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Evaluation of Environmental, Economic and Safety Impacts of Main Engine Failures of Terminal Tugboats by Fuzzy AHP and Fuzzy TOPSIS Methods

Terminal Römorkörlerinin Ana Makine Hatalarının Çevresel, Ekonomik ve Güvenlik Etkilerinin Bulanık AHP ve Bulanık TOPSIS yöntemi ile Değerlendirilmesi

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ABSTRACT

Marine terminals have an important place in the global crude oil supply. Tugboats are one of the major components for marine terminals. Safe and trouble-free operation of tugboats is of critical importance. In this study, a risk analysis was performed by considering the safety, environmental and economic effects of main engine failures for a tugboat operating in a crude oil terminal. In this context, firstly, the importance levels of safety, environmental and economic criteria were determined with the fuzzy AHP method. Then, the risk ranking was carried out for 26 failure modes with the fuzzy TOPSIS method by considering the safety, environmental and economic effects together. The results showed that the most important risk parameter for the marine terminal was safety, followed by economic and environmental parameters. Then, the risk ranking of failure modes was performed with the fuzzy TOPSIS by considering the importance weights of the risk parameter, and the riskiest failure was determined as fuel line leakage. This was followed by air filter blockage and back pressure in the exhaust system, respectively. This study provides a comprehensive risk assessment for tugboats operating in a crude oil terminal and is expected to be an important guide for the relevant stakeholders.

Keywords: Tugboat, Risk analysis, Main engine failure, Fuzzy AHP, Fuzzy TOPSIS

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ÖZET

Deniz terminalleri küresel ham petrol tedarikinde önemli bir yer tutmaktadır. Deniz terminaller için en önemli bileşenlerden biri römorkörlerdir. Römorkörlerin güvenli ve sorunsuz çalışması, kritik öneme sahiptir. Bu çalışmada ham petrol terminalinde görev yapan bir römorkör için ana makine hatalarının güvenlik, çevresel ve ekonomik etkileri birlikte ele alınarak risk analizi gerçekleştirilmiştir. Bu kapsamda ilk olarak bulanık AHP metoduyla güvenlik, çevresel ve ekonomik kriterlerinin önem dereceleri belirlenmiştir. Daha sonra güvenlik, çevresel ve ekonomik etkiler birlikte düşünülerek bulanık TOPSIS yöntemi ile belirlenen 26 hata modu için risk sıralaması yapılmıştır. Sonuçlar, deniz terminal için en önemli risk parametresinin güvenlik olduğunu göstermiş ve bunu ekonomik ve çevresel parametreler izlemiştir. Sonra, risk parametrelerin önem ağırlıkları dikkate alınarak bulanık TOPSIS ile hata modlarının risk sıralaması yapılmış ve en riskli hatanın yakıt hattı sızıntısı olduğu belirlenmiştir. Bunu sırasıyla hava filtresi tıkanıklığı ve egzoz sisteminde geri basınç olması izlemiştir. Bu çalışma ham petrol terminalinde faaliyet gösteren römorkörler için kapsamlı bir risk değerlendirmesi sunmakta olup ilgili paydaşlar için önemli bir rehber olması beklenmektedir.

Anahtar sözcükler: Römorkör, Risk analizi, Ana makine hatası, Bulanık AHP, Bulanık TOPSIS

1. INTRODUCTION

Maritime transport has played a vital role in the global economy. Therefore, maritime trade must continue safely in order to prevent disruption of global trade. It is known that maritime accidents cause serious human injuries or deaths as well as economic losses and also cause significant damage to the environment. Although the probability of most maritime accidents occurring is relatively low, the impact of the accident is great. Therefore, safety studies in maritime remain an important research issue (Tonoğlu *et al.*, 2022).

Multi Criteria Decision Making (MCDM) systems are a decision-making approach used to rank alternatives by evaluating specific criteria. MCDM methods are an important tool for decision makers in different disciplines such as economics and finance (Zhao *et al.*, 2023; Ordu and Tekman, 2024), manufacturing (Abdel-Basset *et al.*, 2020; Ordu and Der, 2023), material selection (Zhang *et al.*,2017; Bulut *et al.*, 2024) and health (Bhaskar and Khan, 2022; Ahmad *et al.*, 2023). MCDM methods are also frequently used in maritime sector. They are especially prominent in topics such as safety, selection and risk analysis (Fan *et al.*, 2020).

