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Evaluation of Critical Operational Faults of Marine Diesel Generator Engines by Using DEMATEL Method

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Abstract

All the electrical demand of ship are provided by diesel generators (DG). Failure of generators due to breakdown can lead to the blackout of the ship which may suddenly cause serious damage to ship's main and/or auxiliary engines, human health and marine environment or any structure at ship's route. Thus, the planned maintenance and repairs of the generators must be done properly without any deficiency or delay. And even then, since the generators run continuously failures may often occur. In this context, this paper provides a DEMATEL (Decision Making Trial and Evaluation Laboratory) method to evaluate the critical operational faults in marine DGs. The DEMATEL method enables to identify and analyze the important faults of marine DG within the respect to the cause-effect relationship diagram. The obtained results of the research will contribute to ship safety at sea and prevention of hazardous machinery effects.

Keywords: *Marine Diesel Generator Engine, DEMATEL, Ship, Machinery Faults.*

Gemi Dizel Jeneratörlerinde Kritik Operasyonel Arızaların DEMATEL Metoduyla Değerlendirilmesi

Öz

Geminin tüm elektriksel gereksinimleri dizel jeneratörler tarafından sağlanmaktadır. Jeneratörlerde meydana gelen arızalar geminin kararmasına (çökmesine) neden olabilir ve bu durum aniden gemi ana makinesi veya yardımcı makinelerinde, insan sağlığına, deniz çevresine veya geminin rotasındaki herhangi bir yapıya ciddi hasarlar verebilir. Bu yüzden, jeneratörlerin planlı bakım ve onarımları düzgün bir şekilde eksiksiz ve zamanında yapılmalıdır. Tüm bunlara rağmen, sürekli çalışan jeneratörlerde arızalar olabilmektedir. Bu kapsamda, bu makale gemi dizel jeneratörlerinde kritik operasyonel arızaları DEMATEL (Karar Verme Deneme ve Değerlendirme Laboratuvarı) metoduyla sunmaktadır. DEMATEL metodu gemi dizel motorlarında meydana gelen önemli arızaları sebep-etki ilişkisi diyagramıyla tanımlanma ve analiz etmeye yaramaktadır. Elde edilen sonuçlar, denizde gemi emniyeti ve tehlikeli makine etkilerinin önlenmesine katkıda bulunacaktır.

Anahtar Kelimeler: *Gemi Dizel Motoru, DEMATEL, Gemi, Makine Arızaları.*

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1. Introduction

In many parts of the ships, especially in the engine rooms, there are "SAFETY FIRST" signs. This means that the safety is the most important concept in ship operations since the consequences of any fault at ship engine(s) may cause irreversible damage to human life, engines as well as cargo aboard ship. International Maritime Organization (IMO) [1], known as the rule-making organization in the maritime sector, has issued many rules and conventions related to safety. The prominent ones are; The International Convention on Standard of Training Certification and Watchkeeping for Seafarer (STCW), The International Convention for the Safety of Life at Sea (SOLAS) and The Convention on the Prevention of Maritime Pollution (MARPOL). However, despite these rules, in the literature, many problems that harm both human health and the environment continue to arise as reported[2]–[5]. Many studies are conducted on the detection of these failures [6]–[10]. The DEMATEL method is also concluded in these studies[11], [12]. Emovon et al. [13] used an averaging technique to include indefinite information acquired from experts to apply solution methods for risk in marine engines. Xi et al. [14] investigated the real observed during the maritime operations on the shores of Shanghai and conducted case studies by Cognitive Reliability Error Analysis Method (CREAM) and DEMATEL method. In the thesis of Emovon [15]various techniques to develop tools for supporting the Reliability Centred Maintenance (RCM) methodology and enhance its efficacy in marine maintenance system applications are presented. Akyuz et al [16] carried out a quantitative ship's fire safety system deficiency analysis with Fuzzy Failure Mode and Effects Analysis (FMEA). Saatçıoğlu et al [17] studied ship engine room casualty analysis by using decision tree method (DTM) to find the frequent faults in engine room. Mullai and Paulsson [18] designed a conceptual model for analyzing marine accidents by using Structural Equation Modeling (SEM) approach. Nguyen [19] performed an application of analytic hierarchy process (AHP) for estimating risks in ship systems based on the data acquired from experts. Özdemir [20] investigated the causes of occupational accidents that took place in ports and the precautions to be taken by using DEMATEL and TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) methods. Even though the DEMATEL is well known and used in many areas like other methods, such approaches are not common in marine sector problems. Therefore, this study will close the gap of maritime literature. Apart from the prior studies, in this study it is aimed to determine the frequent occurrences of faults in the ship's diesel generator and the relationship among faults and effects by using DEMATEL method.

