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Two-Stage Risk Analysis Application in Maritime Tanker Transportation[1]

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Abstract

In maritime transport, tanker ships have a strategic advantage in company fleets. It is necessary to evaluate the risks that may occur in this area. The aim of this study is to determine the risks that may occur in maritime tanker transport and to propose preventive measures in this direction. In addition, determining the importance levels of risk phenomena is another issue aimed within the scope of the study. In this context, a two-stage evaluation process was applied in the study. In the first phase of the study, Failure Mode Effects Analysis (FMEA) was applied. Risk factors determined in line with the views of experts in the field were put forward and their risk priority number was determined. Afterwards, preventive actions were identified in the study. In the second phase of the study, Fuzzy AHP method was applied. In this direction, risk factors were categorised and made comparable among themselves. Importance levels were determined within the scope of the opinions of sector representatives who are experts in their field. Thus, the objectivity level of the study was improved. According to the results of the study, the importance level of the administration and maintenance risk group was found to be the highest. Under this heading, maintenance deficiencies on board, transport of chemical hazardous materials and failure to manage them properly, failure to supply spare parts and critical equipment are listed. The technical failures group was evaluated as the other most important risk group. Under this heading, there are rudder equipment failure, machinery failure and generator failure risk situations.

Keywords: FMEA, Fuzzy AHP, Tanker Transport, Risk Analysis, Maritime Management, Marine Transport Engineering.

[1] This study is derived from the master thesis titled "Two-stage Risk Analysis Application in Maritime Tanker Transportation".

1. Introduction

Countries need processed, semi-processed and finished products to sustain their economic growth. As a result of globalisation, products of various characteristics are transported between supply and demand points (Arıcan et al., 2024). The International Maritime Organisation (IMO) has indicated that approximately 80% of the products are transported by maritime transport. The maritime industry is an important sector that supports the development of world trade and connects its customers to the global system (Zampeta & Chondrokoukis, 2022). In terms of its concept, maritime transport offers the advantages of economy of scale to its customers. Compared to other modes of transport, the low cost of transporting large quantities of products, especially when compared to other modes of transport, encourages individuals, institutions or organisations that are shippers or buyers to use maritime transport. Road, railway, maritime and air transportation are the four main modes of transport. Among these modes of transport, maritime transportation is a determining factor in the supply chain (Özbağ et al., 2023; Aydın & Atak, 2020; Tarı & İnce, 2019). In Figure 1, the values of World Trade Volume, World Maritime Transportation and Other Transport Modes on a yearly basis are expressed in Million Tonnes. Within the scope of the table, the data for 2023 are defined as approximate. However, the numerical value labels in 2024 and 2025 include estimated expectations. When the values expressed in the table are analysed, it is understood that the ratio of maritime transport in the World Trade Volume varies between 84% and 86% depending on the years. The cargo size of other modes of transport (land, air and railway) within the scope of world trade is between 13% and 15%.

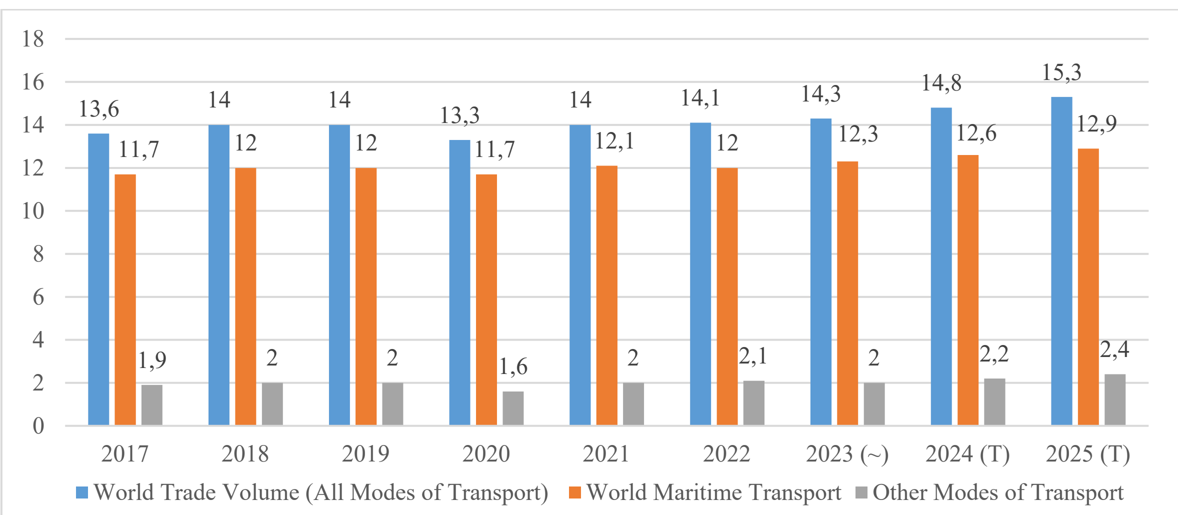

Figure 1. World Freight Transport by Modes of Transport (Million Tonnes)

Risk is the realisation of an unexpected situation that prevents the conclusion of a process or activity as planned in advance. Risk phenomenon is a factor that prepares the ground for the realisation of some hazardous situations, loss of products and services and undesirable situations as a result of events that develop beyond expectations (Özdem, 2024). In this context, there are many operations that need to be carried out gradually in maritime transport. During the implementation of maritime activities, undesirable risks occur due to many reasons such as systemic or human error (Yetkin et al., 2015). The maritime sector involves serious risks due to its business field. These risks are shaped by many factors and vary between different regions and ship types. Errors that may occur on tanker ships can cause a large amount of cargo leakage and environmental pollution as a result of this event. Therefore, risk assessment is one of the important issues in maritime transport, especially for tanker ships carrying dangerous liquid cargoes (Akyüz, 2017; Sur & Kim, 2020; Vanem et al., 2007; Sezer et al., 2023). Maritime transport carries threats that, if realised, will lead to loss of life and property as well as devastating environmental impacts. The high importance and risk coefficient of the maritime sector has been effective in attracting venture capital investments to the sector, especially in recent years (Kamal & Yardımcı, 2019).

International Maritime Dangerous Goods Code (IMDG) for the international transport of dangerous goods by sea was published by the International Maritime Organization (IMO) in 1965. Thus, the processes of transporting dangerous goods by sea have been standardised. In addition, provisions for the prevention of marine pollution are also regulated under the IMDG code (Tatar & Özer, 2018). Within the framework of the IMDG code, a series of regulations have been introduced against risk factors that threaten the environment, life and property safety. As a result of these regulations, all end-to-end handling activities of dangerous goods are carried out within the scope of the code.

Product groups defined as bulk cargo group are generally unprocessed substances used as the main component in production processes. These product groups are transported by tankers and dry bulk carriers. The ships used in tanker transport vary according to their routes (Unal et al., 2022). VLCC type vessels transport liquid cargoes to long distances. Suezmax type tanker ships are suitable for medium distance routes (USA - West Africa). Aframax type vessels are preferred for regional transport. Panamax type tankers are used in and around Panama Canal. Handymax class ships are the preferred type for short-distance routes (Tarı & İnce, 2019). Information on these vessels is given in Table 1. Ship names, capacities and types are shown in the table. In addition, names and capacity information of ship types suitable for dry bulk cargoes are also given.