Although there are many MCDM methods in the literature, the most popular ones are still Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods. Kim *et al.* (2008) examined the fire risk on a passenger ship with the classical AHP method. Nguyen (2009) performed a risk analysis for the ship propulsion system. In the study, the components and auxiliary systems affecting the reliability of the propulsion system were evaluated with the fuzzy AHP method. Elsayed *et al.* (2014) used the fuzzy TOPSIS method for risk analysis of liquefied natural gas (LNG) carriers. Özdemir *et al.* (2018) evaluated occupational accidents on ships from a broad perspective. The fuzzy AHP method was used to rank the factors that caused occupational accidents in the study. Li *et al.* (2010) performed risk assessment for ship integrated navigation system with fuzzy AHP. Başhan *et al.* (2020) applied risk analysis for ship engine room by integrating neutrosophic and fuzzy sets into AHP and TOPSIS method, respectively. While the importance weights of the risk parameters determined with AHP were obtained, the risks were ranked with TOPSIS. Ünver *et al.* (2021) examined the risk analysis of activities carried out during the maintenance process in ship engines. The operations carried out under 10 categories were prioritized in terms of risk with the fuzzy AHP method. Ziquan *et al.* (2021) used the fuzzy TOPSIS method to prioritize the risks arising from occupational health and safety in shipyards and implemented it on a passenger ship. Türk and Özkök (2022) conducted a study by combining the Gaussian approach with Fuzzy AHP to evaluate the risk of falling from a height, which is one of the important accident types occurring in shipyards. Wan *et al*. (2024) analyzed safety investments for increasing maritime transportation in the Arctic Ocean with the fuzzy AHP method.

In addition to individual AHP and TOPSIS studies in the literature, studies using the two methods as a hybrid are also receiving increasing attention. Diagkinis and Nikitakos (2013) conducted a study on the evaluation of equipment maintenance strategies by integrating classical AHP and TOPSIS methods. Alarcin *et al*. (2014) investigated the failures in ship diesel engines. All the failures obtained in the study were divided into six main groups. Then, they used the fuzzy AHP and fuzzy TOPSIS methods to determine the relationship of all failures with auxiliary systems. Emovon (2016) suggested using AHP, DELPI and TOPSIS methods together to determine the maintenance strategy in ships and carried out an application for the ship's central cooling system. Akyildiz and Mentes (2017) examined cargo ship accidents that occurred between 2001-2015 on the coasts and offshores of Turkey. They determined collision as the most common accident type and performed risk analysis using fuzzy AHP and fuzzy TOPSIS methods together. Wan *et al*. (2022) performed risk analysis for oil tankers by integrating fuzzy AHP and TOPSIS methods. They established a risk assessment system using ship, personnel and management factors. After weighting these factors with fuzzy AHP, ship risks were ranked with TOPSIS. Yeo *et al*. (2023) performed a risk analysis for the main engine of a LPG-powered ship. First, the hazards were determined with the failure mode and effect analysis (FMEA) for the LPG marine engine system. Then, the study was integrated with the fuzzy TOPSIS method and risk prioritization was performed. Arıcan and Kara (2024) combined the fuzzy AHP and fuzzy TOPSIS methods for chemical tanker selection. In the study, the most suitable ship selection was carried out by considering the cargo type.

Tugboats are a type of ship with powerful engines and high maneuverability specially designed to perform various tasks. Tugboats undertake critical tasks in marine terminals as well as in special duty areas such as straits, narrow water channels and ports (Koznowski and Łebkowski, 2022). When a crude oil terminal is considered, the trouble-free operation of the main engine and auxiliary systems of the tugboat is of vital importance in terms of global supply chain. When tugboat main engines are compared to the main engines of cargo carriers such as bulk cargo or tankers, it is seen that they operate in very difficult conditions. While a standard cargo carrier ship sails at constant load and speed for long periods, a tugboat is exposed to sudden load changes and different speeds and requires high maneuverability (Lebedevas *et al*., 2021). In this study, a risk analysis was carried out by considering the safety, environmental and economic effects of main engine failures for a tugboat operating in a crude oil terminal. To our knowledge, there is no previous study in the literature that has taken this issue into consideration. Although there are various types of tugboats, terminal tug boats have been taken into consideration and the safety, environmental and economic effects of tugboat main engine failures on marine terminals was focused on. Marine terminals are special ports where crude oil transfer is carried out and the risk is high. Therefore, the trouble-free operation of a tugboat's main engine will also reduce the safety, economic and environmental risks of the marine terminal. In this context, first, an experienced decision-making team was formed on the relevant area. Then, the importance weights of the safety, environmental and economic effects of the failures were determined with the fuzzy AHP method. Finally, a general risk ranking of main engine failures was performed with fuzzy TOPSIS.

2. METHODS

2.1. Fuzzy AHP

The classical AHP method was developed by Satty (1980) included definite judgments and did not take into account uncertainties. In order to overcome these problems, the idea of integrating fuzzy logic into the classical AHP method emerged. First, Van Laarhoven and Pedrycz (1983) used triangular fuzzy numbers in the AHP method. Later, this approach was adopted and fuzzy AHP approaches were introduced to the literature by Buckley (1985) and Chang (1996). In the following years, many researchers have proposed fuzzy AHP methods or improved existing ones. In this study, the Buckley (1985) approach was used because of its simplicity of application steps and its successful applications in many disciplines.