This paper is organized as follows: the research methodology is presented in section 2. Section 3 describes problems and application of the study by including subsections. The final conclusion of this work is given in section 4.

2. Research Methodology

The DEMATEL technique is presented to solve complex and comprehensive decision-making problems [21]. DEMATEL has been generally recognized as one of the practical tools to get the cause and effect relationship between the assessments criteria [22]. It is essentially based on the graph theory which allows investigating and explaining problems by visualization [23]. The method reveals the mutual relationship and the values of influential effect among all the criteria. The fundamental steps of DEMATEL method are briefly described as follows.

Step 1: First step is to build an initial direct-relational matrix for pair-wise comparison of the factors. A group of decision-makers who have profound knowledge and experience about the problem is acquired. Then, they are required to assess the direct effect among each pair of fault factors. The linguistic assessments are converted to numerical values. Consequently, the direct-relation matrix is obtained. A = [a_{ij}] where A is a *nxn* non-negative matrix, a_{ij} represents the direct effect of factor *i* on factor *j*; and when *i* = *j*, the diagonal elements a_{ij} = 0.

Step 2: Secondly, the initial direct-relation matrix is normalized by comparing factors in the same way. The normalized direct-relation matrix *D* = [d_{ij}], can be acquired through an equation (1). All elements in matrix *D* are complying with $0 \leq d_{ij} \leq 1$, and all principal diagonal elements are equal to zero.

$$D = \frac{1}{\max_{1 \leq i \leq n} \sum_{j=1}^{n} a_{ij}} \quad (1)$$

Step 3: The total-relation matrix (*T*) is calculated by using the equation (*2*) where *I* denotes *nxn* identity matrix. The element t_{ij} shows the indirect effects that criterion *i* have on criterion *j*, so that the matrix *T* gives the total relationship among each pair of factors.

$$T=D(I-D)^{-1} \quad (2)$$

Step 4: The sum of rows and columns of matrix *T* is calculated. r_i and c_j are resolved according to the equations (*3*) and (*4*) respectively. In the formula, while r_i denotes all direct and indirect influence given by criterion *i* to all other factors, c_j denotes the degree of influenced effect.

$$r_i = \sum_{1 \leq j \leq n} t_{ij} \quad (3)$$

$$c_j = \sum_{1 \leq i \leq n} t_{ij} \quad (4)$$

When *i* = *j*, r_i+c_j shows all effects are given and received by criterion *i*. That is to say, r_i+c_j expresses both criteria *i*'s impact on the whole system and other system factors impact on factor *i*. So, the indicator r_i+c_j may show the degree of significance that criterion *i* plays in the total system. Contrariwise, the difference of the two, r_i-c_j, presents the net effect that criterion *i* has on the system. Particularly, if the value of r_i-c_j is positive, the factor *i* is a net cause, exposing net causal effect on the system. When r_i-c_j is negative, the factor is a net result gathered into effect group [24], [25].

Step 5: In the latest step, a cause and effect relationship diagram is illustrated according to r_i+c_j and r_i-c_j. Therefore, the complex interrelationship among factors is visualized through the diagram.

3. Evaluation of Critical Operational Failures of Marine Diesel Generator Engines

In this section, DEMATEL approach is applied to evaluate and understand the causes of faults in generators and the interactions of faults with each other. In this way, the relation of the systems to each other will be understood more clearly.

Due to limited knowledge and academic work related to the subject in the literature, relevant marine experts have been consulted. Increasing the number of experts is important for the results of the method to be more precise. In our study, only common problems are mentioned. The handling of all problems may be more useful for literature.

3.1. Problem Description

Considering ship DGs, some failures such as starting the generator for the first time, stopping, irregular operation, and problems in some cylinders, in lubrication oil, fresh water cooling cycle and in exhaust outlet are some of the troubles. The most common causes of these situations have been identified. In this context, Table 1 shows critical operational faults in marine DGs. In the Table 1, C denotes faults.

