar. The similarity of risk factors in two different areas with similar characteristics is a result that proves the consistency of the study.

In Sector Kumkale, 45.30% of the total risks are associated with human factors, 30.48% with external environmental factors, and 24.22% with internal environmental factors (Table

26). Sector Kumkale draws attention as the region where internal environmental factors have the highest risk ratio in the Turkish Straits. The top three risk factors in Sector Kumkale are: lack of communication and coordination (16.22%), failures preventing the vessel's motion (13.80%) and faulty manoeuvre (10.48%) (Table 26, Figure 6). A remarkable result is that two of the three internal environmental factors included in the study are among the top risk factors of Sector Kumkale.

One of the interesting results of the study is that failures preventing the vessel's motion and faulty manoeuvre are among the top 5 risk factors for all sectors, while violation of COLREG Rule 16 and shallow water is not among the top in any sector. A failure preventing the vessel's motion will put the ship not under command. It is expected that a vessel not under command in narrow waters will involve high risk. These results can be expected, given that a faulty manoeuvre can result in a direct accident.

Arslan and Turan (2009) concluded that it is essential to develop ships further technologically to reduce accidents in the Istanbul Strait. In the study of Emecen Kara (2016), it was revealed that the vessels passing through the Turkish Straits are technically neglected and not well maintained. The fact that failures preventing the vessel's motion have a high-risk rate in all sectors supports the results of this study. In addition, it was concluded that human factors increase the accident risk more than internal and external environmental factors in all sectors except Sector Kandilli and Sector Nara (Table 26). This result confirms the conclusion that “the factor that has the biggest share in the occurrence of maritime accidents is human errors”, which is frequently expressed in previous studies in the literature (Arslan and Turan, 2009; Uğurlu et al., 2016).

As a result, it has been revealed that the order of priority of the existing risk factors in the Turkish Straits varies in each sector. That means a ship passing through the Turkish Straits will face different risks in each sector. In addition, very high and very low values encountered in analyses based on a single method were balanced with this study's hybrid approach. At the same time, a combination of human perceptions and data has been used to present the most realistic results.

There are some shortcomings of the hybrid model proposed in this study. A significant number of accident reports must be handled to implement the proposed model. In cases where there are not enough accident reports, the model may not give consistent results. In addition, since some accident reports include statements such as total loss, environmental pollution or economic loss instead of the accident severity, these statements must be converted into accident severity categories used in the study. This causes extra effort. It is essential to consult a sufficient number of experts during the FAHP stage of the model. In addition, the fact that the experts consulted for their opinions are experienced in the industry where the model will be applied, know the region well, and have well-equipped knowledge will increase the quality of the evaluation to be made. Thus, it will be ensured that the model gives consistent results.

7. Conclusion

The Turkish Straits are one of the world's narrowest and most congested waterways in maritime transport; due to this feature, ships in transit face many risks. Therefore, estimation of sector-specific risk factors in the Turkish Straits, where accident occurrences are common, is of great importance for all maritime industry stakeholders. Thus, in this study, an evaluation of the risk factors in the Turkish Straits based on sectors was made. Furthermore, the factors involved in accidents were analysed with a hybrid method integrating FAHP and PRAT methods. With the study, it has been determined that the region with the highest total risk in the Turkish Straits is Sector Kadıköy, in line with the results of previous studies (Arslan and Turan, 2009; Aydogdu et al., 2012; Aydogdu, 2014).

The most important result of this study is that the risks in the Turkish Straits have been presented separately for each sector. Table 26 and Figure 6 in the study demonstrate the current risks and their weights for each sector. The results of this study can help the safe passage by defining the risks that the ships passing through the Turkish Straits may encounter while navigating in a sector-specific manner. In addition, it can be a reference in determining the measures to be taken by the official authorities to increase the safety of navigation in the Turkish Straits.

Finally, the hybrid method used in this study, combining expert knowledge with historical accident data, was considered to be a consistent and feasible risk assessment tool. The FAHP and PRAT models integrated within the study offer two different perspectives on accident analysis. While PRAT presents a reactive approach since it is based on past accident data, the FAHP method acts as a forecasting model for the future with expert judgments and displays a proactive approach. Thus, the combined value produces a result that embodies both approaches. The model has a structure that can be easily applied to different regions and different industries. The parameters (criteria) and weights of the integrated models can be adjusted according to the characteristics of the region or industry to which they will be applied.

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Table 1. Comparison of methods used in accident analysis

Method	How does an accident occur?	The main objective of the analysis	Systems for which the model is suitable	Sample models*
Sequential methods	An event/error triggers another event/error.	Finding the first link in the chain of events that led to the accident.	Simple linear systems	ETA FTA Domino models
Epidemiological methods	It occurs as a result of simultaneous errors/deficiencies at different safety levels.	Detecting errors/deficiencies in safety defence layers.	Complex linear systems	Bow-tie SCM HFACS
Systemic methods	It occurs as a result of the interactions of factors in the system.	To show the interactions and possible resonances of performance changes in different units in the system.	Complex interactive systems	FRAM STAMP AcciMap
Hybrid methods	It does not describe an accident. Appropriate models are combined according to the accident characteristics.	To provide realistic and consistent results by modelling the accidents in the closest way to reality.	All type systems	HFACS+BN HFACS+ANN SWOT+AHP

*Sample Models: ETA: Event Tree Analysis, FTA: Fault Tree Analysis, SCM: Swiss Cheese Model, HFACS: Human Factors Analysis and Classification System, FRAM: Functional Resonance Analysis Method, STAMP: System-Theoretic Accident Model and Processes, BN: Bayesian Networks, ANN: Artificial Neural Network, SWOT: Strengths, Weaknesses, Opportunities, and Threats, AHP: Analytic Hierarchy Process

Table 2. Fuzzy numbers

Linguistic value	Triangular Fuzzy Number	Inverse Triangular Fuzzy Number
Equally Important	(1,1,1)	(1,1,1)
Weakly Importance	(2/3,1,3/2)	(2/3,1,3/2)
Fairly Important	(3/2,2,5/2)	(2/5,1/2,2/3)
Strongly Important	(5/2,3,7/2)	(2/7,1/3,2/5)
Absolutely Important	(7/2,4,9/2)	(2/9,1/4,2/7)

