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Examination of Failures in the Marine Fuel and Lube Oil Separators Through the Fuzzy DEMATEL Method

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Abstract

Separators are essential equipment on ships, regardless of the vessel type or the type of engine installed, whether the main, and auxiliary engines are two-stroke or four-stroke. The primary function of these separators, apart from the bilge separator, is to ensure clean fuel delivery to the main engine and auxiliary machinery by removing water and solid contaminants from the fuel. The efficiency of the separators and the level of maintenance they receive directly influence the performance of the ship's machinery, reducing the likelihood of malfunctions and power loss in systems dependent on clean fuel. However, since separators operate at high speeds using centrifugal force and are composed of numerous intricate components, they are prone to potential failures if not properly maintained. While preparing for this study, four experts were asked about the effects of failures that may occur in the separators. According to the criteria received, the fuzzy DEMATEL method, a multi-criteria decision-making method, was used to evaluate the effects of failures. When the results are examined, the most effective factors are the wear of the bearings, contamination, incorrect assembly of the bowls, and bending of the shaft. It is extremely important to have spare parts available on the ship and to maintain the equipment with sufficient authorized crew.

Keywords: Failure, Fuzzy, DEMATEL, Multi-criteria decision making, Separator

1. Introduction

Separators are designed according to basic physics rules and operate on the principle of separating two liquids that don't mix owing to the density difference [1]. Separators are used to separate liquid mixtures with different densities, such as milk and cream [2]. In this context, separators are used in milk processing plants, oil refineries, and ships to separate the input product from desired outputs and other particles. The working principle is to separate the water and solids in the fuel or oil using the centrifugal force of the system rotating at approximately 7000-9000 rpm. Normally, water and solid particles can be separated over time in fuel storage and settling tanks in ships, owing to density differences. However, because ships are exposed to constant movement, it is not possible for sedimentation to occur in a uniform manner. The importance of separators has emerged at this point. Regardless of how heavily contaminated the fuel is, the separator separates the fuel from water and solid particles in line with its operating principle [3]. Separators are divided into two types, purifiers and clarifiers, based on their working method and structure. While clarifier-type separators have a single outlet for only fuel, purifiers have two outlets for both water and fuel [4,5]. If separators are not used effectively and if their maintenance is not performed on time and as required, particles in the fuel will move towards the equipment using that fuel. Fuel will move towards equipment, which may cause damage to fuel pumps, injectors, and injector nozzles, and cause a decrease in the performance of the machines. This is because uncleaned fuel in the injector damages it and causes poor combustion [6,7]. Therefore, the importance of the fuel system is better understood, particularly for ships that are constantly sailing.

Marine separator systems are designed to separate and clean fuel and oil types such as marine diesel oil, heavy fuel oils

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with a maximum CST of 600, detergent lubricants, very low sulphur fuel oil, ultra-low sulphur fuel oil, and distillate fuels. The parts required for the separation system, shown in Figure 1, are the separator, control unit, valves, heating system, and feed pump. The general flow is dirty or used oil/fuel inlet from A, if it needs to be pumped and heated; oil/fuel circulation from C; water inlet from D; sludge or water outlet from E; and, after passing through pressure switches, cleaned oil/fuel outlet from B.

Many accidents occur on ships, causing environmental pollution, fires, and even death, depending on various factors [8]. When accidents are specifically examined in terms of environmental impact, one of the most important causes of accidents is an inability to perform efficient maneuvers owing to the main engine power loss. One of the reasons for the power loss of the main engine is damage to the injectors and fuel pumps due to the lack of clean fuel [9]. Failures are caused by both fuel issues and maintenance not being carried out at the times specified by the manufacturers [10]. Failure to maintain separators in a timely manner and by competent crews causes many accidents, financial losses, and equipment damage [11,12]. In addition, because separators operate at very high speeds, maintenance, performed by unqualified crews, causes serious accidents to seafarers quickly, resulting in death [3]. Ships have a service life, just like living organisms have a life span. Regular maintenance of equipment and replacement of required parts at the times specified in maintenance books will extend the life of the equipment. A longer lifespan of a ship can be achieved through regular maintenance [13]. Generally, separator failures consist of three main components. The first one is a mechanical function error (vibration, sound, odor, low speed, etc.), the second one is a separation function fault (insufficient separation, insufficient sludge output, bowl opening during operation, etc.), and the third one is a vibration switch failure (difficulty reactivating the vibration electric switch). The faults are specified here: they can be described as dirty separator bowl, shaft curvature, bearing deformation, filter pollution, and insufficient fuel and oil supplied to the separator [14].