In the Buckley approach, as in other methods, the problem is first presented and the criteria are determined. Then, the survey structure is prepared by considering all combinations so that pairwise comparisons can be performed. Linguistic terms and their fuzzy equivalents are determined so that decision makers can make pairwise comparisons. A decision maker team consisting of more than one person makes pairwise comparisons and obtains a fuzzy decision matrix as in Equation 1.

$$\tilde{E}^k = \begin{bmatrix} \tilde{e}^k_{11} \dots\dots \tilde{e}^k_{1n} \\ \dots\dots\dots\dots \\ \tilde{e}^k_{n1} \dots\dots \tilde{e}^k_{nn} \end{bmatrix} \qquad (1)$$

where n is the number of criteria and k is the number of decision makers and $\tilde{E}^k$ is the fuzzy decision matrix. In the next stage, all the evaluations of the decision makers are aggregated. There are many alternative methods for this procedure such as arithmetic mean, geometric mean. The aggregated fuzzy decision matrix is given in Equation 2.

$$\tilde{E}^a = \begin{bmatrix} \tilde{e}^a_{11} \dots\dots \tilde{e}^a_{1n} \\ \dots\dots\dots\dots \\ \tilde{e}^a_{n1} \dots\dots \tilde{e}^a_{nn} \end{bmatrix} \qquad (2)$$

The geometric mean of the triangular numbers in the aggregated fuzzy decision matrix is calculated as shown in Equation 3 and then the fuzzy weights of each criterion are calculated as in Equation 4.

$$\tilde{r}_{i1} = \left(\tilde{e}^1_{i1} \otimes \tilde{e}^2_{i2} \otimes \dots \otimes \tilde{e}^p_{in}\right)^{1/n} \qquad (3)$$

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \dots \oplus \tilde{r}_n)^{-1} \qquad (4)$$

Defuzzification is required to calculate the real world equivalents of the obtained fuzzy expressions. Although there are many approaches for defuzzification, one of the most commonly used methods is the arithmetic mean method. In this method, the defuzzification process is performed as shown in Equation 5.

$$w_i = (l + m + u)/3 \qquad (5)$$

where l, m and u are triangular fuzzy numbers and represent lower, medium and upper values respectively. Finally, normalization must be performed to make meaningful comparisons. The normalization process of the obtained criterion weights is shown in Equation 6.

$$(w_n)_i = \frac{w_i}{\sum w_i} \qquad (6)$$

2.2. Fuzzy TOPSIS

The TOPSIS method, one of the essential decision-making methods, was first introduced by Hwang and Yoon (1981). The key working system of this method is based on the selected alternative being the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. In the classical TOPSIS method, the weights of the criteria and the ratings of the alternatives are carried out using crisp values. However, there are uncertainties for real-world decision-making problems. Therefore, fuzzy logic has been integrated into the TOPSIS method in order to make more realistic modeling (Ertuğrul and Karakaşoğlu, 2009; Nădăban *et al.*, 2016). There are many fuzzy TOPSIS approaches in the literature. The approach proposed by Chen (2000) was used in this study.

In this approach, the alternatives to be ranked are determined. Then, the fuzzy expressions and their equivalents are determined so that the decision makers can make an evaluation. In the first step of the method, the normalized fuzzy decision matrix is obtained as shown in Equations 7, 8 and 9.

$$\tilde{R} = \left[\tilde{r}_{ij}\right] \tag{7}$$

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \tag{8}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{a_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{c_{ij}}\right) \tag{9}$$

When making this calculation, if the relevant criterion is benefit, $c_j^* = \max_i \left\{c_{ij}\right\}$ is taken into account, and if it is cost, $a_j^- = \min_i \left\{a_{ij}\right\}$ is taken into account.

After the triangular fuzzy numbers are normalized to [0,1], they are multiplied by the criteria weights and the weighted normalized fuzzy decision matrix is obtained as shown in Equations 10 and 11.

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{mxn} \tag{10}$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} \cdot \tilde{w}_j \tag{11}$$

Then the fuzzy positive-ideal solution (*FPIS*, A^*) and fuzzy negative-ideal solution (*FNIS*, A^-) are defined as in Equations 12 and 13.

$$A^* = \left(\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*\right) \text{ where } \tilde{v}_j^* = \max_i \left\{v_{ij3}\right\} \tag{12}$$

$$A^- = \left(\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^*\right) \text{ where } \tilde{v}_j^- = \min_i \left\{v_{ij1}\right\} \tag{13}$$

The distance of each alternative from d_i^* and d_i^- is calculated as in Equations 14 and 15.

$$d_i^* = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^*\right) \tag{14}$$

$$d_i^- = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right) \tag{15}$$

Finally, the closeness coefficient (*CC*) given in Equation 16 is calculated for each alternative using d_i^* and d_i^-.

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-} \tag{16}$$

The alternatives are ranked according to the calculated *CC* value. The highest *CC* value is ranked first.