Table 1. *Most Common Faults in DG Engine*

Fault Code	Description
C1	Piston is seized.
C2	The bearings are tightened much above the nominal torque values.
C3	There are unknown objects in the cylinder.
C4	There is a fault in the starting system. The start air reservoirs are under low pressure or the air dryer is faulty and air moist or there is a problem with relay valve.
C5	There is a fault in electrical, electronic systems or starter motor.
C6	The crankshaft cannot rotate at a sufficient speed
C7	Lubrication oil temperature is too high.
C8	Fuel injection is not occurring. There is a problem with the injector(s).
C9	The fuel has poor quality.
C10	Insufficient amount of fuel goes to the cylinders.
C11	The exhaust cannot be thrown.
C12	Pistons or beds are suddenly seized
C13	Fuel filters are plugged.
C14	Combustion does not occur in at least one of the cylinders.
C15	The turbine is surging.
C16	The generator engine cannot be cooled sufficiently.
C17	The governor has advanced all the indexes to the end.
C18	Dense amount of fuel dribbled from the injector.
C19	Oil or fuel is mixed into the intake air.
C20	There is a problem with the cylinder's fuel pump.
C21	The cylinder's injection lance (pipe) is clogged.
C22	The tip of the cylinder injectors is covered with carbon.
C23	There are intense leaks in the valves.
C24	The pressure measuring manometer is defective in the relevant circuit. (for low pressure of cooling oil or water)
C25	The filter of the corresponding station is blocked. (for low pressure of cooling oil or water)
C26	There is a leak in the relevant circuit. (for low pressure of cooling oil or water)
C27	The thermocouple is defective.
C28	There is a problem with cylinder cooling.
C29	There is a problem with fuel advance.
C30	Fuel index and VIT have problems.
C31	The machine is overloaded and the load is fluctuating.
C32	The piston rings are completely worn.
C33	Fuel injection advance has problem.

3.2. Evaluation of Respondents

Because of the limited data in marine industry, experts' judgements are preferred commonly. On ships, there are chief engineers, second engineers and third engineers responsible from ships all engines and machineries. The chief engineer is responsible for all the work in the engine room, and the job is shared among the engineers. Under the supervision of chief engineer, most of the operations are carried out by the second engineer and the third engineer. The third engineer is responsible for the maintenance and repair of the DGs, one of the important auxiliary engines at the ship. Likewise, the compressors are the third engineer's responsibility. Because of the experience of the chief engineers, two of our experts were selected as chief engineers with at least 5 years of experience as chief engineer and one of them was selected as experienced third engineer which also have MSc degree. The problems encountered in the DG were asked to these 3 experts and the relationship between the probable causes and reasons and the effects of the causes on each other were examined.

It has been understood that the results of evaluating the answers given by the experts give overlapping results with the DEMATEL method.

3.3. Application of Proposed Method

First of all, the critical operational faults in marine DG are presented to the marine experts in order to investigate the interaction among each pair of critical faults as provided in Table 1. In accordance with the consensus of experts, Table 2 shows the aggregation matrix. Accordingly, Table 3 demonstrates the normalized decision matrix. Thereafter, Table 4 illustrates total-relation matrix. In the light of above outcomes, the crisp values of $\tilde{r}_i$, $\tilde{c}_j$, $\tilde{r}_i+\tilde{c}_j$, $\tilde{r}_i-\tilde{c}_j$ can be obtained as illustrated in Table 5. In the last stage, cause and effect relationship diagram can be depicted based on the above outcomes.

3.4. Findings

In the light of calculation of the r_i, c_j, r_i+c_j, r_i-c_j, Figure 1 shows the cause-effect relation diagram. According to the diagram, it may be necessary to divide the findings into two groups as causes and effects.

Table 2. *Aggregation Matrix*

	C1	C2	C3	C4	C5	...	C27	C28	C29	C30	C31	C32	C33
C1	0.00	0.33	2.33	0.00	0.00	...	0.00	4.00	1.67	2.00	1.67	4.00	2.00
C2	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C3	2.67	0.00	0.00	0.00	0.00	...	0.00	0.00	0.00	0.00	0.33	1.00	0.00
C4	0.00	0.00	0.00	0.00	0.33	...	0.00	1.33	0.00	0.00	0.67	0.00	0.00
C5	0.00	0.00	0.00	0.33	0.00	...	0.00	0.33	0.33	0.00	0.00	0.00	0.33
...	...	...	...	...	...	...	...	...	...	...	...	...	...
C27	0.00	0.00	0.00	0.00	0.00	...	0.00	1.33	0.00	0.00	0.67	0.67	0.00
C28	1.00	2.00	1.33	0.00	0.67	...	2.67	0.00	1.33	1.33	3.33	2.67	0.67
C29	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00	0.00	3.67	2.00	0.00	4.00
C30	0.00	0.00	0.00	0.00	0.00	...	0.00	0.67	1.67	0.00	3.00	1.00	3.33
C31	3.67	2.00	3.00	0.00	0.00	...	0.00	1.33	1.33	3.33	0.00	1.67	1.33
C32	3.67	0.00	3.00	0.00	0.00	...	0.00	2.67	1.33	1.33	2.33	0.00	1.00
C33	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00	3.67	3.67	3.33	1.33	0.00