Table 3. Reference studies to identify criteria and sub-criteria

Reference No	Author(s) Year	Article Name	Journal Name	Investigation Area
RF1	Squire, 2003	The hazards of navigating the Dover Strait (Pas-de-Calais) traffic separation scheme	The Journal of Navigation	Dover Strait
RF2	Akten, 2004	Analysis of shipping casualties in the Bosphorus.	The Journal of Navigation	İstanbul Strait
RF3	Arslan & Turan, 2009	Analytical investigation of marine casualties at the Strait of Istanbul with SWOT–AHP method	Maritime Policy & Management	İstanbul Strait
RF4	Goerlandt & Kujala, 2011	Traffic simulation based ship collision probability modeling	Reliability Engineering & System Safety	Gulf of Finland
RF5	Qu et al., 2011	Ship collision risk assessment for the Singapore Strait	Accident Analysis & Prevention	Singapore Strait
RF6	Aydogdu et al., 2012	A study on local traffic management to improve marine traffic safety in the Istanbul Strait	The Journal of Navigation	İstanbul Strait
RF7	Zhang et al., 2013	Incorporation of formal safety assessment and Bayesian network in navigational risk estimation of the Yangtze River	Reliability Engineering & System Safety	Yangtze River
RF8	Aydogdu, 2014	A comparison of maritime risk perception and accident statistics in the Istanbul Straight	The Journal of Navigation	İstanbul Strait
RF9	Zaman et al., 2014	Fuzzy FMEA model for risk evaluation of ship collisions in the Malacca Strait: based on AIS data	Journal of Simulation	Malacca Strait
RF10	Uğurlu et al., 2016	The analysis of life safety and economic loss in marine accidents occurring in the Turkish Straits	Maritime Policy and Management	Turkish Strait
RF11	Erol et al., 2018	Analysis of ship accidents in the Istanbul Strait using neuro-fuzzy and genetically optimised fuzzy classifiers	The Journal of Navigation	İstanbul Strait
RF12	İstikbal, 2020	Strait of Istanbul, major accidents and abolishment of left-hand side navigation	Aquatic Research	İstanbul Strait

Table 4. Reference studies for each sub-criterion

References / Criteria	RF1	RF2	RF3	RF4	RF5	RF6	RF7	RF8	RF9	RF10	RF11	RF12
Faulty Manoeuvre	X									X		X
Violation of COLREG Rule 16 (Unsafe Speed)					X				X			
Violation of COLREG Rule 15 (Crossing Situation)	X			X		X		X	X			
Violation of COLREG Rule 10 (TSS)	X	X				X		X				X
Violation of COLREG Rule 13 (Overtaking)						X		X	X			
Lack of Communication and Coordination			X					X				X
Heavy Weather and Sea Conditions	X						X		X	X	X	
Current		X	X					X				X
Dense Traffic	X	X	X	X		X		X	X			
Night		X	X									X
Sharp Turn		X	X					X				X
Narrow Channel		X	X				X					X
Shallow Water		X										
Failures Preventing Vessel's Motion (Main Engine, Rudder, etc.)									X	X	X	
Low-Speed Vessels			X									
Ship Size			X				X	X			X	X

Table 5. Qualifications of experts

Decision Makers (DM)	Professional Position	Service Duration (years)	Strait Passage (no. of times)
DM1	Oceangoing Captain	16	60
DM2	Oceangoing Captain	10	20
DM3	Oceangoing Captain	19	70
DM4	Oceangoing Captain	19	150
DM5	Oceangoing Captain	30	500
DM6	VTS Operator	20	20
DM7	VTS Operator	10	300
DM8	VTS Operator	12	23
DM9	VTS Operator	16	200
DM10	VTS Operator	24	60
DM11	Sea Pilot	19	1500
DM12	Sea Pilot	8	500
DM13	Sea Pilot	17	1500
DM14	Sea Pilot	35	4800
DM15	Sea Pilot	30	4500
DM16	VTS Operator	14	100
DM17	VTS Operator	26	50
DM18	Sea Pilot	16	1000
DM19	Sea Pilot	21	1500
DM20	Sea Pilot	35	5000

Table 6. The elements of hierarchy and their abbreviations (Abb)

Full name of the element	Abb	Full name of the element	Abb
Human Factors	C1	Heavy Weather and Sea Conditions	SC2.1
External Environmental Factors	C2	Current	SC2.2
Internal Environmental Factors	C3	Dense Traffic	SC2.3
Faulty Manoeuvre	SC1.1	Night	SC2.4
Violation of COLREG Rule 16 (Unsafe Speed)	SC1.2	Sharp Turn	SC2.5
Violation of COLREG Rule 15 (Crossing Situation)	SC1.3	Narrow Channel	SC2.6
Violation of COLREG Rule 10 (TSS)	SC1.4	Shallow Water	SC2.7
Violation of COLREG Rule 13 (Overtaking)	SC1.5	Failures Preventing Vessel's Motion	SC3.1
Lack of Communication and Coordination	SC1.6	Ship Size	SC3.2
		Low-Speed Vessels	SC3.3

Table 7. Fuzzy judgement matrix of criteria by DM1

		C1	C2	C3	Fuzzy Priority Weight	Normalised Priority
DM1	**C1**	(1,1,1)	(1,1,1)	(2/5,1/2,2/3)	(0.212, 0.250, 0.303)	0.000
	C2		(1,1,1)	(2/5,1/2,2/3)	(0.212, 0.250, 0.303)	0.000
	C3			(1,1,1)	(0.353, 0.500, 0.682)	1.000

Table 8. Fuzzy judgement matrix of sub-criteria with respect to criteria by DM1

	C1	**SC1.1**	**SC1.2**	**SC1.3**	**SC1.4**	**SC1.5**	**SC1.6**		**Local Priority**
	SC1.1	(1,1,1)	(3/2,2,5/2)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)		0.200
	SC1.2		(1,1,1)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(2/5,1/2,2/3)		0.000
	SC1.3			(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)		0.200
	SC1.4				(1,1,1)	(1,1,1)	(1,1,1)		0.200
	SC1.5					(1,1,1)	(1,1,1)		0.200
	SC1.6						(1,1,1)		0.200
	C2	**SC2.1**	**SC2.2**	**SC2.3**	**SC2.4**	**SC2.5**	**SC2.6**	**SC2.7**	
DM1	**SC2.1**	(1,1,1)	(2/3,1,3/2)	(2/3,1,3/2)	(3/2,2,5/2)	(2/3,1,3/2)	(2/3,1,3/2)	(3/2,2,5/2)	0.178
	SC2.2		(1,1,1)	(1,1,1)	(5/2,3,7/2)	(3/2,2,5/2)	(1,1,1)	(5/2,3,7/2)	0.265
	SC2.3			(1,1,1)	(5/2,3,7/2)	(3/2,2,5/2)	(1,1,1)	(5/2,3,7/2)	0.265
	SC2.4				(1,1,1)	(2/3,1,3/2)	(2/7,1/3,2/5)	(1,1,1)	0.000
	SC2.5					(1,1,1)	(2/5,1/2,2/3)	(2/3,1,3/2)	0.026
	SC2.6						(1,1,1)	(5/2,3,7/2)	0.265
	SC2.7							(1,1,1)	0.000
	C3	**SC3.1**	**SC3.2**	**SC3.3**					
	SC3.1	(1,1,1)	(2/3,1,3/2)	(3/2,2,5/2)					0.582
	SC3.2		(1,1,1)	(2/3,1,3/2)					0.418
	SC3.3			(1,1,1)					0.000

Table 9. Fuzzy judgement matrix of alternatives with respect to sub-criteria by DM1