3. IMPLEMENTATION

In this study, a comprehensive risk assessment was performed for the main engine failures of a tugboat operating in a crude oil terminal. First, an experienced expert group working in a crude oil terminal was formed. Then, using this team consisting of 6 experts and the existing literature, the main engine failures were determined. The main engine failures were determined under six groups as fuel, lubrication, cooling, governor, exhaust and air supply system. Table 1 shows the main engine failures of the tugboat.

A failure of the main engine of a tugboat guiding crude oil tankers during operation will have serious safety, economic and environmental consequences. Safety risks generally include factors such as collision and grounding, loss of maneuverability, crew injuries and fatal incidents, fire and explosion hazard. Environmental risks include factors such as fuel and oil leakage, increased exhaust emissions, and damage to the marine ecosystem. Economic risks include factors such as the halt of the operation due to the failure of the tugboat to operate, costs resulting from the replacement or repair of machine parts, and fines to be paid as a result of accidents or environmental damage. Therefore, in this study, a risk assessment was carried out by considering safety, economic or environmental effects together.

The importance of safety, economic and environmental effects of marine engine failures for the crude oil terminal was evaluated with the determined expert team. In this context, an experienced decision-making team working in a crude oil marine terminal was first established. Table 2 provides the important characteristics of the decision-making group.

In order to conduct a comprehensive risk analysis, it is necessary to determine the importance weights of safety, economic and environmental factors. In this context, a survey including pairwise comparison of these three risk parameters was prepared and the importance weights of the risk parameters were calculated with the fuzzy AHP method.

Table 1. Failure modes of a tugboat main engine

Failure category	Failure codes	Failure modes
Fuel system	F01	Fuel pump failure
	F02	Fuel injector blockage
	F03	Contaminated fuel
	F04	Fuel line leakage
	F05	Fuel filter blockage
Lubrication system	L01	Low oil level
	L02	Oil pump failure
	L03	Oil filter blockage
	L04	Oil leakage
	L05	Contaminated oil
Cooling system	C01	Cooling water leakage
	C02	Cooling water pump failure
	C03	Heat Exchanger contamination
	C04	Thermostat failure
Air supply system	A01	Air leakage
	A02	Air filter blockage
	A03	Insufficient air cooling
	A04	Turbocharger seizing or locking
Governor system	G01	Governor incorrect setting
	G02	Electrical or sensor faults
	G03	ECU failure
	G04	Software errors
Exhaust System	E01	Exhaust valve failure
	E02	Exhaust pipe cracks
	E03	Exhaust muffler failure
	E04	Back pressure in the exhaust system

Table 2. Basic characteristics of the decision-making group

Decision makers	Professional position	Work experience	Education
DM1	Oceangoing Watchkeeping Engineer	11 years	Bachelor Degree
DM2	Chief Engineer	19 years	Associate Degree
DM3	Oceangoing Watchkeeping Engineer	15 years	Bachelor's Degree
DM4	Chief Engineer	23 years	Associate Degree
DM5	Oceangoing Watchkeeping Engineer	12 years	Bachelor Degree
DM6	Mechanical Engineer	5 years	Master's Degree

In the second stage of the study, the economic, environmental and safety impact value that will be created as a result of the occurrence of the failure for 26 failure modes was determined based on each risk parameter. First, the environmental impact of each failure mode was verbally evaluated by the experts, followed by economic and safety evaluations. In order to perform a comprehensive risk analysis, the importance weight of each risk parameter and the related failure mode were evaluated together and the priority order of all failure modes was performed. Linguistic expressions and their fuzzy equivalents required for experts to make an evaluation at the survey stage are given in Table 3.

Table 3. Linguistic and fuzzy expressions for risk parameters and failure modes (Türk and Özkök, 2020).

Risk parameters ratings		Failure modes ratings	
Linguistic term	Membership function	Linguistic term	Membership function
Equal	(1, 1, 1)	Very Low	(1, 1, 3)
Slightly Important	(1, 3, 5)	Low	(1, 3, 5)
Moderate	(3, 5, 7)	Medium	(3, 5, 7)
Very Important	(5, 7, 9)	Good	(5, 7, 9)
Absolutely Important	(7, 9, 9)	Very Good	(7, 9, 9)

In the final stage of the study, preventive recommendations for risky failure modes were given. The flow diagram containing all steps of the methodology applied in the study is shown in Figure 1.