Table 3. *Normalized Decision Matrix*

	C1	C2	C3	C4	C5	...	C27	C28	C29	C30	C31	C32	C33
C1	0.00	0.01	0.05	0.00	0.00	...	0.00	0.09	0.04	0.04	0.04	0.09	0.04
C2	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C3	0.06	0.00	0.00	0.00	0.00	...	0.00	0.00	0.00	0.00	0.01	0.02	0.00
C4	0.00	0.00	0.00	0.00	0.01	...	0.00	0.03	0.00	0.00	0.01	0.00	0.00
C5	0.00	0.00	0.00	0.01	0.00	...	0.00	0.01	0.01	0.00	0.00	0.00	0.01
...	...	...	...	...	...	...	...	...	...	...	...	...	...
C27	0.00	0.00	0.00	0.00	0.00	...	0.00	0.03	0.00	0.00	0.01	0.01	0.00
C28	0.02	0.04	0.03	0.00	0.01	...	0.06	0.00	0.03	0.03	0.07	0.06	0.01
C29	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00	0.00	0.08	0.04	0.00	0.09
C30	0.00	0.00	0.00	0.00	0.00	...	0.00	0.01	0.04	0.00	0.07	0.02	0.07
C31	0.08	0.04	0.07	0.00	0.00	...	0.00	0.03	0.03	0.07	0.00	0.04	0.03
C32	0.08	0.00	0.07	0.00	0.00	...	0.00	0.06	0.03	0.03	0.05	0.00	0.02
C33	0.00	0.00	0.00	0.00	0.00	...	0.00	0.00	0.08	0.08	0.07	0.03	0.00

Table 4. *Total Relation Matrix*

	C1	C2	C3	C4	C5	...	C27	C28	C29	C30	C31	C32	C33
C1	0.07	0.05	0.12	0.01	0.01	...	0.03	0.15	0.09	0.12	0.12	0.16	0.11
C2	0.01	0.00	0.01	0.00	0.00	...	0.00	0.01	0.00	0.00	0.01	0.01	0.00
C3	0.08	0.02	0.03	0.01	0.00	...	0.01	0.03	0.02	0.03	0.03	0.05	0.02
C4	0.01	0.01	0.02	0.01	0.01	...	0.01	0.04	0.01	0.02	0.03	0.02	0.01
C5	0.01	0.01	0.01	0.01	0.00	...	0.00	0.01	0.02	0.01	0.01	0.01	0.02
...	...	...	...	...	...	...	...	...	...	...	...	...	...
C27	0.01	0.01	0.01	0	0	...	0.01	0.04	0.01	0.01	0.03	0.03	0.01
C28	0.09	0.08	0.1	0.02	0.02	...	0.08	0.06	0.08	0.1	0.15	0.12	0.07
C29	0.04	0.02	0.04	0.01	0.01	...	0.01	0.03	0.05	0.15	0.1	0.04	0.14
C30	0.06	0.03	0.07	0.02	0.02	...	0.01	0.06	0.1	0.09	0.14	0.08	0.14
C31	0.14	0.07	0.13	0.02	0.01	...	0.02	0.08	0.09	0.15	0.08	0.1	0.09
C32	0.15	0.04	0.14	0.02	0.01	...	0.03	0.12	0.08	0.1	0.13	0.07	0.08
C33	0.04	0.02	0.05	0.01	0.01	...	0.01	0.03	0.12	0.14	0.13	0.07	0.06

3.4.1. Cause Factors

In order to asses the critical and operational faults in the course of DG operation, it is necessary to focus on the cause factor of fault analysis which requires more attention. In the view of Figure 1, C14 (Combustion does not occur in at least one of the cylinders) has the highest r_i-c_j value among the all factors in cause group. This means that C14 has more impact on the whole process. Afterwards, C17 (The governor has advanced all the indexes to the end) is the second most important causal factor since it ranks second place among the all factors. Consequently, it has huge impact on the entire DG operations. The third most important factor among the entire process is C7 (Lubrication oil temperature is too high) ranks third place among the process. Likewise, C10 (Insufficient amount of fuel