Table 1. Bulk cargo ships according to their capacities (Tarı & İnce, 2019).

Tanker Ships		Bulk Cargo Ships	
Name	**Capacity**	**Name**	**Capacity**
VLCC	180.000 DWT - 320.000 DWT	Capsize	150.000 DWT - 200.000 DWT
Suezmax	120.000 DWT - 200.000 DWT	Panamax	50.000 DWT - 79.999 DWT
Aframax	80.000 DWT - 199.999 DWT	Handymax	10.000 DWT - 50.000 DWT
Panamax	50.000 DWT - 79.999 DWT	Handy	< 10.000 DWT
Handymax	10.000 DWT - 50.000 DWT		

The aim of this study is to determine the risks that may occur in maritime tanker transport and to put forward preventive measures in this direction. In addition, determining the priority levels of risk factors in line with the opinions of sector representatives is another issue aimed to be achieved within the scope of the study.

The main problem of the study is to determine numerically the risk groups that may occur in maritime tanker transport and the superiorities of these groups among each other. The study is important because it expresses the determination of the risks that may occur in maritime tanker transport and preventive activities. The fact that maritime tanker transport is approached with a two-stage evaluation process is another issue that emphasises the importance of the research.

2. Literature Review

The potential for the emergence of risk factors is strengthened when the characteristics of the cargo shipped within the scope of transport activities, the hazard levels and the specific need for additional safety measures are not clearly defined (Ma et al., 2024). Qualified human resources are the determining factor in the occurrence of maritime accidents. Providing this resource requires strong training systems (Han et al., 2024). The risk phenomenon in maritime tanker transport is a complex field of study that develops within many factors and may have negative effects on life, property and the environment in terms of its consequences (Uğurlu et al., 2021). More than 50% of the oil and oil products produced in the world are transported between two points using tanker ships. From this perspective, risk analysis applications are important in maritime tanker transport (Vidmar & Perkovič, 2018).

In this section, risk analysis studies previously conducted in the maritime sector have been examined in accordance with the theme of the study. In this context, academic studies were evaluated. The main purpose of the literature review is to determine the current situation as a result of the studies conducted in the maritime sector and maritime tanker transport.

Başar (2010) conducted a study to determine the most risky points in the study area by considering different traffic conditions in the Dardanelles. As a result of the simulations and risk analysis, it was determined that the Nara bend is the bottleneck point of the strait due to its topographic structure and the existing system. According to the results of this simulation; it shows that a 25 per cent increase in the current traffic increases the number of waiting vessels 43 times and the waiting time increases 29 times. Zeng et al. (2017) In this paper, a Bayesian Network (BN) based methodology is proposed to deal with the challenge of risk analysis in RoPax transport. A case study involving this RoPax transport process is conducted. The case study is applied in Bohai Bay, China. The results of this study show that the BN model can effectively assess the problem of lack of data and interrelatedness of processes in risk analysis. In addition, it is stated that the development stages of unexpected risks can be modelled and a risk mitigation preventive decision set can be provided.

Zhou and other researchers (2019) applied adaptive neuro-fuzzy inference system (ANFIS) to predict the risk level of near-accident situations during tanker voyages. In this context, the factors directly affecting the accident situation, the factors indirectly affecting the accident situation and the main factors that almost lead to the accident were analysed. As a result of the study, control measures were proposed to improve safety during tanker transport. In this study conducted by Westgaard and co-authors (2007), a number of financial risk factors were identified. They analysed the empirical effects of these factors on tanker shipping stock returns using an OLS regression. World yield, industrial production, US exchange rate, oil prices, US crude oil inventories, US crude oil voyages and tanker fleet size. Among the identified factors, the world return and the US exchange rate are found to be positively correlated with the returns of a value-weighted tanker inventory portfolio. Crude oil stocks and crude oil transports are negatively correlated. Changes in oil price and tanker fleet size are insignificant in explaining tanker stock returns.

Melnyk et al (2022) analysed the characteristics of the risk assessment process and compared the quality of its implementation with accident rates in the world merchant fleet. In terms of its results, this study states that most accidents can be avoided if maritime operations pay due attention to the risk assessment of maritime operations and, in particular, to certain elements of the human factor. Fu at al., (2023) aimed to reduce the maritime accidents occurring in the Arctic sea and to strengthen the transport system in question. In this context, they made a risk assessment of the ships operating in Arctic waters. In this direction, the authors have tried to create an index of remedial measures by observing the accident scenarios and potential risk influencing factors of ice navigation, navigation risks for ice navigation in Arctic waters and the navigation situation of the ship in the sea ice environment. In a study by Szubrycht (2020), the maritime trade in the Baltic Sea in the context of the geographical and hydrometeorological conditions of the Baltic Sea. In this context, the author aims to minimise the possibility of maritime accidents in the Baltic Sea. In addition, a risk analysis of maritime traffic engineering, shipbuilding and oil spill response capabilities of the Baltic states has been carried out. Furthermore, the publication proposes a definition of a crisis situation in the maritime domain and sets out when a maritime accident or incident can create a crisis situation in the maritime domain. Accordingly, it is emphasised that the ship crew should be at an adequate level and continuous training activities should be adopted.

Chai et al. (2017) conducted a study to develop a quantitative risk assessment model for ship collisions. In this study, the consequences of loss of human life and oil pollution that may occur as a result of collision are discussed. According to the results of the study, container ships, bulk cargo ships and oil tanker ships are considered as the ship types subject to collision. In addition, it is emphasised that passenger and Ro-Ro ships have low collision frequency and may cost human life in case of an accident. It was seen that oil tankers involved in a ship accident would cause serious consequences. Accordingly, it was emphasised that oil tanker traffic should be supervised and kept under control. Montewka et al. (2010) analysed the risk factors for collision of oil tankers. In this study, MDTC estimation method was used. Ship manoeuvres are evaluated within the scope of the method. This method refers to the ships that will cause oil pollution of an accident in the Gulf of Finland, namely oil tanker ships. In a study conducted by Chen et al. (2015), they conducted a risk analysis of ship accidents in Shenzhen waters. In this context, accidents that occurred between 2003 and 2012 were included in the study. Bayesian network and fault tree analysis were used in this study. According to the results of the analysis, the risk of accidents in Shenzhen waters is lower than the pre-warning value level and a continuous decrease has been observed throughout the period.

3. Method

3.1. Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects analysis is an analysis method developed for the prevention of potential failures or risks. With this method, severity, probability and detectability estimates are made for each identified risk (Yılmaz, 2000). FMEA was first developed by the United States Army. Subsequently, it was implemented by NASA to predict system and equipment failures (Özfırat, 2014). The FMEA technique allows the assessment of risks from an inductive point of view. The basic rule is to identify possible risks within a system and to determine preventive steps (Özakın, 2021).