This study investigated the general situation of failures, the spares that should be available on the ship, the importance of maintenance performed by authorized persons, and the determination of the root causes of the failures. Additionally, it examined the benefit of using the multi-criteria decision-making (MCDM) method to counter possible failures, thereby enhancing the longevity and performance of the equipment. MCDM methods are statistical tools used in complex decision-making processes where multiple factors need to be evaluated. These methods aim to rank or choose among alternatives based on different evaluation criteria. The development of MCDM methods began with the introduction of various approaches in the mid-20th century. These methods continue to be developed by considering the decision-making process in a broader context, including technologies such as artificial intelligence and machine learning [15]. Fuzzy-logic-based methods can be especially effective in cases of uncertainty and imprecise information. Methods such as fuzzy DEMATEL, fuzzy TOPSIS, fuzzy PROMETHEE, and fuzzy VIKOR can help in making better decisions by handling uncertainty and multiple criteria in complex decision-making processes [16,17]. Each method has advantages and disadvantages, and the choice of method may vary depending on the problem context, data situation, and user preferences. Expertise is required to effectively use these methods, and careful analysis is essential to obtain accurate results. Fuzzy DEMATEL helps to handle data containing uncertainty more effectively than other MCDM methods; therefore, it is more suitable for complex systems such as fault detection [18]. Fuzzy-logic-based MCDM methods are widely used in various fields. To provide some examples of these studies, such methodologies are employed in the detection of skin cancer in the medical field [19], in the diagnosis of cattle diseases in the veterinary field [20], in dryer oven systems in the food sector [21], and in the field of social life in individual emotion analysis [22].

Current examples of usage areas are abundant in open literature, including conference proceedings and scientific articles. This study will share information on ship-specific studies and some of the publications examined in this context are as follows. Tamer et al. [23] investigated MCDM applications in postgraduate theses and journal papers for Turkish naval architecture and marine engineering area. Tuncel et al. [24] applied a Quadratic Mean fuzzy AHP

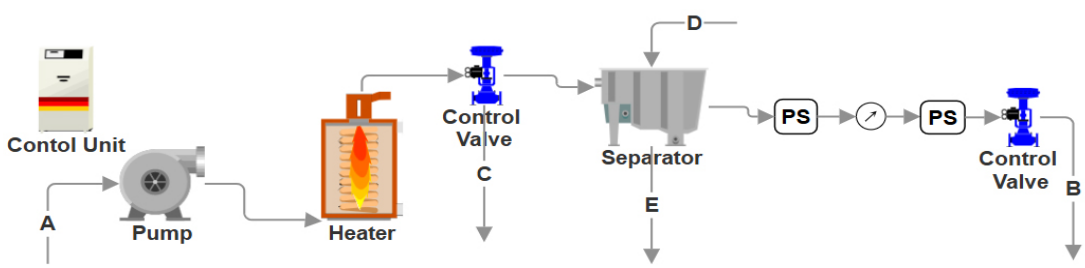

***Figure 1.** Marine seperator system [3]*

method to the preparation steps of electronic nautical charts for navigation, to identify probable risks. The hybrid fuzzy AHP-TOPSIS method, applied by Demirel [25], was used for selecting a roll motion stabilizer to reduce the roll motion of a fishing boat. The study was conducted by Erol [26] to determine the ship type to be built in shipyards in Turkey using fuzzy TOPSIS and fuzzy VIKOR methods. A new fuzzy TOPSIS method based on global fuzzy sets was used by Demirel [27] to select a stabilizer that directly affects many criteria, such as comfort, safety, and speed of passenger ships. Wang et al. [28] made a risk assessment based on advanced fuzzy multiple criteria such as MULTIMORA, AHP, and Monte Carlo simulations for fires occurring in the engine room of ships. Madi et al. [29] examined the prominent criteria in the selection of ports where ships call for different purposes using the fuzzy decision-making method on the Malaysian example. Jianping et al. [30] optimized ship main dimensions and main engine power using fuzzy decision-making theory, considering economic data. Risk analyses were carried out by Ceylan [31] employing failure mode and effect analysis for high-pressure air systems, which are critical to safely preventing accidents and ensuring ship operations.

Bashan and Demirel [32] evaluated the critical operational faults of marine diesel generators using the DEMATEL method, to detect relationships between faults. Bucak et al. [33] presented strategies created using the fuzzy AHP method to prevent ship-borne emissions in the strait of Istanbul. Balin et al. [34] explained the reasons for the failures occurring in the auxiliary systems of the ship's main engine, their effects on the system, and their degree of severity with the fuzzy DEMATEL method. Failure modes, effects, and criticality analysis were carried out by Ahmed and Gu [35] using the fuzzy logic method, based on empirical and statistical data regarding boiler failures that cause loss of life, health problems, and large-scale material damage on ships. Yucesan et al. [36] examined the failures of ship diesel generators by evaluating them with the best-worst method based on fuzzy logic. Marichal et al. [37], a new approach for the predictable maintenance of separators was presented in using a Genetic Neuro-Fuzzy System. Bashan et al. [38] used the fuzzy logic-based best-worst method to examine the 20 most critical failure types, frequently seen in ship heavy fuel oil separators.

It is important that the fuel and oil separators used on ships are maintained and operated according to their working principles. If the oil separator cannot adequately separate water and waste oil from the oil, rapid wear may occur in the bearings of the main engine and auxiliary generator, which may prevent the completion of the journey. Fuel that has not been purified by separators is delivered from the service fuel tank to the fuel pump, passing through a filter before being sent to the main engine and auxiliary generator. Any unrefined fuel that traverses the filter can carry particulates, which may inflict damage on the fuel pumps and injectors, thereby hindering the required power output. Therefore, maintenance of separators on ships is of great importance. One of the main motivations of this study is that the fuzzy DEMATEL method has not been used before to perform an analysis with a similar number of faults. In this study, guided by expert opinions, 20 types of failures frequently seen in the fuel and oil separators used on ships were identified, and the effects and importance of these failures on each other were analyzed by applying the fuzzy DEMATEL technique.