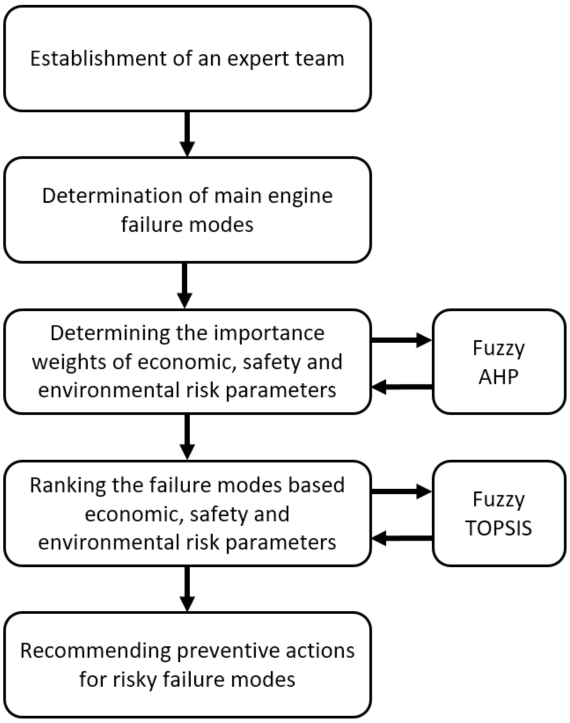

Figure 1. Flow chart of the study

4. RESULT AND DISCUSSIONS

In this study, risk assessment of main engine failures of terminal tugboats was carried out in terms of crude oil marine terminal. For risk analysis, environmental, economic and safety criteria were taken into consideration and global risk level of the failures was determined. In other words, environmental, economic and safety effects of determined main engine failures were integrated and failures were ranked. Firstly, the importance of environmental, economic and safety criteria determined for risk assessment was determined by the fuzzy AHP method. Individually collected pairwise comparison matrices were aggregated with geometric mean approach and given in Table 4. The central consistency index (CCI) value suggested by Bulut *et al.* (2012) was calculated as 0.0157. Since the maximum limit for the three criteria was 0.31, it was seen that the aggregated matrix was consistent.

As shown in Section 2, following the steps of the fuzzy AHP method, first the geometric mean of the fuzzy comparison matrix was calculated and then the fuzzy weight matrix was obtained. In the next step, the obtained fuzzy expressions were defuzzified. In the last step, the crisp values were normalized and the weight of each criterion was obtained. Table 5 shows the fuzzy weight matrix, crisp value and normalized weights of the risk criteria.

According to the decision-making group, the most important criterion when evaluating the risk of a tugboat main engine failure was the safety impact of the relevant failure. The importance level of the safety criterion was determined as 50%. The second important criterion was determined as the economic impact with 30%. The decision-making group considered the environmental impact as a relatively less important criterion with a 20% importance weight. After the weights of the criteria were obtained, the second stage of the study was started. In this stage, the impact of 26 main engine failures determined for each criterion was evaluated by the decision-making group. Then, each evaluation data was aggregated with arithmetic mean approach and presented in Table 6.

The normalized aggregated fuzzy decision matrix was given in Table 7. Then, the fuzzy weight matrix obtained with the fuzzy AHP was multiplied with the normalized fuzzy decision matrix and thus the weighted normalized fuzzy decision matrix was obtained. This matrix was given in Table 8. In the next step, FPIS and FNIS were calculated. Then, the distances of each failure according to FPIS and FNIS were calculated. Finally, *CC* values were obtained for each failure. The distance values, *CC* values and risk ranking of each failure were given in Table 9.

The riskiest failure among the main engine failures was determined by the decision-making group as “fuel line leakage (F04)”. If a fuel line leak occurs, the leaked fuel may come into contact with hot surfaces and this causes a high fire risk. In addition, the fuel vaporizing in the engine room, which is a closed area, may cause an explosion. These cause serious safety problems. From an economic perspective, fuel loss increases operating costs. Maintenance costs increase due to line replacement and cleaning. If the fuel leaks into the sea, the company may face serious fines due to environmental pollution. From an environmental impact perspective, serious air pollution affecting human health may occur on the ship due to the vaporization of leaked fuel and unburned hydrocarbons. If the leak reaches the sea, it will have a serious negative impact on marine life. All these effects were evaluated together by the decision-making group and the riskiest main engine failure was fuel line leakage.

Table 4. Aggregated pairwise comparison matrix for risk parameters

	Environmental	Economic	Safety
Environmental	(1, 1, 1)	(0.447, 0,693, 1.308)	(0.231, 0,333, 0.561)
Economic	(0.765, 1.442, 2.236)	(1, 1, 1)	(0.417, 0.637, 1.104)
Safety	(1.783, 3.004, 4.333)	(0.905, 1.57, 2.399)	(1, 1, 1)

Table 5. Fuzzy weight matrix, crisp value and normalized weight for risk parameters

	Fuzzy weight matrix	Crisp value	Normalized weight
Environmental	(0.106, 0.188, 0.388)	0.227	0.20
Economic	(0.154, 0.298, 0.581)	0.344	0.30
Safety	(0.264, 0.514, 0.938)	0.572	0.50

Table 6. Aggregated fuzzy decision matrix for failure modes.