In the FMEA method, the Risk Priority Number (RPN) is found by multiplying the severity, probability and detectability components. This situation is formulated in Figure 2. The probability component shows the frequency of occurrence of the hazard. The severity value indicates the extent to which the risk or hazard will have an impact during its realisation. The determinability component is the value of the extent to which the error can be detected before it occurs (Özfırat, 2014).

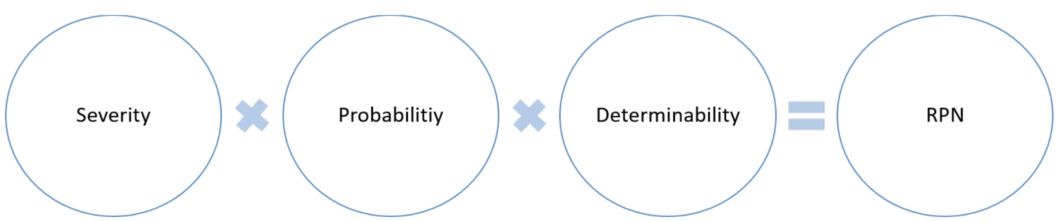

Figure 2. RPN Formula.

Figure 3 illustrates the application process of the FMEA method. Accordingly, in the first stage, after collecting preliminary information about the subject of study, the flow chart of the system is determined. Then the failure mode is defined. What is meant to be expressed by the definition of the failure mode is to examine each component that makes up the process and to clarify the types of errors that may occur at these points. After the failure mode is also determined, the RPN is found. The process at the point of finding the RPN takes place as previously described in Figure 2. After this step, corrective measures are taken and the process is re-evaluated.

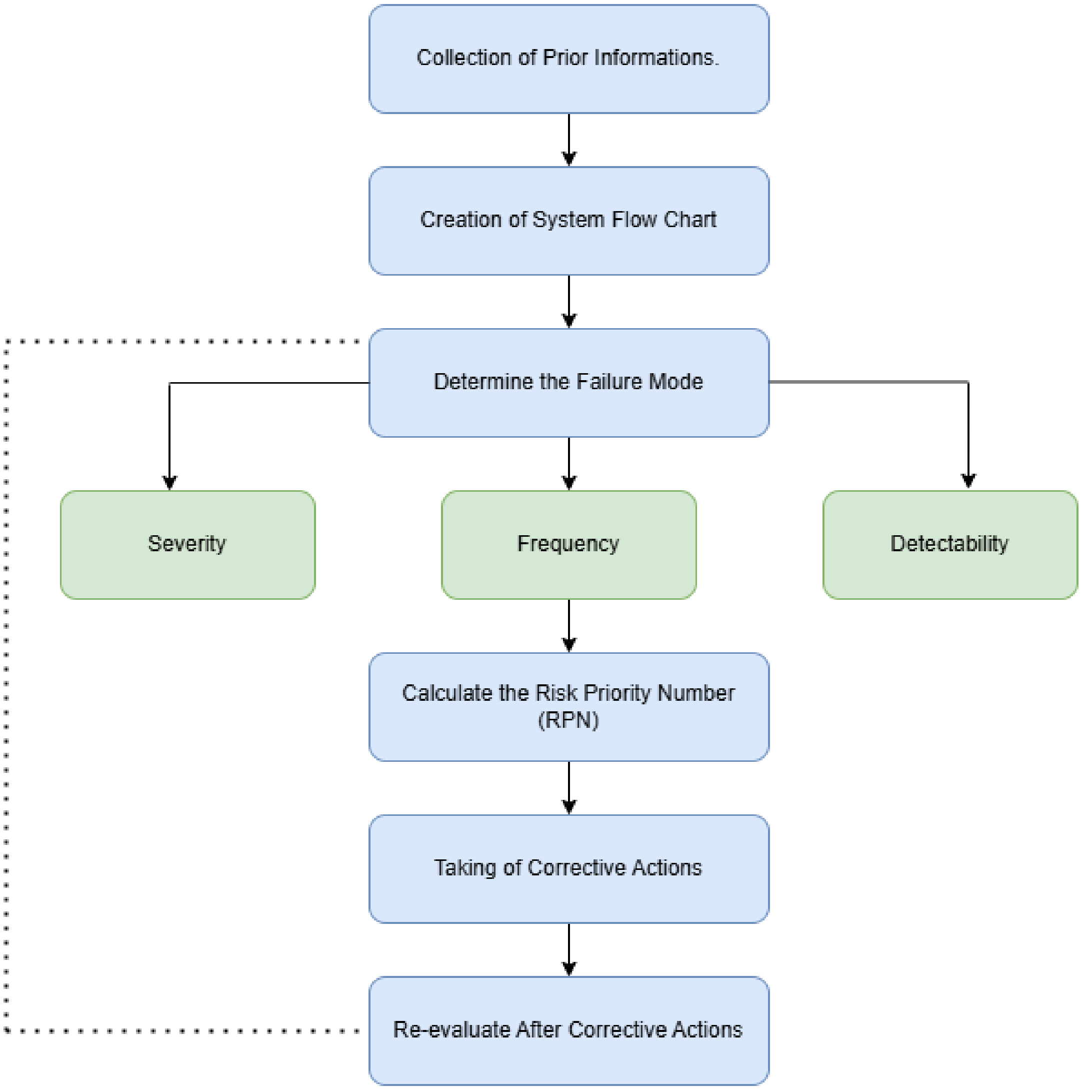

Figure 3. Application process of FMEA method.

In the FMEA technique, a scale is used to measure risk severity. Accordingly, risk effects are scored between 1 and 10. While 1 represents the lowest risk effect, 10 represents the highest risk effect (Yılmaz, 2000). The severity scale is given in Table 2.

Table 2. Severity scale (Yılmaz, 2000).

Levels	Criteria
10	Failure causes massive problems, system failure and non-compliance with the law.
8 – 9	The error causes a high level of satisfaction and affects the functionality of the system.
6 – 7	Failure causes customer satisfaction and system efficiency to decrease. Repairs are essential.
3 – 5	Minor impact on product or process performance. The fault is recognised by the customer and there is some disruption to the use of the product.
1 – 2	Insignificant impact on product or process performance. The error is not recognised by customers.

In the FMEA technique, probability refers to the frequency of the risk. In other words, the realisation of the error or risk indicates the probability of occurrence of errors during the period of use of the product or system (Eren & Pamuk, 2020). The values of the probability rating are given in table 3.

Table 3. Degrees of probability (Eren & Pamuk, 2020).

Probability of Error	Possible Error Rate	Levels
It's almost certainly	More than 1/2 to 1/3	9 – 10
Very high	1/8	7
	1/20	8
Medium	1/80	4
	1/400	5
	1/2000	6
Very Low	1/15000	2
	1/150000	3
Almost Impossible	Less than 1/1500000	1

The detectability factor refers to the extent to which the risk or error can be predicted before it occurs (Özfırat, 2014). The values for this aspect are detailed in Table 4.

Table 4. Detectability factor (Özfırat, 2014).