2. Research Method

2.1. Fuzzy Logic and Fuzzy Set

In classical logic, until recently, belonging was a concept that was usually measured and evaluated from 0 to 1. However, there may not always be clear values, such as zero and one; preferences and importance orders may come into play and tell us the possibilities. Therefore, a fuzzy logic evaluation was performed by Zadeh [39].

Triangular fuzzy numbers can be represented as (a1, a2, a3), as shown in Figure 2 [27], and the function of the fuzzy number $\tilde{A}$ is specified in Equation 1. Fuzzy numbers show small, medium, and large probabilities.

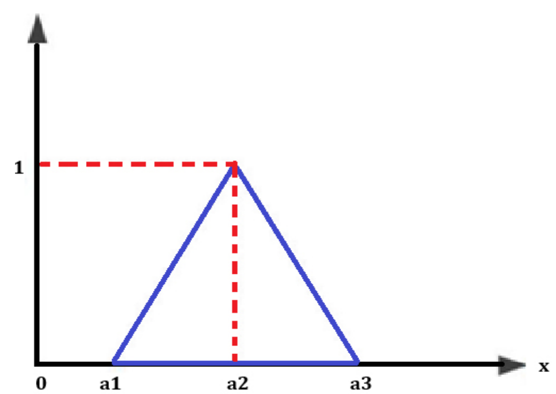

Figure 2. *Triangular fuzzy numbers*

$$f_{\tilde{A}}(x) = \begin{Bmatrix} 0, & x < a1 \\ \frac{(x-a1)}{(a2-a1)}, & a1 \leq x \leq a2, \\ \frac{(a3-x)}{(a3-a2)}, & a2 \leq x \leq a3, \\ 0, & x > a3 \end{Bmatrix} \quad (1)$$

$\tilde{A}$ and $\tilde{B}$ are determined as (a1, a2, a3) and (b1, b2, b3), the operation to be performed between them is as in Equations 2-5;

$$\tilde{A}(+)\tilde{B} = (a_1, a_2, a_3)(+)(b_1, b_2, b_3) = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \quad (2)$$

$$\tilde{A}(-)\tilde{B} = (a_1, a_2, a_3)(-)(b_1, b_2, b_3) = (a_1 - b_1, a_2 - b_2, a_3 - b_3) \quad (3)$$

$$\widetilde{A}(\times)\widetilde{B} = (a_1, a_2, a_3)(\times)(b_1, b_2, b_3) = (a_1 b_1, a_2 b_2, a_3 b_3) \quad (4)$$

$$\widetilde{A}(\div)\widetilde{B} = (a_1, a_2, a_3)(\div)(b_1, b_2, b_3) = (a_1/b_1, a_2/b_2, a_3/b_3) \quad (5)$$

Normalization of fuzzy numbers using the "crisp score" method $\widetilde{\varpi}_{ij}^{k} = \left(a_{1ij}^{k}, a_{2ij}^{k}, a_{3ij}^{k}\right)$ shows the impact of criterion i on criterion j based on expert opinions. Normalization, Equation 6-9;

$$x a_{1ij}^{k} = \left(a_{1ij}^{k} - \min a_{1ij}^{k}\right)/\Delta_{\min}^{\max} \quad (6)$$

$$x a_{2ij}^{k} = \left(a_{2ij}^{k} - \min a_{2ij}^{k}\right)/\Delta_{\min}^{\max} \quad (7)$$

$$x a_{3ij}^{k} = \left(a_{3ij}^{k} - \min a_{3ij}^{k}\right)/\Delta_{\min}^{\max} \quad (8)$$

$$\Delta_{\min}^{\max} = \max r_{ij}^{n} - \min l_{ij}^{n} \quad (9)$$

Left (ls) and right (rs) normalized values, Equations 10 and 11;

$$xls_{ij}^{k} = xa_{2ij}^{k}/\left(1 + xa_{2ij}^{k} - xa_{1ij}^{k}\right) \quad (10)$$

$$xls_{ij}^{k} = xa_{3ij}^{k}/\left(1 + xa_{3ij}^{k} - xa_{2ij}^{k}\right) \quad (11)$$

Calculation of Crisp values, Equation 12 and 13;

$$x_{ij}^{k} = \left[xls_{ij}^{k}\left(1 - xls_{ij}^{k}\right) + xrs_{ij}^{k} \times xrs_{ij}^{n}\right]/\left(1 - xls_{ij}^{k} + xrs_{ij}^{k}\right) \quad (12)$$

$$\widetilde{\varpi}_{ij}^{k} = \min a_{ij}^{n} + x_{ij}^{n}\Delta_{\min}^{\max} \quad (13)$$

Integrating the surveys conducted by k experts (14),

$$\widetilde{\varpi}_{ij}^{k} = 1/k\left(\widetilde{\varpi}_{ij}^{1} + \widetilde{\varpi}_{ij}^{2} + \ldots + \widetilde{\varpi}_{ij}^{k}\right) \quad (14)$$

2.2. Fuzzy DEMATEL Method

The DEMATEL method is a powerful technique for elucidating cause-effect relationships and interdependencies within complex systems, which offers a suitable approach to unraveling this complexity. By assigning not only weights to criteria but also quantifying their interrelationships, DEMATEL provides a more comprehensive analysis. Furthermore, its visual representation of intricate relationships enhances understanding and facilitates the interpretation and communication of findings to decision-makers.