	SC1.1	**Türkeli**	**Kandilli**	**Kadıköy**	**Marmara**	**Gelibolu**	**Nara**	**Kumkale**
	Türkeli	(1,1,1)	(1,1,1)	(1,1,1)	(3/2,2,5/2)	(3/2,2,5/2)	(1,1,1)	(3/2,2,5/2)
	Kandilli		(1,1,1)	(1,1,1)	(3/2,2,5/2)	(3/2,2,5/2)	(1,1,1)	(3/2,2,5/2)
	Kadıköy			(1,1,1)	(3/2,2,5/2)	(3/2,2,5/2)	(1,1,1)	(3/2,2,5/2)
	Marmara				(1,1,1)	(1,1,1)	(2/5,1/2,2/3)	(1,1,1)
	Gelibolu					(1,1,1)	(2/5,1/2,2/3)	(1,1,1)
	Nara						(1,1,1)	(3/2,2,5/2)
	Kumkale							(1,1,1)
	SC1.2							
	Türkeli	(1,1,1)	(1,1,1)	(3/2,2,5/2)	(5/2,3,7/2)	(3/2,2,5/2)	(1,1,1)	(3/2,2,5/2)
	Kandilli		(1,1,1)	(3/2,2,5/2)	(5/2,3,7/2)	(3/2,2,5/2)	(1,1,1)	(3/2,2,5/2)
	Kadıköy			(1,1,1)	(2/3,1,3/2)	(1,1,1)	(2/5,1/2,2/3)	(1,1,1)
	Marmara				(1,1,1)	(2/3,1,3/2)	(2/7,1/3,2/5)	(2/3,1,3/2)
	Gelibolu					(1,1,1)	(2/5,1/2,2/3)	(1,1,1)
	Nara						(1,1,1)	(3/2,2,5/2)
	Kumkale							(1,1,1)
DM1	**SC1.3**							
	Türkeli	(1,1,1)	(1,1,1)	(1,1,1)	(3/2,2,5/2)	(1,1,1)	(1,1,1)	(1,1,1)
	Kandilli		(1,1,1)	(1,1,1)	(3/2,2,5/2)	(1,1,1)	(1,1,1)	(1,1,1)
	Kadıköy			(1,1,1)	(3/2,2,5/2)	(1,1,1)	(1,1,1)	(1,1,1)
	Marmara				(1,1,1)	(2/5,1/2,2/3)	(2/5,1/2,2/3)	(2/5,1/2,2/3)
	Gelibolu					(1,1,1)	(1,1,1)	(1,1,1)
	Nara						(1,1,1)	(1,1,1)
	Kumkale							(1,1,1)
	….	….	….	….	….	….	….	….
	….	….	….	….	….	….	….	….
	….	….	….	….	….	….	….	….
	SC3.3							
	Türkeli	(1,1,1)	(2/3,1,3/2)	(3/2,2,5/2)	(5/2,3,7/2)	(3/2,2,5/2)	(2/3,1,3/2)	(5/2,3,7/2)
	Kandilli		(1,1,1)	(5/2,3,7/2)	(7/2,4,9/2)	(5/2,3,7/2)	(1,1,1)	(7/2,4,9/2)
	Kadıköy			(1,1,1)	(2/3,1,3/2)	(1,1,1)	(2/7,1/3,2/5)	(2/3,1,3/2)
	Marmara				(1,1,1)	(2/3,1,3/2)	(2/9,1/4,2/7)	(1,1,1)
	Gelibolu					(1,1,1)	(2/7,1/3,2/5)	(2/3,1,3/2)
	Nara						(1,1,1)	(7/2,4,9/2)
	Kumkale							(1,1,1)

Table 10. Expert weighting scale

Criteria	Class	Point
Professional Competence	Maritime Pilot	3
	VTS Operator	2
	Oceangoing Master	1
Service Period (Years)	≥15 years	3
	10 – 14 years	2
	0 – 9 years	1
Number of Strait Passages	≥100	3
	50 – 99	2
	0 – 49	1

Table 11. Weighting of decision-makers

Decision Maker	**Position**			**Strait Passage (Time)**			**Service Duration (Year)**			**Total Score (TS)**	**Weight (W_E)**
	Sea Pilot	VTS Operator	Oceangoing Captain	100+ Times	50-99 Times	0-49 Times	15+ Years	10-14 Years	0-9 Years		
1			✓		✓		✓			6	0.041
2			✓			✓		✓		4	0.027
3			✓		✓		✓			6	0.041
4			✓	✓			✓			7	0.048
5			✓	✓			✓			7	0.048
6		✓				✓	✓			6	0.041
7		✓		✓				✓		7	0.048
8		✓				✓		✓		5	0.034
9		✓		✓			✓			8	0.055
10	✓					✓	✓			6	0.041
11	✓			✓			✓			9	0.062
12	✓			✓					✓	7	0.048
13	✓			✓			✓			9	0.062
14	✓			✓			✓			9	0.062
15	✓			✓			✓			9	0.062
16		✓		✓				✓		7	0.048
17		✓			✓		✓			7	0.048
18	✓			✓			✓			9	0.062
19	✓			✓			✓			9	0.062
20	✓			✓			✓			9	0.062

Table 12. Individual expert weights and de-fuzzified priorities of criteria and sub-criteria for each DM

	DM1	DM2	DM3	….	DM19	DM20	Aggregate Priorities
W_E =	0.041	0.027	0.041		0.062	0.062	
C1	0.000	0.418	0.451	….	0.333	1.000	0.479
SC1.1	0.000	0.118	0.085	….	0.000	0.000	0.114
SC1.2	0.000	0.053	0.064	….	0.000	0.000	0.036
SC1.3	0.000	0.071	0.085	….	0.025	0.250	0.074
SC1.4	0.000	0.053	0.011	….	0.000	0.250	0.054
SC1.5	0.000	0.053	0.085	….	0.000	0.250	0.078
SC1.6	0.000	0.071	0.120	….	0.308	0.250	0.122
C2	0.000	0.000	0.226	….	0.333	0.000	0.203
SC2.1	0.000	0.000	0.032	….	0.080	0.000	0.035
SC2.2	0.000	0.000	0.032	….	0.039	0.000	0.046
SC2.3	0.000	0.000	0.032	….	0.053	0.000	0.034
SC2.4	0.000	0.000	0.032	….	0.053	0.000	0.016
SC2.5	0.000	0.000	0.032	….	0.053	0.000	0.031
SC2.6	0.000	0.000	0.032	….	0.039	0.000	0.028
SC2.7	0.000	0.000	0.032	….	0.015	0.000	0.014
C3	1.000	0.582	0.324	….	0.333	0.000	0.318
SC3.1	0.582	0.262	0.108	….	0.333	0.000	0.217
SC3.2	0.418	0.188	0.108	….	0.000	0.000	0.069
SC3.3	0.000	0.131	0.108	….	0.000	0.000	0.032

Table 13. Individual expert weights and de-fuzzified priorities of alternatives for each DM