Level	Detection
10	Impossible
9	Very Difficult
8	Difficult
7	Very Little
6	Little
5	Medium
4	Above Middle
3	High
2	Very High
1	Almost Certain

3.2. Fuzzy Analytic Hierarchy Process (FAHP)

The concept of fuzzy logic was first used by Zadeh (Zadeh, 1965). Fuzzy logic provides a great advantage in obtaining results close to reality with its ability to manage uncertainties. This method is one of the methods used to make sense of uncertainties (Yılmaz & Şahin, 2023). Fuzzy set theory allows judgements or situations to be examined between intervals divided into degrees instead of evaluating them between fixed values. The main reason for this is that decision makers are not clear in their decisions on some issues (Aktaş et al., 2020).

In this study, Chang's rank analysis technique was applied to determine the criteria weights of risk phenomena, the stages of this method are stated below (Chang, 1996: 653):

Stage 1: The value of the fuzzy synthetic order with respect to criterion i is defined as shown in formula (1).

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \times \left[\sum_{m}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} \quad (1)$$

At this stage, fuzzy summation is applied to the m level analysis formula to ensure $\sum_{j=1}^{m} M_{g_i}^{j}$ equality. This is expressed in formula (2).

$$\sum_{j=1}^{m} M_{g_i}^{j} = \left[\sum_{m}^{n} l_j , \sum_{j=1}^{m} m_j , \sum_{j=1}^{m} u_j\right]^{-1} \quad (2)$$

At this stage, the formula for the fuzzy addition of $\left[\sum_{i=1}^{n} l_j , \sum_{j=1}^{m} M_{g_i}^{j} \right]^{-1}, M_{g_i}^{j}$ $(j = 1, 2, 3.., \mathrm{m})$ is shown in (3).

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j} = \left[\sum_{i=1}^{n} l_i , \sum_{i=1}^{n} m_j , \sum_{i=1}^{n} u_i\right] \quad (3)$$

The inverse operation of the vector in this formula is performed in the fourth formula. This step is shown in formula (4).

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left[\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right] \quad (4)$$

Stage 2: The degree of occurrence of the M2≥M1 situation is expressed in formula (5).

$$(M2 \geq M1) = \sup_{y \geq x} \left[\min\left(\mu_{M_1}(x), \mu_{M_2}(y)\right)\right] \quad (5)$$

10

However, it can also be defined by formula (6).

$$V\ (M2 \geq M1) = hgt\ (M_1 \cap M_2) = \mu_{M_2} \ \ (\mathrm{d}) \quad (6)$$

$$= \begin{cases} 1 & m_2 \geq m_1, \\ 0 & l_1 \geq u_2, \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise, \end{cases}$$

The intersection area of D at the upper level is the point where it coincides on the y-axis.

Stage 3: the probability level of a concave fuzzy number being greater than k concave fuzzy numbers Mi (i=1, 2, ..., k) is presented in formula (7) below.

$$V(M \geq M_1, M_2, \ldots, M_k) = V\ [(M \geq M_1)\ ve\ (M \geq M_2\ ve \ldots ve\ (M \geq M_k)], \quad (7)$$

$$= \min V\ (M \geq M_i), i = 1,2,3, \ldots, k$$

in the form of,

$$d'(A_i) = \min V\ (S_i \geq S_k), k = 1,2, \ldots, n; k \neq i \quad (8)$$

After this step, the weight vector is calculated. In Formula (9)

$$W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T \quad (9)$$

A_i (i=1,2,...,n) in the formula shows as many values as n.

Stage 4: The normalised weight vector formula is shown in (10) below.

$$W = (d\ (A_1),\ d\ (A_2), \ldots\ ,\ d\ (A_n))^T \quad (10)$$

W represents a non-fuzzy number.

In this study, triangular expressions were expressed with Saaty's five-stage scale. This is clearly seen in Table 5.

Table 5. Fuzzy triangle scale (Arıcan et al., 2023).

Verbal Expressions	**Saaty Scale**	**Fuzzy Triangular Scale**
Equally important	1	(1, 1, 1)
Weakly significant	3	(2, 3, 4)
Quite important	5	(4, 5, 6)
Absolutely essential	7	(6, 7, 8)
Absolutely critical	9	(9, 9, 9)

Risk factors have been determined under 6 main criteria and sub-criteria belonging to these main criteria. The main criteria are divided into 6 main criteria as Technical Failures, Administration and Maintenance, Operational Factors, Personnel Training, Working Conditions, Environmental Hazards and Training. The hierarchical model indicating this situation is given in Figure 4.

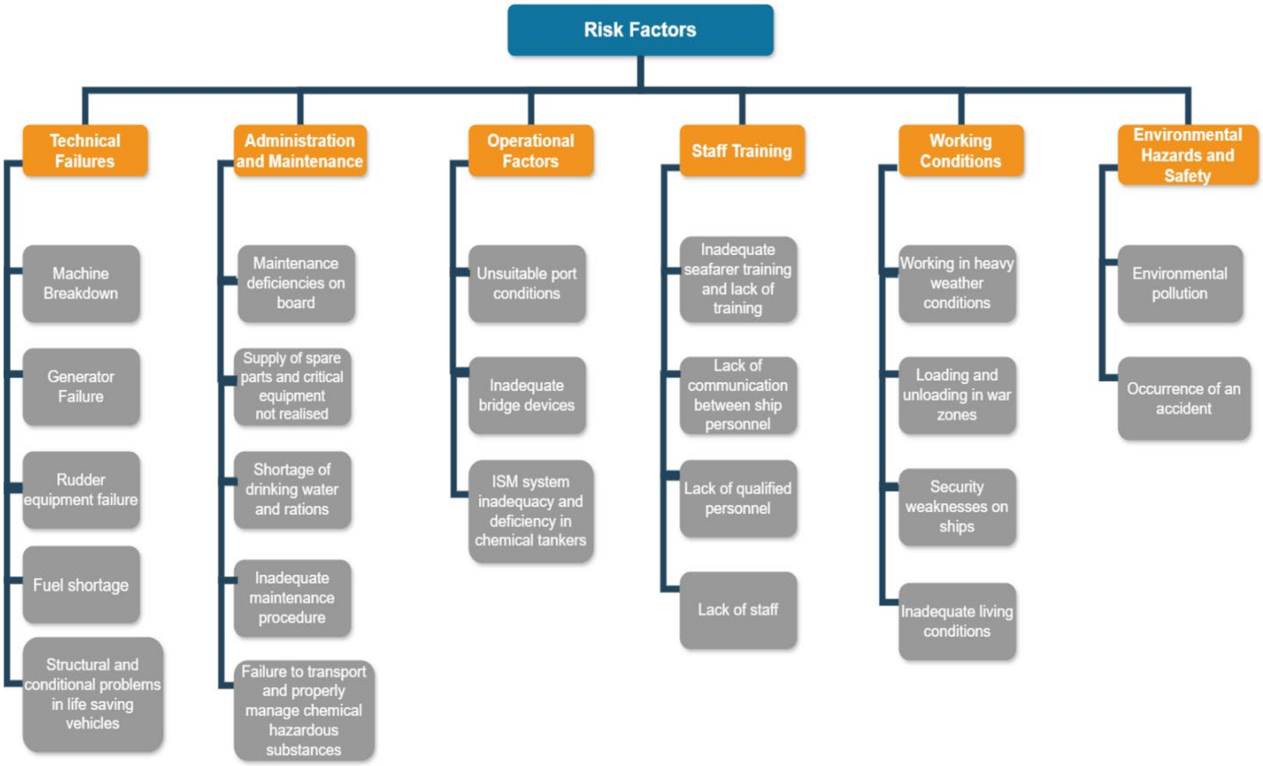

Figure 4. Hierarchy model of risk factors.