In this method, the problems are first determined, the relationship coefficients between these problems are assigned, necessary matrices are calculated, and their graphs are drawn. The most important thing here is that determination of problems and assignment of coefficients are done by experts. For this purpose, various fuzzy DEMATEL methods have been proposed using the fuzzy set approach. In this study, instead of coefficients 0, 1, 2, 3, and 4, coefficients (0.0, 0.0, 0.25), (0.25, 0.50, 0.75) were used, as shown in Table 1 [29].

The selection of triangular fuzzy logic within the DEMATEL method offers significant advantages due to its computational efficiency, simplicity, and ability to address uncertainty in expert assessments. Triangular fuzzy numbers provide a structured yet flexible means of representing subjective judgments,

Table 1. *Fuzzy scale*

Linguistic expressions	Triangular fuzzy numbers
Little effective	(0.00; 0.00; 0.25)
Less effective	(0.00; 0.25; 0.50)
Normal effective	(0.25; 0.50; 0.75)
Very efficient	(0.50; 0.75; 1.00)
Too effective	(0.75; 1.00; 1.00)

effectively capturing variations in expert opinions while maintaining a relatively low computational burden. Their linear nature facilitates both interpretation and application, making them particularly suitable for decision-making scenarios where precise numerical values are difficult to obtain. Furthermore, utilizing Excel for the crisp score method enhances accessibility and ease of implementation, enabling efficient analysis while preserving methodological rigor. This integration strengthens the reliability and interpretability of the DEMATEL method, ensuring its applicability across diverse domains [40].

During the analysis, four experts who gained experience by working as oceangoing chief engineers on different types of ships, were asked to give their opinions about separator failures and to determine the importance of these failures. Each of the experts whose opinions were received has 10 or more years of experience. The first expert has twelve years of experience as a chief engineer, the second expert has twenty-eight years of experience as a chief engineer, the third expert has five years of experience as a chief engineer and ten years of experience as a separator service engineer, and the fourth expert has seven years of experience as a chief engineer and six years of experience as a machine inspector. Figure 3.

In the third step, a direct relationship matrix A = n×n is created by using triangular fuzzy numbers and comparing the factors, as shown in Equation 15. It also T_{ij} indicates the degree to which factor i affects factor j.

$$A = \left[t_{ij}\right]_{n\times n} \quad (15)$$

Subsequently, based on the direct relationship matrix A, the normalized relationship matrix S is determined by the

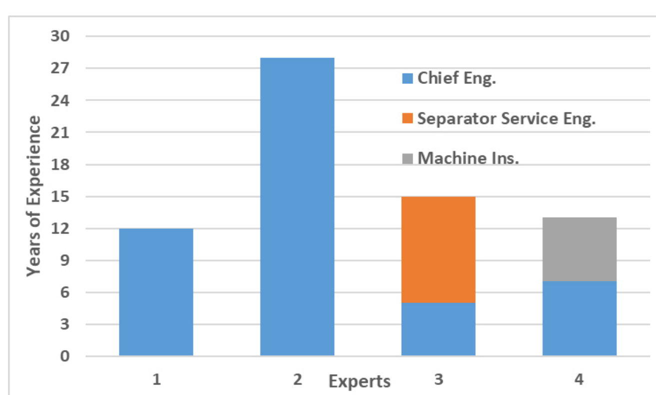

Figure 3. *Years of experience of experts*

following calculation: (k experts) Equations 16 and 17 in the fourth step.

$$S = k \times A \tag{16}$$

$$k = \frac{1}{\max_{1\le i\le n} \sum_{j=1}^{n} aij} \tag{17}$$

In the fifth step, the total relationship matrix T is obtained through the operation of the normalized relationship matrix S with identity matrix I, as given by Equation 18.

$$T=S\,(I - S)^{-1} \tag{18}$$

In the sixth step, the D and R vectors are obtained by adding the rows and columns in the total relationship matrix: Equations 19-21. To create a cause-effect graph, (D-R) and (D + R) vectors must be placed on a graph. In this graph, the horizontal axis D+R indicates "Importance" and the vertical axis D-R indicates "Relationship." If D-R is greater than 0, it indicates a particular outcome; if it is less than 0, it suggests a different result.

$$T = \left[t_{ij}\right]_{n\times n},\ i,j=1,2,\ldots,n. \tag{19}$$

$$D = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n} = \left[t_i\right]_{n\times 1} \tag{20}$$

$$R = \left[\sum_{j=1}^{n} t_{ij}\right]_{1\times n} = \left[t_j\right]_{n\times 1} \tag{21}$$