		DM1	DM2	DM3	….	DM19	DM20	Aggregate Priorities
	W_E =	0.041	0.027	0.041	….	0.062	0.062	
SC1.1	Türkeli	0.000	0.002	0.005	….	0.000	0.000	0.007
	Kandilli	0.000	0.040	0.026	….	0.000	0.000	0.033
	Kadıköy	0.000	0.025	0.014	….	0.000	0.000	0.028
	Marmara	0.000	0.002	0.005	….	0.000	0.000	0.004
	Gelibolu	0.000	0.012	0.005	….	0.000	0.000	0.008
	Nara	0.000	0.025	0.026	….	0.000	0.000	0.027
	Kumkale	0.000	0.012	0.005	….	0.000	0.000	0.007
SC1.2	Türkeli	0.000	0.004	0.009	….	0.000	0.000	0.002
	Kandilli	0.000	0.010	0.014	….	0.000	0.000	0.009
	Kadıköy	0.000	0.010	0.008	….	0.000	0.000	0.008
	Marmara	0.000	0.004	0.009	….	0.000	0.000	0.002
	Gelibolu	0.000	0.007	0.008	….	0.000	0.000	0.003
	Nara	0.000	0.010	0.009	….	0.000	0.000	0.009
	Kumkale	0.000	0.007	0.008	….	0.000	0.000	0.002
SC1.3	Türkeli	0.000	0.004	0.014	….	0.001	0.036	0.005
	Kandilli	0.000	0.020	0.020	….	0.008	0.048	0.022
	Kadıköy	0.000	0.012	0.008	….	0.008	0.048	0.019
	Marmara	0.000	0.007	0.008	….	0.001	0.010	0.005
	Gelibolu	0.000	0.007	0.014	….	0.005	0.048	0.009
	Nara	0.000	0.012	0.020	….	0.001	0.048	0.018
	Kumkale	0.000	0.007	0.002	….	0.001	0.010	0.004
….	….	….	….	….	….	….	….	….
….	….	….	….	….	….	….	….	….
SC3.3	Türkeli	0.000	0.007	0.012	….	0.000	0.000	0.002
	Kandilli	0.000	0.040	0.020	….	0.000	0.000	0.011
	Kadıköy	0.000	0.040	0.015	….	0.000	0.000	0.005
	Marmara	0.000	0.005	0.012	….	0.000	0.000	0.001
	Gelibolu	0.000	0.007	0.015	….	0.000	0.000	0.002
	Nara	0.000	0.024	0.020	….	0.000	0.000	0.010
	Kumkale	0.000	0.007	0.015	….	0.000	0.000	0.002

Table 14. Aggregate priorities

		Türkeli	Kandilli	Kadıköy	Marmara	Gelibolu	Nara	Kumkale
C1	**0.479**							
SC1.1	0.114	0.007	0.033	0.028	0.004	0.008	0.027	0.007
SC1.2	0.036	0.002	0.009	0.008	0.002	0.003	0.009	0.002
SC1.3	0.074	0.005	0.019	0.016	0.005	0.009	0.016	0.004
SC1.4	0.054	0.005	0.014	0.012	0.004	0.006	0.010	0.004
SC1.5	0.078	0.007	0.015	0.016	0.005	0.012	0.018	0.005
SC1.6	0.122	0.016	0.023	0.024	0.009	0.014	0.020	0.015
C2	**0.203**							
SC2.1	0.035	0.005	0.008	0.005	0.003	0.003	0.007	0.004
SC2.2	0.046	0.001	0.020	0.006	0.000	0.001	0.016	0.001
SC2.3	0.034	0.005	0.006	0.008	0.002	0.005	0.006	0.002
SC2.4	0.016	0.001	0.004	0.005	0.001	0.001	0.002	0.001
SC2.5	0.031	0.001	0.014	0.003	0.001	0.001	0.011	0.001
SC2.6	0.028	0.001	0.013	0.004	0.001	0.001	0.008	0.001
SC2.7	0.014	0.001	0.003	0.003	0.000	0.002	0.003	0.001
C3	**0.318**							
SC3.1	0.217	0.018	0.056	0.048	0.010	0.018	0.049	0.018
SC3.2	0.069	0.007	0.019	0.015	0.001	0.006	0.017	0.004
SC3.3	0.032	0.002	0.011	0.005	0.001	0.002	0.010	0.002

Table 15. Normalised FAHP results

	Türkeli	Kandilli	Kadıköy	Marmara	Gelibolu	Nara	Kumkale
SC1.1	8.01	12.21	13.46	8.82	8.63	11.89	9.85
SC1.2	2.80	3.46	3.96	4.06	3.22	3.88	2.71
SC1.3	6.41	7.12	7.89	10.11	9.34	7.06	4.97
SC1.4	5.66	5.27	5.62	7.95	6.94	4.31	5.38
SC1.5	8.41	5.75	7.65	10.33	13.22	7.70	7.48
SC1.6	19.43	8.70	11.73	18.23	15.28	8.87	21.33
SC2.1	5.64	2.95	2.62	6.11	3.74	3.14	5.20
SC2.2	1.12	7.42	2.93	0.77	1.43	7.02	1.44
SC2.3	5.46	2.13	4.08	3.57	5.53	2.81	2.80
SC2.4	1.31	1.49	2.47	2.17	1.30	0.90	1.43
SC2.5	1.02	5.29	1.21	1.35	1.08	4.68	1.20
SC2.6	1.36	4.77	1.98	1.12	1.17	3.30	1.22
SC2.7	1.29	1.28	1.51	0.74	1.71	1.29	1.38
SC3.1	21.27	21.08	22.97	20.68	19.00	21.46	25.75
SC3.2	8.68	7.12	7.41	2.68	6.34	7.30	5.17
SC3.3	2.15	3.96	2.51	1.31	2.06	4.40	2.70
Sum	100	100	100	100	100	100	100

Table 16. Accident statistics in Sector Kadıköy

	Event	Sum	Average time for an event (Months)
SC1.1	Faulty Manoeuvre	106	1.132
SC1.2	Violation of COLREG Rule 16 (Unsafe Speed)	55	2.182
SC1.3	Violation of COLREG Rule 15 (Crossing Situation)	24	5.000
SC1.4	Violation of COLREG Rule 10 (TSS)	18	6.667
SC1.5	Violation of COLREG Rule 13 (Overtaking)	16	7.500
SC1.6	Lack of Communication and Coordination	94	1.277
SC2.1	Heavy Weather and Sea Conditions	74	1.622
SC2.2	Current	9	13.333
SC2.3	Dense Traffic	159	0.755
SC2.4	Night	112	1.071
SC2.5	Sharp Turn	5	24.000
SC2.6	Narrow Channel	12	10.000
SC2.7	Shallow Water	10	12.000
SC3.1	Failures Preventing Vessel's Motion	9	13.333
SC3.2	Ship Size	41	2.927
SC3.3	Low Speed Vessels	32	3.750
	Total Accident in Sector	187	

Table 17. Scoring of the probability factor

Probability Factor (P)	Description of Undesirable Event	Frequency of Events Occurring
5	Unavoidable	1 event during period ≤ 3 months
4	Almost assured	1 event during period > 3 and ≤ 6 months
3	Probability 50%	1 event during period > 6 and ≤ 12 months
2	Almost improbable	1 event during period >12 and ≤ 24 months
1	Impossible	1 event during period > 24 months

Table 18. Scoring of the frequency factor

Frequency Factor (F)	Number of Events Occurred
5	Events occurred > 100 times
4	Events occurred > 50 and ≤ 100 times
3	Events occurred > 20 and ≤ 50 times
2	Events occurred > 5 and ≤ 20 times
1	Events occurred ≤ 5 times