Tanker taşımacılığında uzmanlaşmış kişilerin değerlendirmelerinden yola çıkılarak elde edilen The risk factors obtained from the assessments of people specialised in tanker transport are grouped under 6 main headings. According to this, the risks are: Technical failures, administration and maintenance, operational factors, personnel training, working conditions, environmental hazards and accidents. These groupings will be compared with the FAHP method and the importance levels of the risk groups will be determined. Table 6 shows this grouping.

Table 6. Coding of criteria titles.

Main Criteria	Technical Failures (C1)	Administration and Maintenance (C2)	Operational Factors (C3)	Staff Training (C4)	Working Conditions (C5)	Environmental Hazards and Safety (C6)
Sub Criteria	Machine Breakdown (C_{11})	Maintenance deficiencies on board (C_{21})	Unsuitable port conditions (C_{31})	Inadequate seafarer training and lack of training (C_{41})	Working in heavy weather conditions (C_{51})	Environmental pollution (C_{61})
	Generator Failure (C_{12})	Supply of spare parts and critical equipment not realised (C_{22})	Inadequate bridge devices (C_{32})	Lack of communication between ship personnel (C_{42})	Loading and unloading in war zones (C_{52})	Occurrence of an accident (C_{62})

	Rudder equipment failure (C_{13})	Shortage of Drinking Water and Rations (C_{23})	ISM system inadequacy and deficiency in chemical tankers (C_{33})	Lack of qualified personnel (C_{43})	Security weaknesses on ships (C_{53})
	Fuel shortage (C_{14})	Inadequate maintenance procedure (C_{24})		Lack of staff (C_{44})	Inadequate living conditions (C_{54})
	Structural and conditional problems in life saving vehicles (C_{15})	Failure to transport and properly manage chemical hazardous substances (C_{25})			

Table 6 shows the main and sub criteria to be used in the FAHP process with the grouping made. Accordingly; Technical Failures, Administration and Maintenance, Operational Factors, Personnel Training, Working Conditions, Environmental Hazards and Safety criteria constitute the main criteria. Under the main criterion of technical malfunctions, there are sub-criteria of machinery malfunction, generator malfunction, steering equipment malfunction, fuel shortage, structural and conditional problems in life saving vehicles. Under the main criterion of administration and maintenance, the following sub-criteria are listed: lack of maintenance on board, lack of supply of spare parts and critical equipment, shortage of drinking water and provisions, inadequate maintenance procedure, transport of chemical hazardous materials and inappropriate management. When the main criterion of operational factors is evaluated; it is divided into three sub-criteria as unsuitable port conditions, inadequate bridge devices and inadequacy of ISM system in chemical tankers. Under the main criterion of personnel training; it is divided into four sub-criteria as inadequate seafarer training and lack of training, lack of communication between ship personnel and not employing qualified personnel. The main criterion of working conditions is divided into four sub-groups: working under heavy weather conditions, loading and unloading in war zones, security weaknesses in ships, inadequate living conditions and lack of personnel. The last main criterion is divided into two sub-criteria as the occurrence of environmental pollution and the occurrence of accidents.

The main purpose of the questionnaire prepared within the scope of the study is to provide access to a qualified data directory for the identification, measurement and rating of risk factors in maritime tanker transport. In this direction, the questionnaire consists of three parts. In the first part, the participants were asked to indicate the risk factors that may be experienced within the scope of tanker transport. In the second part, it was asked to determine the severity, probability and determineability scores of the risk factors according to the specified FMEA analysis criteria. In the third part of the questionnaire, risk factors were categorised and FAHP analysis was applied. The survey was conducted with the participation of 8 participants in total. The participants consisted of people specialised in maritime tanker transport. The data obtained within the scope of the survey were compiled and made meaningful by FMEA and FAHP methods. Preventive recommendations were also presented to the risk factors identified within the scope of FMEA analysis. Table 7 shows the profile information of the survey participants. According to this In the table, experts are classified according to their duties and experience. The opinions of 3 Ship Captains, 3 Chief Engineers and 2 Deck Inspectors working in tanker transport were utilised.

Table 7. Expert Information.

Expert	Duty	Experience
Expert 1	Ship Captain	17
Expert 2	Ship Captain	20
Expert 3	Ship Captain	19
Expert 4	Chief Engineers	16
Expert 5	Chief Engineers	18
Expert 6	Chief Engineers	16
Expert 7	Deck Inspectors	15
Expert 8	Deck Inspectors	15

4. Findings

Within the scope of this study, 30 risk factors were identified by interviewing sector representatives. Some of the identified risk factors were excluded from the scope of the study because they were similar to each other and expressed the same situations. Similar factors were eliminated and 23 risk factors were taken as the focus of the study. In the second stage, an online survey was conducted and the identified risk factors were evaluated. As a result of the survey, the opinions of the sector representatives required for FMEA and FAHP methods were obtained. In this direction, FMEA method was applied first.

4.1. Analysis of Risk Phenomena within the Context of Failure Mode and Effects Analysis (FMEA)

23 risk factors were evaluated by FMEA analysis. The effects of these risk factors are discussed within the scope of the FMEA table. Then, in order to prevent these hazard situations, preventive actions were proposed. The new RPN values of the preventive actions obtained under the existing risk conditions were evaluated within the scope of this table and expressed numerically. In general, risk factors such as: rudder equipment, inadequate maintenance procedure, maintenance deficiencies on board, transport of chemical hazardous materials and not managing them properly, not replenishing spare parts and critical equipment, working in heavy weather conditions, machinery failure have come to the fore in the FMEA analysis application. This situation is given in Table 8. In addition, within the scope of preventive recommendations, it can be observed that the new rpn values have decreased compared to the previous values.

Table 8. FMEA Table.