Finally, the importance weights are calculated by applying the obtained D and R values to Equations 22 and 23 in the seventh step.

$$w_i = \left\{\left(\tilde{D}_i^{def} + \tilde{R}_i^{def}\right)^2 + \left(\tilde{D}_i^{def} - \tilde{R}_i^{def}\right)^2\right\}^{\frac{1}{2}} \tag{22}$$

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \tag{23}$$

3. Results and Discussion

Experts' opinions were sought to explain the reasons for the 20 selected faults. When the fault notification section of the separator is examined, more faults can be seen. However, experts agree that these faults are interconnected. For example, if the electric motor that enables the separator to operate does not receive any electricity (the cable may be broken), this is not considered a fault caused by the operation of the separator. However, if the electric motor does not receive electricity at the correct frequency, the separator will initially operate for a short time, but then the motor will burn out. Consequently, the separator will not operate properly and, eventually, cause it to fail.

For some other cases, experts' opinions are as follows. The maximum bending distance of the separator shaft is 0.04 mm. If this shaft bending remains unnoticed, because the vibration occurring during the operation of the separator will cause the lower and upper bearings that support the shaft, or the rubber buffers connected to the upper bearing and the lower bearing, to deteriorate. These situations actually trigger each other. It is not known whether the real failure is due to the bending of the separator shaft or the deterioration of one of the upper or lower bearings. Since it is equipment consisting of parts that frequently interact and are interconnected, the root causes of failures in machines such as separators are not easily determined. In line with the most experienced events, the root causes of the most frequently encountered failures have been identified. To determine the parts and elements that cause or may cause failure in separators based on manufacturer manuals and expert experiences, the 20 factors in Table 3 can be identified [3].

Table 2. *DEMATEL method analysis steps*

Step	Definition
1	Determining the purpose of the problem and establishing the decision group
2	Determination of criteria and creation of fuzzy scales
3	Decision makers evaluate the bilateral relationships between factors and create a direct relationship matrix
4	Creation of normalized direct relationship matrix
5	Creating the total relationship matrix
6	Creating the impact-factor graph
7	Calculation of importance weights

Table 3. *Possible separator failures [3]*

C1	Wear or lubrication of friction elements	C11	Bowl shaft bending
C2	Belt tension is too weak or it is slipping	C12	Overheating, wear of the upper and/or lower bearing
C3	Electric motor failure	C13	Defect of shaft upper bearing rubber damper
C4	Incorrect energy supply	C14	Unbalanced waste sediment within the waste area
C5	Bearing deformation or wear	C15	Very low oil level in oil tank
C6	50 Hz pulley powered by 60 Hz power supply	C16	Incorrect power transfer or frequency supply
C7	High position of paring disc incorrect	C17	Bowl does not close or leaks
C8	Bowl imbalance**	C18	Bowl casing drain obstructed
C9	Height adjustment of paring disc is incorrect	C19	Upper bearing leak
C10	Vibration dampers in frame feet worn out	C20	Condensation

The total number of failures identified was 20, and details such as poor cleaning, improper assembly, insufficient disc, bowl tightness, and incompatibility of separator parts were stated for C8 Bowl imbalance (**). At the end of the evaluations, four matrices were obtained and converted from linguistic expressions into fuzzy number matrices, as shown in Table 4. Each expert created the matrices, which are presented as real examples in Table 3, by determining the degree of influence of the criteria on each other using the triangular fuzzy scale in Table 1.

In line with the information provided by the experts, a 20×20 matrix was created, and solutions were derived by applying Equations 9, 11, 12, 13, and 14. The direct-relationship matrix in Table 5, was created by averaging the values.

In the fourth step, the normalized direct relationship matrix in Table 6 was formed as a result of calculations 2 and 3, using the direct relationship matrix.

The normalized relationship matrix was processed with the number four, and the Table 7 was established.

When formulas 5, 6, and 7 were applied to the total relationship matrix, the D, R, D+R, and D-R values were shown in Table 8.

Using the values in Table 8, the (D+R)-(D-R) cause-effect factor relationship graph is shown in Figure 4. It can be seen that C1, C5, C8, C10, C11, C12, C13, C19, and C20, which have the highest D+R value above 0, are of the highest importance. It is observed that the D+R values remaining above zero have the highest value and importance. To mention these, C5 "bearing damage or wear", C12 "upper and/or lower bearing overheated, damaged or worn", C11 "bowl shaft bending", C8 "bowl imbalance", C13 "shaft upper bearing rubber damper defect", C18 "bowl casing drain obstructed", C10 "vibration dampers in frame feet worn out", C19 "upper bearing leakage", and C16 "incorrect power transmission or frequency supply (50/60 Hz)". As can be seen, bearing wear is of the highest importance. C5 is considered bearing wear. C12 is considered to be the wear of one of the upper or lower bearings, and it indicates that the bearing for the shaft has started to weaken. C11 shows that the bearings have started to deteriorate due to the bending of the shaft. Since more force will be created in the bearings due to the centrifugal effect because of the high-speed rotation of the shaft, the bearings will start to deteriorate. C8, bowl imbalance, is caused by inadequate and improper separator maintenance. Therefore, the separator will operate with excessive vibration, will not be able to perform sufficient separation, and will wear the bearings and cause failure. C13 identifies a defect in the shaft upper bearing rubber damper. Due to the loss of the rubber damper feature, the separator will start to wear the upper bearing, resulting from the hard closing of the bowl caused by the opening and closing of water while the solid waste and water outlet is discharged. Eventually, it will wear the lower bearing and cause the shaft to bend. C18: The bowl casing drain is obstructed due to the blockage of the solid waste and water outlet of the separator. Consequently, the amount of used oil/fuel in the bowl will increase as it cannot clean