Table 19. Severity statistics in Sector Kadıköy

Abb	Event	Sum	Severity Type: Very Serious = 3	Severity Type: Serious = 2	Severity Type: Less Serious = 1	Severity score: Very Serious	Severity score: Serious	Severity score: Less Serious	Total Severity Score	Average Severity Score
SC1.1	Faulty Manoeuvre	106	1	104	1	3	208	1	212	2.00
SC1.2	Violation of COLREG Rule 16 (Unsafe Speed)	55	1	54	0	3	108	0	111	2.02
SC1.3	Violation of COLREG Rule 15 (Crossing Situation)	24	1	23	0	3	46	0	49	2.04
SC1.4	Violation of COLREG Rule 10 (TSS)	18	0	18	0	0	36	0	36	2.00
SC1.5	Violation of COLREG Rule 13 (Overtaking)	16	0	16	0	0	32	0	32	2.00
SC1.6	Lack of Communication and Coordination	94	1	93	0	3	186	0	189	2.01
SC2.1	Heavy Weather and Sea Conditions	74	4	70	0	12	140	0	152	2.05
SC2.2	Current	9	0	9	0	0	18	0	18	2.00
SC2.3	Dense Traffic	159	2	157	0	6	314	0	320	2.01
SC2.4	Night	112	0	111	1	0	222	1	223	1.99
SC2.5	Sharp Turn	5	0	5	0	0	10	0	10	2.00
SC2.6	Narrow Channel	12	0	12	0	0	24	0	24	2.00
SC2.7	Shallow Water	10	0	10	0	0	20	0	20	2.00
SC3.1	Failures Preventing Vessel's Motion	9	2	7	0	6	14	0	20	2.22
SC3.2	Ship Size	41	0	41	0	0	82	0	82	2.00
SC3.3	Low Speed Vessels	32	1	31	0	3	62	0	65	2.03

Table 20. Scoring of the severity type

Severity Type (ST)	Score
Very Serious	3
Serious	2
Less Serious	1

Table 21. Scoring of the severity factor

Severity Factor (S)	Average Severity Score
3	Severity Score > 2
2	Severity Score > 1 and ≤ 2
1	Severity Score ≤ 1

Table 22. Calculations of the risk value for each sub-criterion in Sector Kadıköy

Abb	Event	Probability Factor (P) *(Table 16,17)*	Frequency Factor (F) *(Table 16,18)*	Severity Factor (S) *(Table 19,21)*	Risk Value (R) *(P×F×S)*	Normalised Risk Value (R%)
SC1.1	Faulty Manoeuvre	5	5	2	50	9.03
SC1.2	Violation of COLREG Rule 16 (Unsafe Speed)	5	4	3	60	10.83
SC1.3	Violation of COLREG Rule 15 (Crossing Situation)	4	3	3	36	6.50
SC1.4	Violation of COLREG Rule 10 (TSS)	3	2	2	12	2.17
SC1.5	Violation of COLREG Rule 13 (Overtaking)	3	2	2	12	2.17
SC1.6	Lack of Communication and Coordination	5	4	3	60	10.83
SC2.1	Heavy Weather and Sea Conditions	5	4	3	60	10.83
SC2.2	Current	2	2	2	8	1.44
SC2.3	Dense Traffic	5	5	3	75	13.54
SC2.4	Night	5	5	3	75	13.54
SC2.5	Sharp Turn	2	1	2	4	0.72
SC2.6	Narrow Channel	3	2	2	12	2.17
SC2.7	Shallow Water	3	2	2	12	2.17
SC3.1	Failures Preventing Vessel's Motion	2	2	3	12	2.17
SC3.2	Ship Size	5	3	2	30	5.42
SC3.3	Low Speed Vessels	4	3	3	36	6.50
	Sum				554	100

Table 23. PRAT (R) risk value of each sub-criterion

	Türkeli	**Kandilli**	**Kadıköy**	**Marmara**	**Gelibolu**	**Nara**	**Kumkale**	**Total Risk Value in Turkish Straits**
SC1.1	12	36	50	2	18	12	12	142
SC1.2	4	12	60	1	3	2	2	84
SC1.3	1	3	36	2	3	2	2	49
SC1.4	2	12	12	1	8	4	12	51
SC1.5	2	2	12	2	12	2	2	34
SC1.6	12	12	60	2	18	2	12	118
SC2.1	18	2	60	1	4	2	8	95
SC2.2	2	36	8	1	12	12	12	83
SC2.3	4	18	75	1	2	8	2	110
SC2.4	36	24	75	2	6	4	12	159
SC2.5	1	36	4	1	1	12	2	57
SC2.6	2	36	12	1	1	12	2	66
SC2.7	2	8	12	1	8	12	12	55
SC3.1	6	8	12	1	2	4	2	35
SC3.2	3	8	30	2	18	4	2	67
SC3.3	3	8	36	1	2	4	12	66
Sum	110 (8.65%)	261 (20.54%)	554 (43.59%)	22 (1.73%)	118 (9.28%)	98 (7.71%)	108 (8.50%)	1271 (100%)

Table 24. PRAT (R%) normalised risk value of each sub-criterion

	Türkeli	Kandilli	Kadıköy	Marmara	Gelibolu	Nara	Kumkale
SC1.1	10.91	13.79	9.03	9.09	15.25	12.24	11.11
SC1.2	3.64	4.60	10.83	4.55	2.54	2.04	1.85
SC1.3	0.91	1.15	6.50	9.09	2.54	2.04	1.85
SC1.4	1.82	4.60	2.17	4.55	6.78	4.08	11.11
SC1.5	1.82	0.77	2.17	9.09	10.17	2.04	1.85
SC1.6	10.91	4.60	10.83	9.09	15.25	2.04	11.11
SC2.1	16.36	0.77	10.83	4.55	3.39	2.04	7.41
SC2.2	1.82	13.79	1.44	4.55	10.17	12.24	11.11
SC2.3	3.64	6.90	13.54	4.55	1.69	8.16	1.85
SC2.4	32.73	9.20	13.54	9.09	5.08	4.08	11.11
SC2.5	0.91	13.79	0.72	4.55	0.85	12.24	1.85
SC2.6	1.82	13.79	2.17	4.55	0.85	12.24	1.85
SC2.7	1.82	3.07	2.17	4.55	6.78	12.24	11.11
SC3.1	5.45	3.07	2.17	4.55	1.69	4.08	1.85
SC3.2	2.73	3.07	5.42	9.09	15.25	4.08	1.85
SC3.3	2.73	3.07	6.50	4.55	1.69	4.08	11.11
Sum	100	100	100	100	100	100	100