No	The Danger	Effects of the Hazard	RPN Value				Recommended Activities	New RPN Values			
			S	P	D	RPN		S	P	D	RPN
1	Machine failure	Failure to control the vessel	9	8	3	216	Planned maintenance activities to be conducted	5	4	3	60
2	Generator failure	Failure to supply the ship's electrical needs	8	7	3	168	Planned maintenance activities to be conducted	3	3	3	27
3	Environmental pollution	Threat to the life of living life	8	4	7	224	Managing the waste on board within environmentally friendly processes	3	2	5	30
4	Lack of personnel	Reduced ship efficiency	7	8	3	168	Employing staff	2	3	3	18
5	Rudder equipment fault	Safety of navigation risk	9	7	8	504	Organising planned maintenance activities	5	5	6	150
6	Fuel shortage	The vessel cannot fulfil its functions	4	2	1	8	Realising the fuel purchase in appropriate for the route	2	2	1	4
7	Occurrence of an accident situation	Ship and regional security is negatively affected	8	5	6	240	Conducting frequent inspections for the efficient functioning of tools and equipment	5	5	6	150
8	Non-supply of spare parts and critical equipment	Ship functions become nonfunctional	1 0	8	4	320	Stocking of frequently used parts on board	3	4	3	36
9	Shortage of drinking water and rations	Personnel psychology is negatively affected	3	5	2	30	Determination of ration supply points suitable for the route	3	2	2	12
10	Maintenance lacks on board	Risk coefficient of operational processes increases	8	9	6	432	Planned maintenance activities to be carried out	4	3	4	48
11	Not employing qualified personnel	Decrease in operational efficiency	9	7	3	189	Getting support from experts for the selection of qualified personnel	3	4	3	36

12	Failure to transport and properly manage chemical hazardous substances	Environmental problems and threats to human life	10	8	4	320	Adoption of standards set by international organisations (IMDG Code)	5	4	4	80
13	Lack of and inadequacy of ISM system on chemical tankers	Failure to ensure ship safety and threat to environmental safety	7	3	6	126	Taking action to eliminate deficiencies	4	3	3	36
14	Lack of communication between personnel	Realisation of operational failures	4	3	4	48	Periodic inspection of communication equipment	3	2	2	12
15	Bridge devices inadequate	Ship safety cannot be achieved	8	3	3	72	Complete supply of bridge devices	4	3	3	36
16	Inadequate living conditions	Personnel psychology is negatively affected	4	5	6	120	To take measures to prevent living conditions from falling below standards	4	3	4	48
17	Security weaknesses on ships	Ship safety cannot be ensured	9	6	4	216	Carrying out planned maintenance and inspection activities	5	3	3	45
18	Inadequate seafarer training and lack of training	Operational efficiency decreases	8	4	6	192	Regular measurement of staff recruitment and training	5	4	3	60
19	Structural and conditional problems in life saving vehicles	Increases the risk of death	8	5	2	80	Carrying out planned maintenance activities	4	3	2	24
20	Unsuitable harbour conditions	Operational delays and cost increases	7	6	2	84	Obtaining detailed information about the ports within the route	5	5	2	50
21	Working in heavy weather conditions	Risk to the safety of personnel and ship	6	8	5	240	Carrying out route planning studies according to weather forecasts	4	5	5	100

22	Loading and unloading operations in war zones	Risk to personnel and ship safety	5	2	7	70	Prioritising personnel and ship safety and conducting route operations in this context	4	2	5	40
23	Inadequate maintenance procedure	Reduced operational efficiency	7	7	6	294	Procedures are developed by experts in accordance with the needs	5	4	4	80

The trends of the RPN scores obtained with the FMEA table in Table 8 are expressed in Figure 5. Accordingly, in figure 5, the RPN values are given in columns and the new RPN values obtained as a result of preventive actions are given as a line graph on a single graph. It can be seen from the graph that there are significant improvements in the risk priority numbers in case appropriate preventive measures are taken against the related errors.

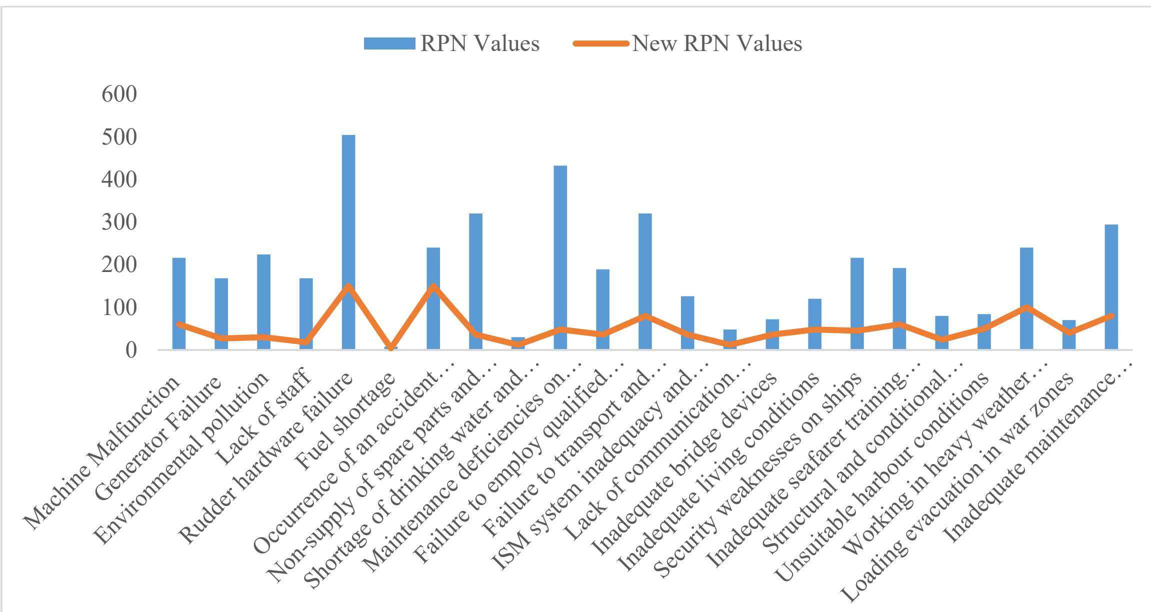

Figure 5. Comparison of RPN values.

4.2. Analysis of Risk Phenomena within the Scope of Fuzzy Analytical Hierarchy Process (FAHP)

In order to determine the priority levels of the risk factors, the main criteria were compared with each other in the first stage. Within the scope of the analysis, the criteria weights were determined and the superiorities of the criteria were determined. The analyses were made by analysing within the scope of Microsoft Excel module. The comparison matrix of the main criteria is given in Table 9.

Table 9. Comparison matrix of main criteria.

Criteria	C1			C2			C3			C4			C5			C6		
	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u
C1	1,00	1,00	1,00	1,00	3,00	5,00	1,00	3,00	5,00	3,00	5,00	7,00	3,00	5,00	7,00	3,00	5,00	7,00
C2	0,20	0,33	1,00	1,00	1,00	1,00	5,00	7,00	9,00	5,00	7,00	9,00	1,00	3,00	5,00	1,00	3,00	5,00
C3	0,04	0,07	0,10	0,11	0,14	0,20	1,00	1,00	1,00	3,00	5,00	7,00	5,00	7,00	9,00	1,00	3,00	5,00
C4	0,14	0,20	0,33	0,11	0,14	0,20	0,14	0,20	0,33	1,00	1,00	1,00	3,00	5,00	7,00	5,00	7,00	9,00
C5	0,14	0,20	0,33	0,20	0,33	1,00	0,11	0,14	0,20	0,14	0,20	0,33	1,00	1,00	1,00	3,00	5,00	7,00
C6	0,14	0,20	0,33	0,20	0,33	1,00	0,20	0,33	1,00	0,11	0,14	0,20	0,14	0,20	0,33	1,00	1,00	1,00

As a result of the pairwise comparisons of the main criteria, the importance weight of each criterion is expressed. The result values of this iteration are presented in Table 10.