Table 4. *Fuzzy number matrices*

	C1	C2	C3	…	C18	C19	C20
C1	(1.00;1.00;1.00)	(0.50;0.75;1.00)	(0.50;0.75;1.00)	…	(0.00;0.25;0.50)	(0.50;0.75;1.00)	(0.00;0.00;0.25)
C2	(0.00;0.00;0.25)	(1.00;1.00;1.00)	(0.00;0.25;0.50)	…	(0.25;0.50;0.75)	(0.25;0.50;0.75)	(0.25;0.50;0.75)
C3	(0.00;0.00;0.25)	(0.00;0.00;0.25)	(1.00;1.00;1.00)	…	(0.00;0.00;0.25)	(0.00;0.00;0.25)	(0.00;0.00;0.25)
…	…	…	…	…	…	…	…
C18	(0.00;0.25;0.50)	(0.00;0.00;0.25)	(0.00;0.00;0.25)	…	(1.00;1.00;1.00)	(0.50;0.75;1.00)	(0.50;0.75;1.00)
C19	(0.00;0.00;0.25)	(0.00;0.00;0.25)	(0.00;0.00;0.25)	…	(0.00;0.00;0.25)	(1.00;1.00;1.00)	(0.50;0.75;1.00)
C20	(0.00;0.00;0.25)	(0.00;0.00;0.25)	(0.00;0.00;0.25)	…	(0.00;0.00;0.25)	(0.00;0.00;0.25)	(1.00;1.00;1.00)

Table 5. *Direct relationship matrix*

	C1	C2	C3	…	C18	C19	C20
C1	1.00	0.57	0.51	…	0.71	0.97	0.00
C2	0.00	1.00	0.21	…	0.36	0.29	0.64
C3	0.16	0.28	1.00	…	0.00	0.00	0.00
…	…	…	…	…	…	…	…
C18	0.21	0.00	0.00	…	1.00	0.97	1.02
C19	0.00	0.00	0.00	…	0.00	1.14	1.02
C20	0.00	0.00	0.00	…	0.00	0.00	1.90

Table 6. *Normalized direct relationship matrix*

	C1	C2	C3	…	C18	C19	C20
C1	0.10	0.05	0.05	…	0.02	0.09	0.00
C2	0.00	0.10	0.02	…	0.03	0.03	0.06
C3	0.02	0.03	0.10	…	0.00	0.00	0.00
…	…	…	…	…	…	…	…
C18	0.02	0.00	0.00	…	0.10	0.09	0.10
C19	0.00	0.00	0.00	…	0.00	0.11	0.10
C20	0.00	0.00	0.00	…	0.00	0.00	0.18

itself sufficiently. Therefore, the separator will first work with the increased oil/fuel, as mentioned, then it will become tightly covered with solid waste, which will cause damage to its bearings. The C10 vibration dampers in the frame feet are worn out. During the first operation of the separator, the adhesion of the friction elements inside the electric motor causes vibration in the separator until its speed stabilizes. Worn-out vibration dampers in frame feet provide a balance by damping this vibration. If the vibration damper is worn out, it will not be able to dampen the vibration during the operation of the separator. It will transmit the centrifugal force on the shaft and bowls to the bearings, causing damage to them. C19 upper bearing leakage is a part of the separator.

Table 7. *Total relationship matrix*

	C1	C2	C3	…	C18	C19	C20
C1	0.15	0.11	0.09	…	0.27	0.19	0.20
C2	0.02	0.12	0.04	…	0.34	0.23	0.26
C3	0.03	0.04	0.11	…	0.10	0.10	0.16
…	…	…	…	…	…	…	…
C18	0.07	0.05	0.03	…	0.14	0.19	0.28
C19	0.01	0.01	0.01	…	0.01	0.15	0.14
C20	0.01	0.01	0.01	…	0.00	0.02	0.23

Table 8. *Crisp values*

	D	R	D+R	D-R
C1	1.8	1.2	2.9	0.6
C2	1.0	1.2	2.2	-0.2
C3	0.5	1.0	1.5	-0.5
C4	2.2	0.4	2.6	1.9
C5	1.5	2.6	4.0	-1.1
C6	1.4	0.3	1.7	1.1
C7	0.9	0.1	1.0	0.8
C8	1.7	1.6	3.3	0.0
C9	0.6	0.2	0.8	0.4
C10	0.7	2.2	2.9	-1.5
C11	1.4	2.0	3,4	-0.7
C12	1.2	2.6	3.8	-1.4
C13	1.0	2.2	3.2	-1.1
C14	1.5	1.1	2.6	0.4
C15	0.8	0.2	0.9	0.6
C16	2.4	0.3	2.7	2.1
C17	1.2	1,2	2.4	0.0
C18	1.9	1.0	2.9	1.0
C19	0.7	2.1	2.8	-1.4
C20	0.5	1.6	2.1	-1.1