Failure codes	Environmental			Economic			Safety		
F01	3.00	5.00	7.00	2.33	4.33	6.33	4.33	6.33	8.00
F02	3.00	5.00	6.67	4.67	6.67	8.00	4.00	6.00	8.00
F03	2.33	4.33	6.33	3.33	5.33	7.33	4.33	6.33	8.00
F04	5.00	7.00	8.33	3.00	5.00	7.00	5.00	7.00	8.33
F05	2.67	4.00	5.67	3.33	5.33	7.33	2.33	4.00	6.00
L01	3.00	5.00	7.00	3.33	5.33	7.33	3.67	5.67	7.67
L02	2.00	4.00	6.00	4.67	6.67	8.33	4.00	6.00	8.00
L03	2.67	4.67	6.33	3.33	5.33	7.33	2.67	4.33	6.33
L04	4.33	6.33	8.33	2.33	4.33	6.33	4.67	6.67	8.33
L05	2.33	4.33	6.33	4.33	6.33	8.00	2.00	3.33	5.33
C01	3.00	5.00	7.00	1.67	3.00	5.00	4.33	6.33	8.00
C02	3.00	5.00	6.67	3.33	5.33	7.33	4.00	6.00	8.00
C03	2.67	4.67	6.33	4.33	6.33	8.00	2.33	4.33	6.33
C04	1.33	2.33	4.33	4.00	6.00	8.00	5.00	7.00	8.33
A01	1.00	1.67	3.67	2.00	4.00	6.00	3.00	5.00	7.00
A02	3.33	5.33	7.33	4.33	6.33	8.33	4.00	6.00	8.00
A03	2.00	4.00	6.00	2.00	4.00	6.00	2.67	4.67	6.67
A04	2.33	4.00	6.00	2.67	4.67	6.67	4.00	6.00	7.67
G01	2.33	4.33	6.33	4.00	6.00	8.00	4.00	6.00	8.00
G02	1.67	3.33	5.33	4.67	6.67	8.00	3.00	5.00	7.00
G03	2.00	4.00	6.00	3.67	5.67	7.67	2.00	3.67	5.67
G04	1.67	3.33	5.33	4.00	6.00	8.00	3.67	5.67	7.33
E01	2.33	4.33	6.33	2.33	4.00	6.00	4.00	6.00	7.67
E02	4.33	6.33	8.00	4.33	6.33	8.00	3.33	5.33	7.33
E03	3.00	5.00	7.00	2.00	4.00	6.00	3.33	5.33	7.33
E04	2.67	4.67	6.67	3.33	5.33	7.33	5.00	7.00	8.67

Table 7. Normalized fuzzy decision matrix for failure modes

Failure codes	Environmental			Economic			Safety		
F01	0.36	0.6	0.84	0.28	0.52	0.76	0.50	0.73	0.92
F02	0.36	0.6	0.8	0.56	0.8	0.96	0.46	0.69	0.92
F03	0.28	0.52	0.76	0.4	0.64	0.88	0.50	0.73	0.92
F04	0.6	0.84	1	0.36	0.6	0.84	0.58	0.81	0.96
F05	0.32	0.48	0.68	0.4	0.64	0.88	0.27	0.46	0.69
L01	0.36	0.6	0.84	0.4	0.64	0.88	0.42	0.65	0.88
L02	0.24	0.48	0.72	0.56	0.8	1	0.46	0.69	0.92
L03	0.32	0.56	0.76	0.4	0.64	0.88	0.31	0.50	0.73
L04	0.52	0.76	1	0.28	0.52	0.76	0.54	0.77	0.96
L05	0.28	0.52	0.76	0.52	0.76	0.96	0.23	0.38	0.62
C01	0.36	0.6	0.84	0.2	0.36	0.6	0.50	0.73	0.92
C02	0.36	0.6	0.8	0.4	0.64	0.88	0.46	0.69	0.92
C03	0.32	0.56	0.76	0.52	0.76	0.96	0.27	0.50	0.73
C04	0.16	0.28	0.52	0.48	0.72	0.96	0.58	0.81	0.96
A01	0.12	0.2	0.44	0.24	0.48	0.72	0.35	0.58	0.81
A02	0.4	0.64	0.88	0.52	0.76	1	0.46	0.69	0.92
A03	0.24	0.48	0.72	0.24	0.48	0.72	0.31	0.54	0.77
A04	0.28	0.48	0.72	0.32	0.56	0.8	0.46	0.69	0.88
G01	0.28	0.52	0.76	0.48	0.72	0.96	0.46	0.69	0.92
G02	0.2	0.4	0.64	0.56	0.8	0.96	0.35	0.58	0.81
G03	0.24	0.48	0.72	0.44	0.68	0.92	0.23	0.42	0.65
G04	0.2	0.4	0.64	0.48	0.72	0.96	0.42	0.65	0.85
E01	0.28	0.52	0.76	0.28	0.48	0.72	0.46	0.69	0.88
E02	0.52	0.76	0.96	0.52	0.76	0.96	0.38	0.62	0.85
E03	0.36	0.6	0.84	0.24	0.48	0.72	0.38	0.62	0.85
E04	0.32	0.56	0.8	0.4	0.64	0.88	0.58	0.81	1.00

Table 8. Weighted normalized fuzzy decision matrix for failure modes.