Table 10. Normalised values of the main criteria.

Criteria	Criteria Weights
C1	0,235848
C2	0,245606
C3	0,228209
C4	0,179932
C5	0,110404
C6	0,034049

18

Accordingly, C2 (Administration and Maintenance) criterion has been determined as the criterion with the highest priority. Following C2 criterion, the criterion with the highest priority was found to be C1 (Technical Failures). C1 was followed by C3 (Operational Factors), C4 (Personnel Training), C5 (Working Conditions) and C6 (Environmental Hazards and Safety).

The matrix obtained as a result of pairwise comparisons of the criteria belonging to the technical failures (C1) subgroup within the scope of FAHP analysis is shown in Table 11.

Table 11. Comparison matrix for sub-criterion C.

Criteria	C_{11}			C_{12}			C_{13}			C_{14}			C_{15}		
	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u
C_{11}	1,00	1,00	1,00	5,00	7,00	9,00	0,14	0,20	0,33	1,00	3,00	5,00	1,00	3,00	5,00
C_{12}	0,20	0,33	1,00	1,00	1,00	1,00	0,14	0,20	0,33	3,00	5,00	7,00	0,20	0,33	1,00
C_{13}	5,00	7,00	9,00	3,00	5,00	7,00	1,00	1,00	1,00	3,00	5,00	7,00	1,00	3,00	5,00
C_{14}	0,20	0,33	1,00	0,14	0,20	0,33	0,14	0,20	0,33	1,00	1,00	1,00	5,00	7,00	9,00
C_{15}	0,20	0,33	1,00	1,00	3,00	5,00	0,20	0,33	1,00	0,11	0,14	0,20	1,00	1,00	1,00

The non-fuzzy numbers expressing the criteria weights as a result of a series of iterations following this comparison are shown in table 12 below.

Table 12. Weight values of C1 sub-criteria.

Criteria	Criteria Weights
C_{11}	0,334906
C_{12}	0,115893
C_{13}	0,334906
C_{14}	0,147174
C_{15}	0,067121

When the sub-criteria of the technical failures criterion were analysed in pairs, it was determined that machine failure (C_{11}) and rudder equipment failure (C_{13}) were the two criteria with the same degree of importance. These are followed by fuel shortage (C_{14}), generator failure (C_{12}) and structural and conditional problems in lifesaving vehicles (C_{15}).

The sub-criteria related to criterion C2 have been evaluated within the scope of FAHP logic in line with the opinions received from the sector representatives. The matrix for the pairwise comparison of the criteria, which is a part of this evaluation process, is shown in Table 13.

Table 13. Comparison matrix for sub-criterion C2.

Criteria	C_{21}			C_{22}			C_{23}			C_{24}			C_{25}		
	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u
C_{21}	1,00	1,00	1,00	0,11	0,14	0,20	0,11	0,14	0,20	0,14	0,20	0,33	0,15	0,17	0,60
C_{22}	5,00	7,00	9,00	1,00	1,00	1,00	0,11	0,14	0,20	3,00	5,00	7,00	0,20	0,33	1,00
C_{23}	0,04	0,07	0,10	5,00	7,00	9,00	1,00	1,00	1,00	1,00	3,00	5,00	0,20	0,33	1,00
C_{24}	3,03	5,00	7,14	0,14	0,20	0,33	0,20	0,33	1,00	1,00	1,00	1,00	0,14	0,20	0,33
C_{25}	1,67	5,88	6,67	1,00	3,00	5,00	1,00	3,00	5,00	3,00	5,00	7,00	1,00	1,00	1,00

The non-fuzzy weight values obtained as a result of pairwise comparisons of the sub-criteria are given in Table 14.

Table 14. Weight values of C2 sub-criteria.

Criteria	Criteria Weights
C_{21}	0,222077
C_{22}	0,222077
C_{23}	0,201711
C_{24}	0,132057
C_{25}	0,222077

As stated in Table 14, the criteria of lack of maintenance on board (C_{21}), lack of replenishment of spare parts and critical equipment (C_{22}), and lack of proper management of the process of transporting chemical hazardous materials (C_{25}) were identified as criteria with the same level of importance. Two other criteria, shortage of drinking water and rations (C_{23}) and inadequate maintenance procedures (C_{24}) were prioritised.

The pairwise comparison matrix of the three sub-criteria under the main criterion of operational factors (C3) is presented in Table 15.

Table 15. Comparison matrix.

Criteria	C_{31}			C_{32}			C_{33}		
	l	m	u	l	m	u	l	m	u
C_{31}	1,00	1,00	1,00	3,00	5,00	7,00	1,00	3,00	5,00
C_{32}	0,14	0,20	0,33	1,00	1,00	1,00	0,20	0,33	1,00
C_{33}	0,90	0,95	0,99	1,00	3,00	5,00	1,00	1,00	1,00

The non-fuzzy criterion weights obtained by normalising the sub-criteria within the scope of the logical process as expressed in the fourth step are expressed in Table 16.

Table 16. Normalised criteria weights.

Criteria	Criteria Weights
C_{31}	0,480047
C_{32}	0,039907
C_{33}	0,480047

The importance levels of the normalised criteria are; unsuitable port conditions (C_{31}), inadequate ISM system on tankers (C_{33}) and finally inadequate bridge devices (C_{32}).

The pairwise comparison matrix of four sub-criteria related to the main criterion of Personnel Training (C4) is given in Table 17.

Table 17. Pairwise comparison matrix of C4 sub-criteria.

Criteria	C_{41}			C_{42}			C_{43}			C_{44}		
	l	m	u	l	m	u	l	m	u	l	m	u
C_{41}	1,00	1,00	1,00	3,00	5,00	7,00	0,20	0,33	1,00	0,20	0,33	1,00
C_{42}	0,14	0,20	0,33	1,00	1,00	1,00	0,14	0,20	0,33	0,33	0,20	1,00
C_{43}	0,90	0,95	0,99	3,00	5,00	7,00	1,00	1,00	1,00	1,00	3,00	5,00
C_{44}	1,00	3,00	5,00	1,00	5,00	3,00	0,20	0,33	1,00	1,00	1,00	1,00

Sub-criteria were normalised and converted to non-fuzzy values. Criteria weights are expressed in Table 18 below.

Table 18. Normalised criteria weights.

Criteria	Criteria Weights
C_{41}	0,287091
C_{42}	0,017214
C_{43}	0,355456
C_{44}	0,340239

When the criteria are ranked in terms of their weights, the criterion with the highest importance value is the criterion of not employing qualified personnel (C_{43}). this criterion is followed by the criteria of lack of personnel (C_{44}), lack of inadequate seafarer training and instruction (C_{41}), lack of communication (C_{42}).