It is where the bowl part and the shaft part are separated from each other and an O-ring is used as a sealing element. If this O-ring has lost its sealing feature, the used oil/fuel will leak into the shaft part, causing the shaft to slip in the bearings. It may mix with the oil in the chamber where the lower bearing is located, spoil the properties of the oil, or prevent the separator from turning over by causing the belt to become over-lubricated due to excess oil splashing. Regarding issue C16, incorrect power transmission or frequency supply (50/60 Hz), it is important that the electricity supplied to the motor enabling the separator to operate is at the appropriate voltage and frequency. If it is supplied at an incorrect frequency or voltage, even if it operates the separator, it will damage the electric motor, and it will not be able to operate properly.

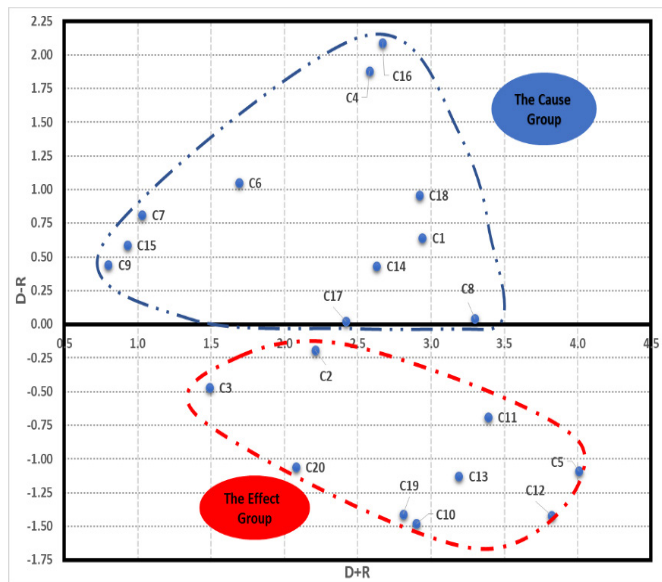

Figure 4. *Cause-effect factors relationship graph*

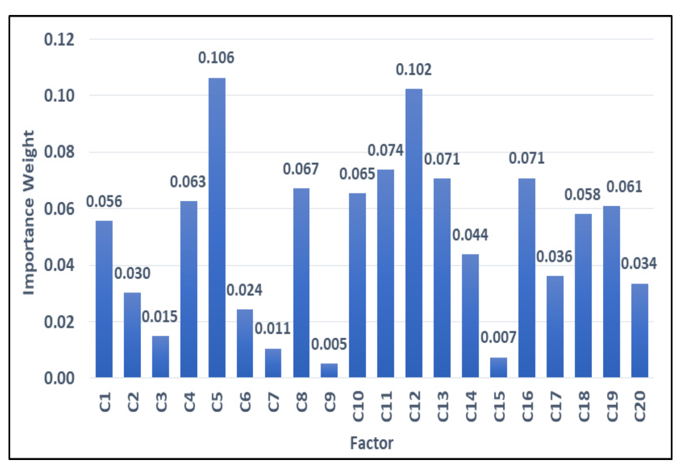

Figure 5. *Importance weights of factors*

It is seen that the values where D-R values are above zero affect other factors more. These are C16 [incorrect power transmission or frequency supply (50/60 Hz)], C4 [incorrect power supply (50 Hz instead of 60 Hz)], C6 (50 Hz pulley operating with 60 Hz power supply), C18 (bowl casing drain obstructed), C7 (high position of paring disc incorrect), C1 (friction elements worn or oily) and C15 (oil level in oil case is too low). As seen in the examination, it is very important to provide the voltage and frequency of the electricity to be given to the electric motor that will operate the separator correctly. Failure to supply electricity or incorrect supply will cause the separator not to work at all or to work incorrectly. After the correct electricity is supplied to the electric motor, it is important for the electric motor to transfer its rotational energy to the separator with the correct pulley in order to ensure the correct speed of the separator and separation. After the separator is running, if the outlet part of the separator is clogged, the separation will not be healthy since the separator will not be able to clean itself and the control unit will be warned via the outlet pressure of the separator, causing the separator to stop itself. If the high position of paring disc is incorrect, the separator will not be able to create outlet pressure while it is running and will release used oil/fuel, solid waste and water to the outlet, and will send a signal to the control unit to stop itself. If the friction elements are worn or oily, the friction elements will not be able to fully adhere to the pulley during the rotation of the electric motor and will not be able to fully transfer the speed which is needed to achieve proper revolution. For this reason, the separator will not be able to provide the speed required for separation and will release used oil/fuel to the solid waste and water outlet. If the oil level in the oil case is very low, there will be no problem in the separator operation at first, but later, since there will be insufficient lubrication and cooling in the lower bearing, the bearing will deteriorate very quickly. This will create vibration in the operation of the separator, causing the upper bearing to deteriorate via the shaft and finally the shaft to deteriorate.