Failure codes	Environmental			Economic			Safety		
F01	0.04	0.11	0.33	0.04	0.15	0.44	0.13	0.38	0.87
F02	0.04	0.11	0.31	0.09	0.24	0.56	0.12	0.36	0.87
F03	0.03	0.10	0.29	0.06	0.19	0.51	0.13	0.38	0.87
F04	0.06	0.16	0.39	0.06	0.18	0.49	0.15	0.42	0.90
F05	0.03	0.09	0.26	0.06	0.19	0.51	0.07	0.24	0.65
L01	0.04	0.11	0.33	0.06	0.19	0.51	0.11	0.34	0.83
L02	0.03	0.09	0.28	0.09	0.24	0.58	0.12	0.36	0.87
L03	0.03	0.11	0.29	0.06	0.19	0.51	0.08	0.26	0.69
L04	0.05	0.14	0.39	0.04	0.15	0.44	0.14	0.40	0.90
L05	0.03	0.10	0.29	0.08	0.23	0.56	0.06	0.20	0.58
C01	0.04	0.11	0.33	0.03	0.11	0.35	0.13	0.38	0.87
C02	0.04	0.11	0.31	0.06	0.19	0.51	0.12	0.36	0.87
C03	0.03	0.11	0.29	0.08	0.23	0.56	0.07	0.26	0.69
C04	0.02	0.05	0.20	0.07	0.21	0.56	0.15	0.42	0.90
A01	0.01	0.04	0.17	0.04	0.14	0.42	0.09	0.30	0.76
A02	0.04	0.12	0.34	0.08	0.23	0.58	0.12	0.36	0.87
A03	0.03	0.09	0.28	0.04	0.14	0.42	0.08	0.28	0.72
A04	0.03	0.09	0.28	0.05	0.17	0.47	0.12	0.36	0.83
G01	0.03	0.10	0.29	0.07	0.21	0.56	0.12	0.36	0.87
G02	0.02	0.08	0.25	0.09	0.24	0.56	0.09	0.30	0.76
G03	0.03	0.09	0.28	0.07	0.20	0.53	0.06	0.22	0.61
G04	0.02	0.08	0.25	0.07	0.21	0.56	0.11	0.34	0.79
E01	0.03	0.10	0.29	0.04	0.14	0.42	0.12	0.36	0.83
E02	0.05	0.14	0.37	0.08	0.23	0.56	0.10	0.32	0.79
E03	0.04	0.11	0.33	0.04	0.14	0.42	0.10	0.32	0.79
E04	0.03	0.11	0.31	0.06	0.19	0.51	0.15	0.42	0.94

Table 9. Ranking of failure modes

Failure codes	di*	di-	CCİ	Rank
F04	0.087	0.470	0.844	1
A02	0.101	0.458	0.819	2
E04	0.108	0.446	0.806	3
F02	0.124	0.432	0.777	4
L04	0.132	0.427	0.764	5
L02	0.134	0.421	0.759	6
E02	0.134	0.420	0.758	7
G01	0.144	0.412	0.741	8
C02	0.161	0.393	0.709	9
C04	0.168	0.390	0.699	10
F03	0.167	0.387	0.699	11
L01	0.178	0.377	0.679	12
F01	0.193	0.361	0.652	13
G04	0.215	0.339	0.612	14
A04	0.231	0.322	0.582	15
G02	0.240	0.316	0.569	16
E01	0.252	0.302	0.545	17
C01	0.253	0.301	0.543	18
C03	0.258	0.296	0.534	19
E03	0.264	0.290	0.523	20
L03	0.292	0.262	0.473	21
L05	0.331	0.222	0.401	22
F05	0.336	0.218	0.394	23
G03	0.338	0.216	0.390	24
A03	0.344	0.211	0.381	25
A01	0.388	0.166	0.299	26

Air filter blockage (A02) was determined as the second most risky main engine failure. Air filter blockage weakens the flow of intake air and can cause inefficient combustion. Especially in critical maneuvers, sudden drops in engine power can cause serious ship accidents. Inefficient combustion also causes serious problems in economic terms. In addition, a significant increase in exhaust emissions can be observed because of incomplete combustion.

The third risky main engine failure was calculated as *back pressure in the exhaust system* (E04). In such a case, the engine may misfire, which can pose a serious safety risk for critical maneuvers. It can increase operating costs by causing increased fuel consumption. It can cause more wear on engine components and increase maintenance and repair costs. It can cause a serious increase in exhaust emissions because of incomplete combustion.