Table 25. Combined FAHP-PRAT ranking for each sub-criterion in Sector Kadıköy

Origin of the Event	Abb	Event	PRAT (R%)	FAHP (A%)	CFP (0.5×R% + 0.5×A%)
Human	SC1.1	Faulty Manoeuvre	9.03	13.46	11.24
	SC1.2	Violation of COLREG Rule 16 (Unsafe Speed)	10.83	3.96	7.39
	SC1.3	Violation of COLREG Rule 15 (Crossing Situation)	6.50	7.89	7.20
	SC1.4	Violation of COLREG Rule 10 (TSS)	2.17	5.62	3.89
	SC1.5	Violation of COLREG Rule 13 (Overtaking)	2.17	7.65	4.91
	SC1.6	Lack of Communication and Coordination	10.83	11.73	11.28
External Environment	SC2.1	Heavy Weather and Sea Conditions	10.83	2.62	6.73
	SC2.2	Current	1.44	2.93	2.19
	SC2.3	Dense Traffic	13.54	4.08	8.81
	SC2.4	Night	13.54	2.47	8.00
	SC2.5	Sharp Turn	0.72	1.21	0.97
	SC2.6	Narrow Channel	2.17	1.98	2.07
	SC2.7	Shallow Water	2.17	1.51	1.84
Internal Environment	SC3.1	Failures Preventing Vessel's Motion	2.17	22.97	12.57
	SC3.2	Ship Size	5.42	7.41	6.41
	SC3.3	Low Speed Vessels	6.50	2.51	4.51

Table 26. Combined FAHP-PRAT (CFP) result

		Türkeli	Kandilli	Kadıköy	Marmara	Gelibolu	Nara	Kumkale
Human	SC1.1	9.46	13.00	11.24	8.95	11.94	12.07	10.48
	SC1.2	3.22	4.03	7.39	4.30	2.88	2.96	2.28
	SC1.3	3.66	4.13	7.20	9.60	5.94	4.55	3.41
	SC1.4	3.74	4.94	3.89	6.25	6.86	4.19	8.24
	SC1.5	5.11	3.26	4.91	9.71	11.69	4.87	4.66
	SC1.6	15.17	6.65	11.28	13.66	15.27	5.45	16.22
External Environment	SC2.1	11.00	1.86	6.73	5.33	3.57	2.59	6.30
	SC2.2	1.47	10.61	2.19	2.66	5.80	9.63	6.28
	SC2.3	4.55	4.51	8.81	4.06	3.61	5.49	2.32
	SC2.4	17.02	5.34	8.00	5.63	3.19	2.49	6.27
	SC2.5	0.96	9.54	0.97	2.95	0.96	8.46	1.53
	SC2.6	1.59	9.28	2.07	2.83	1.01	7.77	1.54
	SC2.7	1.55	2.17	1.84	2.64	4.25	6.76	6.24
Internal Environ	SC3.1	13.36	12.07	12.57	12.61	10.35	12.77	13.80
	SC3.2	5.70	5.09	6.41	5.89	10.80	5.69	3.51
	SC3.3	2.44	3.51	4.51	2.93	1.88	4.24	6.91

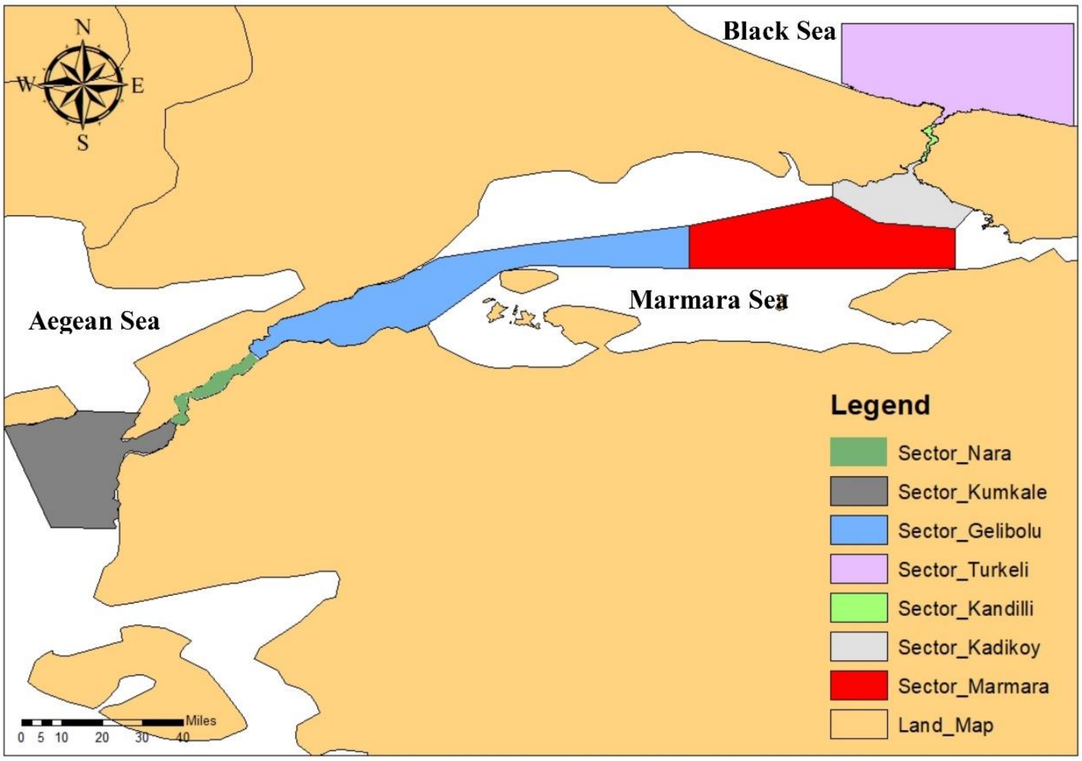


Figure 1. Turkish Straits Vessel Traffic Services area (KEGM, 2019)