Finally, the importance weights of the factors resulting from the calculations in step 7 are presented in Figure 5. In this case, those with the highest importance are C1, C5, C8, C10, C11, C12, C13, C18, and C19. The wear or lubrication of friction elements, deformation or wear of bearings, bowl imbalance, wear of vibration dampers in frame feet, bowl shaft bending, overheating, deformation or wear of upper and/or lower bearings, defect of the upper shaft bearing rubber damper, bowl casing drain obstructed, and upper bearing leakage were found to be of the highest importance. Here, the important factor is the experience gained by the experts owing to the failure they encountered, which is the reason for the different results between the importance weights. C20, C19, C13, C12, C10, and C5 were also affected by the other criteria. These are condensation, upper bearing leakage, defects of the shaft upper bearing rubber damper, overheating, deformation or wear of the upper and/or lower bearings, wear of the vibration dampers in the frame feet, and deformation or wear of the bearings. Separators are very sensitive equipment that consecutive parts inside affect each other. As can be seen here, while bearings can cause other failures, they are also the parts most quickly affected by incorrect assembly and imbalance in the bowl.

4. Conclusion

It is difficult to state a clear root cause for machines consisting of many interconnected parts, such as separators. Because the parts that make up the separator are interconnected and damage to any one of these parts will cause damage to the others. Separators are equipment that enable the ship to sail smoothly, ensure long-term operation of the machines like main engine and auxiliary generator, increase their performance, prevent the wear of materials such as fuel pumps and injectors, where fuel is actively used in the main engine and auxiliary generator, and make profits in the long term. Therefore, it should not be considered as fuel. The active operation of oil separators protects the moving parts of the machines and prevents damage to its crankshaft.

The C8 separator encompasses various parameters that can influence its operational efficiency, including bowl imbalance, contamination, and assembly inaccuracies. To ensure optimal performance, it is essential to adhere to the maintenance schedules specified by the manufacturer for the separators. Drawing on expert experience, several critical maintenance practices should be emphasized: regular replacement of bearings, thorough cleaning of the bowl, precise assembly with appropriate measurements, and conducting inspections at intervals established by the manufacturer. A significant concern in the operation of separators is the heightened risk of equipment failures resulting from assembly errors. Given the intricate design of separators, where numerous components are interrelated and rotate at high speed, even minor discrepancies in assembly or balance can lead to inadequate cleaning performance. Such deficiencies not only compromise the efficacy of the equipment but may also accelerate wear and deformation of the components. When the importance weight is examined, it can be seen that the factors C5 (bearing deformation or wear) and C12 (overheating, deformation or wear of the upper and/or lower bearings) are of high importance. According to the experience of experts, two factors of this importance are stated that it is known that C5 and others, which have the highest value and importance, will actually cause failures that will affect each other if the maintenance is not performed according to the manufacturer's recommendation, within the maintenance hours, with original spare parts and by authorized crew.

The factors that affect the other criteria are C16 [incorrect power transfer or frequency supply (50/60 Hz)] and C4 [incorrect energy supply (instead of 50 Hz, 60 Hz)], which will cause the equipment to not work properly, so there will be no efficiency from the separator and the equipment will be damaged. C16 and others, which have the most effect on other factors, cause the electric motor of the separator to fail to operate at all or to operate inadequately due to the lack of appropriate electricity or frequency to the electric motor that will enable the separator to operate. In addition, it is seen that the correct electrical voltage and frequency to the electric motor, the suitability of the friction elements in the electric motor and finally the harmony of the transmission element connecting the electric motor to the shaft of the separator have a high effect on the efficient operation of the separator. The factor most affected by the other criteria is C10, that is, vibration dampers in frame feet worn out. It is stated that the separator is the most affected factor as the balancing force acts on the vibration dampers in the frame feet to constantly balance even the smallest vibration during the initial start-up, stopping, and rocking of the ship in the wavy sea.

Generally, the situation seen by the experts in the application field is expressed as follows. The maintenance manual is not read sufficiently and due to this, the separator is maintained after more running hours, the spare parts are not used originally, the separator is repaired with the wrong spare parts due to the wrong material demand, the separation process is not effective or cannot be separated at all due to the installation of O-rings in the wrong place during maintenance. It is very difficult to diagnose failure due to inadequate cleaning of the maintained parts. In the future, separators produced for ships can be mounted with magnetic frame legs without being fixed to the ship. In addition, oil and fuel separators to be used on ships can be produced by creating an electromagnetic field or using a geared electric motor of an appropriate diameter instead of the bearings used in the separators. By this way, the most important causes of failure, determined according to expert opinions, are prevented. Subsequent research will focus on developing comprehensive maintenance manuals integrating expert insights and technological advancements to minimize separator failures.

Footnotes

Authorship Contributions

Concept design: S. Ayvaz, and A. S. Karakurt, Data Collection or Processing: S. Ayvaz, and A. S. Karakurt, Analysis or Interpretation: S. Ayvaz, Literature Review: S. Ayvaz, and A. S. Karakurt, Writing, Reviewing and Editing: A. S. Karakurt.

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