Fuel injector blockage (F02) emerged as the fourth risky main engine failure. The biggest safety effect of fuel injector blockage is the sudden decrease in engine power. This situation is of vital importance for tugboats operating in crude oil marine terminals, especially during critical maneuvers. Fuel injector blockage will undoubtedly increase operating and maintenance costs. The environmental result will be increased emissions.

Oil leakage (L04) was ranked fifth as a critical failure. Oil leakage has significant effects in terms of safety. Leaking oil can cause fire by contacting hot engine parts. In addition, leaking oil can cause work accidents by creating slippery surfaces on the engine room floor. Finally, engine components can be damaged with insufficient lubrication and serious ship accidents can occur with sudden engine stoppage. If early precautions are not taken against oil loss, it will also increase operating costs. If the oil leakage reaches the sea, the company may have to pay a serious fine. From an environmental perspective, oil leakage reaching the sea will negatively affect marine life.

Oil pump failure (L02), a fault related to the lubrication system, was determined as the sixth risky fault. Oil pump failure has two important effects in terms of safety. First, there is a risk of fire due to excessive friction and heat accumulation due to lack of lubrication. Second, sudden losses in engine power may occur and the maneuverability of the tugboat may be impaired. The cost of replacing the oil pump and related components is an important effect in terms of economy. In addition, major damage may occur in important engine parts such as crankshaft, bearing and piston, which may cause significant costs. From an environmental perspective, an increase in emissions is expected. Then, oil pump failure was followed by "exhaust pipe cracks (E02)", "governor incorrect setting (G01)", "cooling water pump failure (C02)" and "thermostat failure (C04)". The two least risky faults were determined by the decision-making team as "insufficient air cooling (A03)" and "air leakage (A01)".

To prevent fuel line leakage, hoses and connections should be checked regularly to ensure there is no wear or corrosion. Fuel line pipes should be made of sea-resistant and high-quality material. The most important action to prevent air filter blockage is to perform the maintenance procedure regularly and replace it using the appropriate filter. Preventing blockages or soot accumulation in the exhaust system that may restrict exhaust flow is the basic precaution to be taken for back pressure in the exhaust system. Therefore, regular observation and maintenance are very critical. In addition, monitoring of exhaust system data by the engine personnel is also an important action. Using quality fuel and a problem-free turbocharger system reduces back pressure in the exhaust system formation.

5. CONCLUSIONS

Despite the rules and regulations prepared by international organizations and local authorities for the safe operation of ships and the prevention of marine or environmental pollution, accidents occur at sea every year. These accidents cause serious human injuries or deaths, economic losses, and marine pollution. Therefore, risk studies in maritime remain an important research area in the literature. In this study, the main engine-related failures of a tugboat operating in a crude oil terminal were discussed. Therefore, it is an important issue to consider the safety, environmental and economic effects of the main engine failure in terms of the crude oil terminal. In this study, these effects were evaluated together and the risk prioritization of main engine failures was carried out.

In the first part of the study, the importance weights of these parameters were determined in order to perform risk analysis by taking into account the safety, environmental and economic effects. In this context, a survey was applied to the decision-making team consisting of 6 experts and the results were obtained with the fuzzy AHP method. Then, the fuzzy TOPSIS method was used for the risk prioritization of the determined main engine failures. The decision-making team verbally evaluated the safety, environmental and economic effects of each failure mode. The obtained data were aggregated and the final risk prioritization was carried out.

The results revealed that the riskiest failure mode was fuel line leakage (F04). This was followed by air filter blockage and back pressure in the exhaust system, respectively. The lowest risk level main engine failures for a crude oil terminal were determined as “insufficient air cooling (A03)” and “air leakage (A01)”.

When a failure occurs in the main engine of tugboats operating in marine terminals, engine performance may decrease or sudden power losses may occur. Especially in critical situations, power loss and reduced maneuverability may endanger the safety of the marine terminal. Flammable and combustible crude oil may leak, major explosions may occur and serious property and life losses may occur. In addition, leaked crude oil may cause irreparable environmental disasters and damage the marine ecosystem. The trouble-free operation of the main engine, which is considered the heart of a tugboat, will also reduce the safety, economic and environmental risks of the marine terminal. Therefore, the results obtained from this study should be taken into consideration by the relevant stakeholders and preventive measures should be implemented for risky failure modes.

In this study, only the main engine system is considered. In future studies, risk studies should be conducted that take into account different systems of terminal tugs and preventive actions should be determined for risky failure modes. In addition, the probability of main engine failures was not taken into account in this study. The main focus of the study is to determine the perceived risk level for a crude oil terminal if a failure occurs. Since main engine failures are considered, the probability of some failures occurring may be low and some may be high. Therefore, a risk assessment can be made from a different perspective that takes this into account in the future.

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CONFLICT OF INTERESTS

The author(s) declare that for this article they have no actual, potential or perceived conflict of interests.

ETHICS COMMITTEE PERMISSION

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