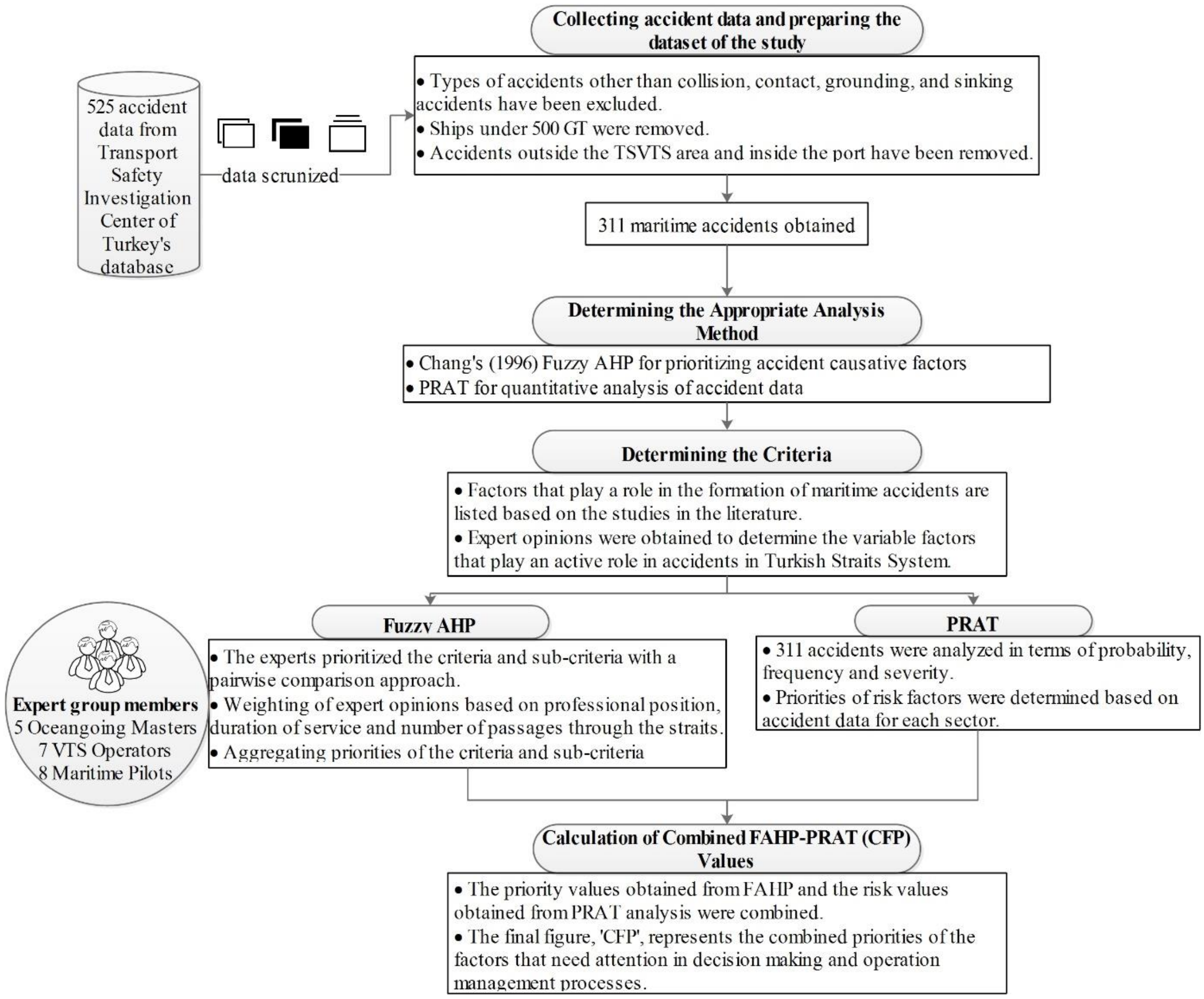


Figure 2. Flow chart of the methodology followed in the study

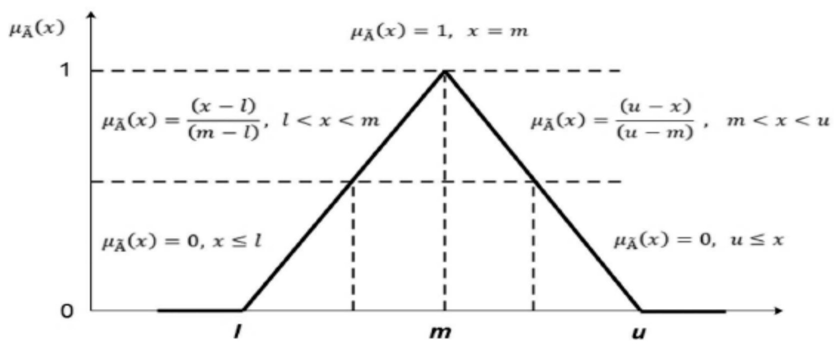


Figure 3. An example of a triangular membership function

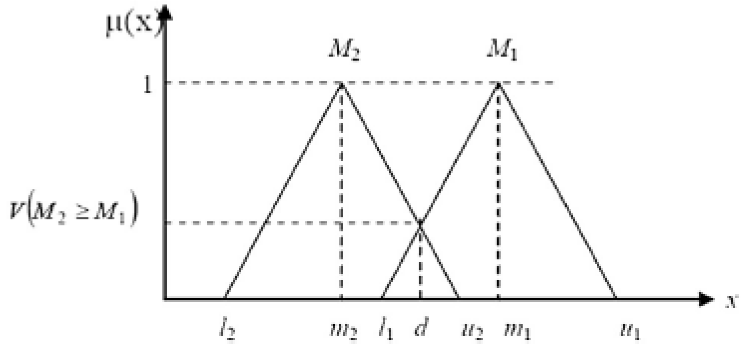


Figure 4. The intersection between M1 and M2 (Chang, 1996)