Four sub-criteria related to the main criterion C5 were evaluated within the scope of expert opinions. In the context of the FAHP method used in this process, the comparison matrix of the sub-criteria with each other is expressed in Table 19.

Table 19. Comparison table.

Criteria	C_{51}			C_{52}			C_{53}			C_{54}		
	l	m	u	l	m	u	l	m	u	l	m	u
C_{51}	1,00	1,00	1,00	1,00	3,00	5,00	3,00	5,00	7,00	3,00	5,00	7,00
C_{52}	0,20	0,33	1,00	1,00	1,00	1,00	0,20	0,33	1,00	5,00	7,00	9,00
C_{53}	0,90	0,95	0,99	1,00	3,00	5,00	1,00	1,00	1,00	0,11	0,14	0,20
C_{54}	0,14	0,20	0,33	0,11	0,14	0,20	5,00	7,00	9,00	1,00	1,00	1,00

The normalised and non-fuzzy weights of the criteria in Table 19 are expressed in Table 20.

Table 20. Normalised criteria weights.

Criteria	Criteria Weights
C_{51}	0,368687
C_{52}	0,258414
C_{53}	0,135243
C_{54}	0,237657

As a result of the normalised iteration, working under severe weather conditions (C_{51}) was found to be the sub-criteria with the highest degree of importance. This criterion was followed by loading and unloading activities in war zone (C_{52}), inadequate living conditions (C_{54}) and security vulnerabilities on board (C_{53}). The main criterion C6 has two sub-criteria. These are: the occurrence of environmental pollution and the occurrence of accidents. The respondents identified one of these two criteria, the occurrence of accidents (C_{62}), with a verbal importance rating of completely important.

4.3. Comparison of FMEA and FAHP Results

The total RPN values obtained within the scope of the risk analysis performed by FMEA analysis, which is one of the risk analysis methods, and FAHP method, which is one of the multi-criteria decision making methods, and the results of the FAHP criteria weights are shown in Table 21.

Table 21. Criteria weights and RPN values.

Criteria	Criteria Weights	RPN Values	Normalised RPN Values
C1	0,235848	976	0,235
C2	0,245606	1402	0,337
C3	0,228209	282	0,067
C4	0,179932	606	0,145
C5	0,110404	646	0,155
C6	0,034049	240	0,057

The main criterion of Administration and Maintenance (C2) was prioritised to be in the first place in both methods used. Technical Failures main criterion (C1) was prioritised as the second most important criterion in both methods. In the FMEA method, the main criterion of Working Conditions (C5) is ranked third, while in the FAHP technique, the main criterion of Operational Factors is ranked third. Personnel Training main criterion (C4) was evaluated as fourth in the solution algorithm of both methods. In the FMEA technique, the Operational Factors main criterion (C3) is ranked fifth, while in the FAHP method, the working conditions main criterion (C5) is ranked fifth. Environmental Hazards and Safety main criterion (C6) is ranked sixth in both methods. 22

5. Discussion and Conclusion

Due to the structure of the product group carried in maritime tanker transport, it contains many risks. With the FMEA analysis carried out within the scope of this study, the risks that may occur in maritime tanker transport have been determined. Accordingly, the risks are: machine failure, generator failure, environmental pollution, lack of personnel, rudder equipment failure, fuel shortage, accident situation, failure to supply spare parts and critical equipment, shortage of drinking water and provisions, maintenance deficiencies on board, lack of qualified personnel, transport of chemical hazardous materials and not managing them properly, inadequacy and deficiency of ISM system in chemical tankers, lack of communication between ship personnel, inadequate bridge devices, inadequate living conditions, security weaknesses in ships, inadequate seaman training and lack of training, structural and conditional problems in life saving vehicles, unsuitable port conditions, working in heavy weather conditions, loading and unloading operations in war zones. Within the scope of the FMEA analysis, each risk element was compiled into six categories. This compilation process facilitated the comparison of RPN scores and FAHP criteria weights. In this context, the administration and maintenance group has the highest level of importance in both methods. Technical failures group was determined as the risk group with secondary importance in both methods. As a result of this situation, the risk phenomena in these two groups were evaluated by the participants as the most important root causes. Environmental hazards and safety cluster was ranked sixth in terms of importance level in both methods. It is understood that the risk elements within the environmental hazards and safety group are evaluated by the participants as the phenomena that will be observed in case the other group risks are realised. At the point of prevention of risks, planned maintenance and inspection activities, employment of qualified personnel and increasing the knowledge and experience of personnel can prevent the risks that may occur to a great extent.

Elidolu et. al, (2022), in their studies aimed to evaluate the risks associated with the gas freeing process in oil and chemical tanker ships, as this operation poses significant safety hazards for crew and the environment. The authors employed numerical risk analysis techniques, specifically a fault tree analysis (FTA) approach, to identify and quantify potential hazards. Their findings revealed that improper operational practices and equipment failures are the primary contributors to accidents during the gas freeing process. The study highlights the importance of training, standardization, and robust safety protocols to mitigate these risks. Sezer et al., (2023), their research was conducted to address the safety concerns arising from cracks in cargo tanks on oil and chemical tankers, which can lead to environmental disasters and operational disruptions. The authors utilized a hybrid methodology combining the Bow-Tie model, Dempster-Shafer (DS) evidence theory, and the Human Error Assessment and Reduction Technique (HEART) to analyze risks comprehensively. The study revealed that human errors, combined with aging infrastructure and improper maintenance, significantly increase the likelihood of cargo tank cracks. Recommendations for regular maintenance, human error mitigation strategies, and advanced monitoring technologies were proposed. Besides, Gao (2022), his study focused on analyzing the risks involved in tanker cargo handling operations, a critical yet high-risk aspect of maritime logistics. The author introduced an integrated risk analysis method that combined the Cloud Model and Decision-Making Trial and Evaluation Laboratory (DEMATEL) techniques. The findings emphasized that human error, coupled with mechanical failures and insufficient risk awareness, are the dominant risk factors in cargo handling operations. The study provides a roadmap for implementing enhanced risk management strategies, including advanced training programs and more effective risk communication protocols. In addition, Liu et al. carried out an FMEA method study based on expert trust network within the scope of risk management. From this point of view, the acquisition and evaluation of data in both studies are based on expert trust network. Therefore, in these two studies, the opinions of experts in the field were considered as the starting point.

When the study is evaluated in terms of its contributions, the risk phenomena that may occur in maritime tanker transport have been expressed to the maritime literature and sector. In this context, maritime companies will be able to easily see the risk factors that may occur in the tanker ships in their fleets. In the stage of determining the importance weights of the risks, which represents the second stage of the study, the priority factors that companies should take precautions are stated.

The application of the FMEA method with classical methods and the execution of the AHP technique within the framework of fuzzy logic facilitated the optimum results of the study. In addition, the FMEA method can identify possible errors that may occur in the future. The methods used and the progressive application of these methods express the strength of the study.

The study was limited to tanker transport and tanker type bulk carriers. In future studies, a two-stage evaluation can also be carried out in dry bulk cargo transport. In addition, it would be useful to evaluate the effects of recently increasing geographical risks on maritime insurance in this context.

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