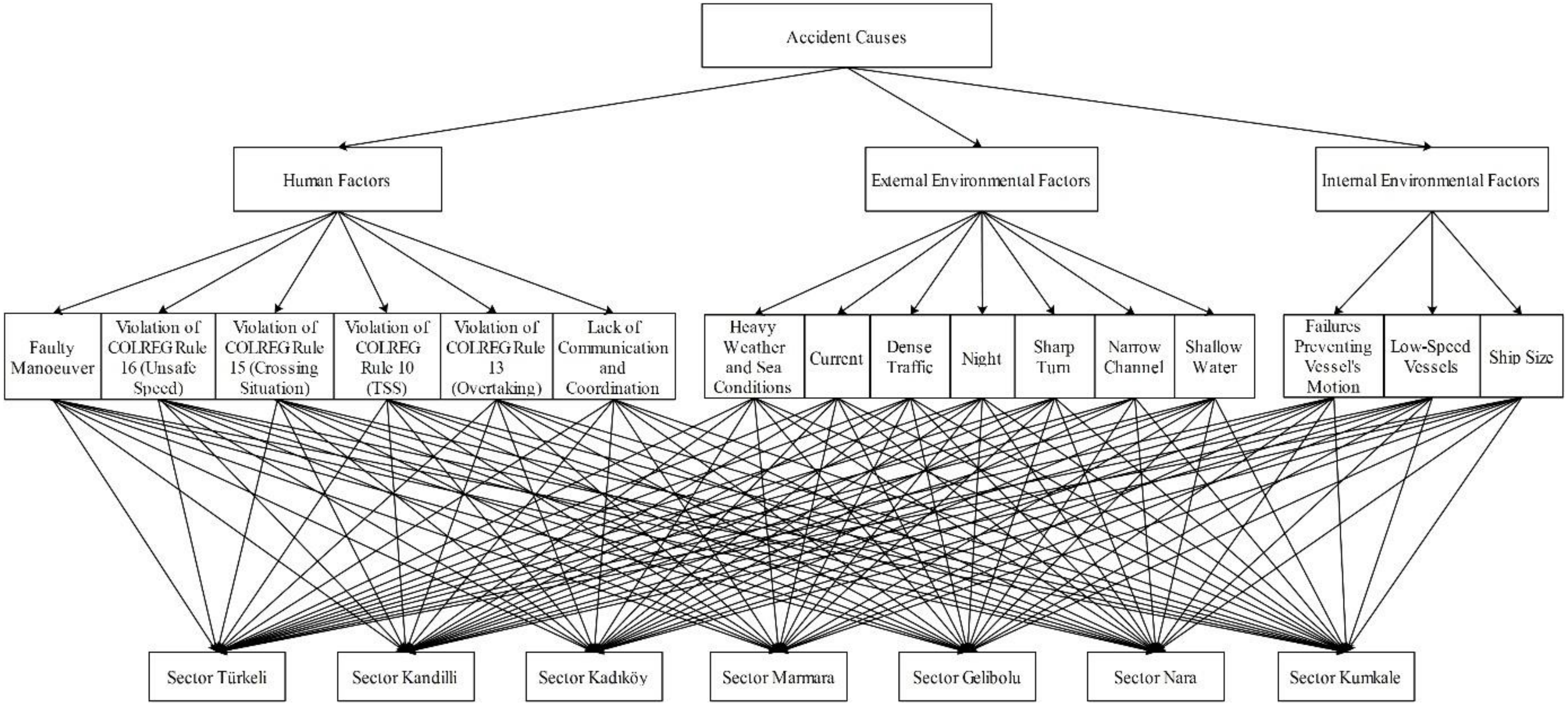
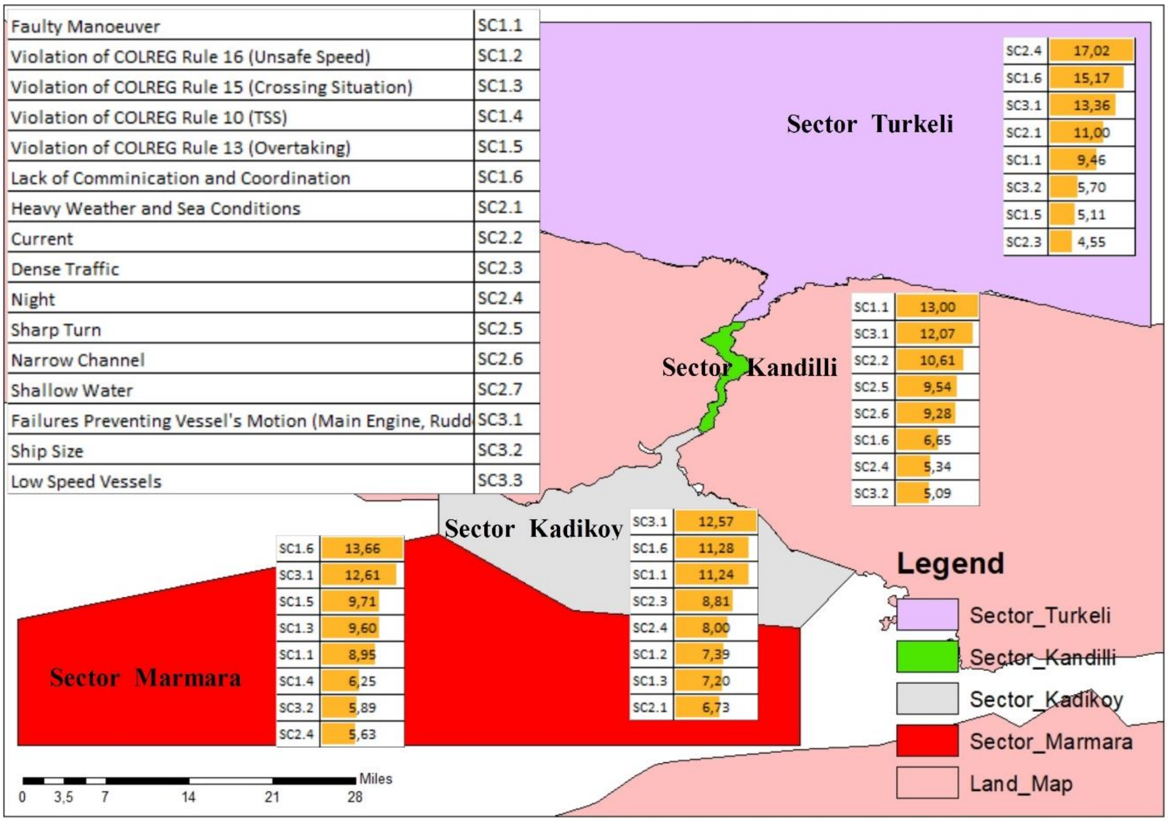
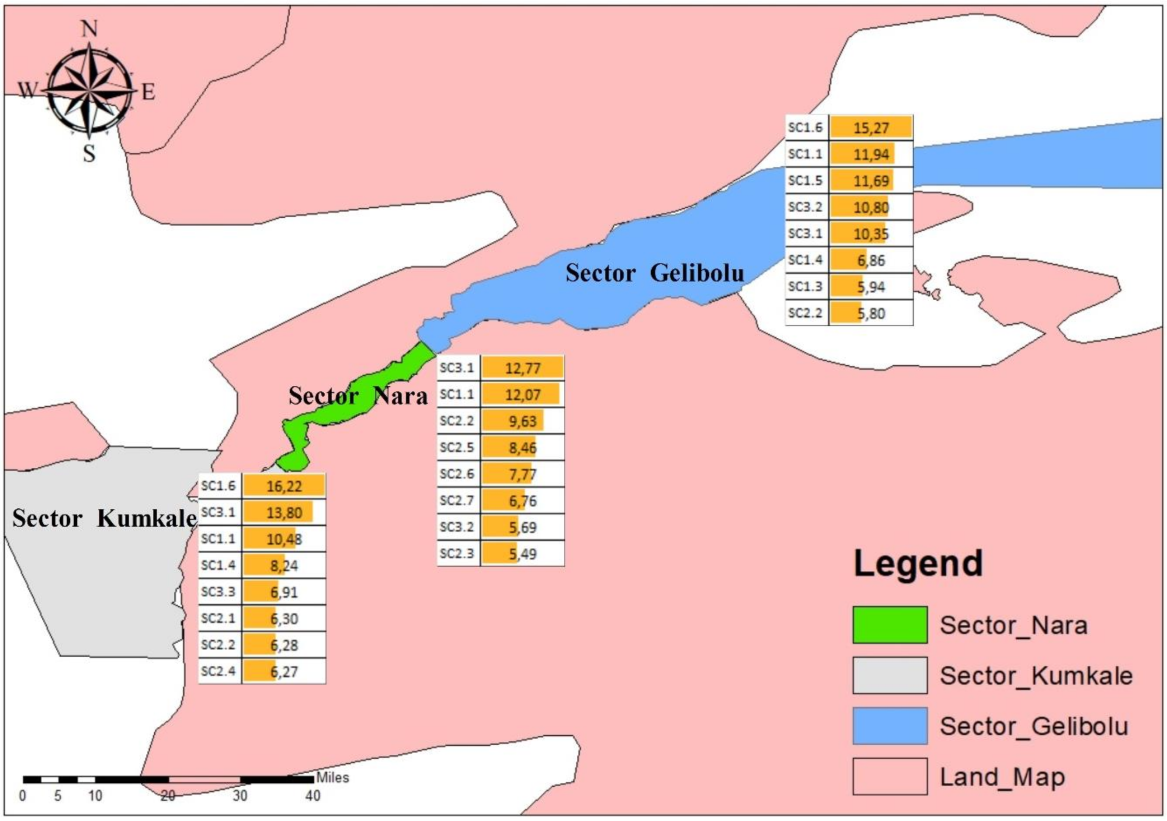


Figure 5. Hierarchical structure of the study



a)



b)

Figure 6. a). Istanbul Strait, b). Canakkale Strait Combined FAHP-PRAT results