***Table 5.** Crisp Values of $\tilde{r}_i$, $\tilde{c}_j$, $\tilde{r}_i+\tilde{c}_j$, $\tilde{r}_i-\tilde{c}_j$*

	R_i	C_j	R_i+C_j	R_i-C_j		R_i	C_i	R_i+C_i	R_i-C_i
C1	2.49	1.79	4.28	0.70	**C18**	1.22	1.72	2.94	-0.51
C2	0.15	1.00	1.15	-0.85	**C19**	0.29	1.26	1.56	-0.97
C3	0.97	2.09	3.06	-1.12	**C20**	1.09	2.00	3.08	-0.91
C4	0.69	0.62	1.31	0.07	**C21**	1.09	1.43	2.52	-0.34
C5	0.37	0.41	0.79	-0.04	**C22**	1.62	1.46	3.09	0.16
C6	1.82	1.46	3.28	0.37	**C23**	0.86	0.96	1.82	-0.10
C7	3.00	1.77	4.77	1.23	**C24**	0.39	0.38	0.76	0.01
C8	1.75	1.81	3.56	-0.05	**C25**	0.84	2.34	3.18	-1.49
C9	0.88	2.69	3.56	-1.81	**C26**	1.14	1.67	2.82	-0.53
C10	2.41	1.37	3.78	1.03	**C27**	0.43	0.62	1.05	-0.18
C11	1.37	1.77	3.14	-0.39	**C28**	2.50	1.63	4.13	0.86
C12	2.65	2.42	5.08	0.23	**C29**	1.95	1.78	3.74	0.17
C13	1.00	1.79	2.78	-0.79	**C30**	2.61	2.43	5.04	0.18
C14	3.12	0.90	4.02	2.22	**C31**	2.47	2.33	4.80	0.14
C15	0.74	0.66	1.40	0.08	**C32**	2.47	1.98	4.45	0.49
C16	1.81	1.56	3.37	0.25	**C33**	1.90	2.02	3.92	-0.11
C17	3.39	1.39	4.78	2.01					

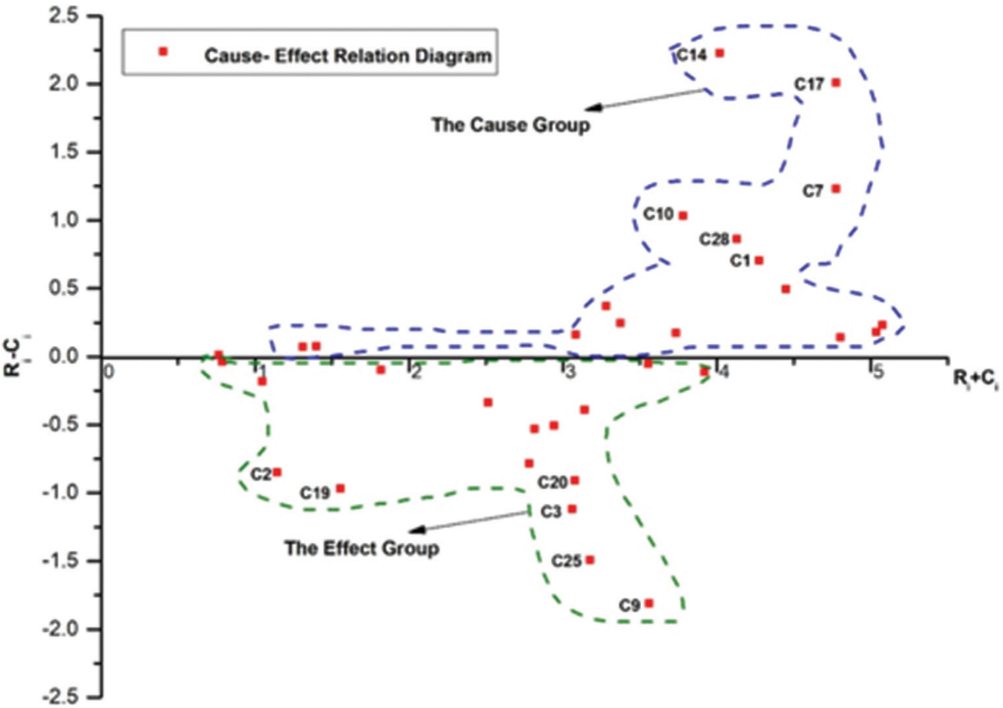

***Figure 1.** Cause-Effect Relation Diagram*

goes to the cylinders) is another important factor among the whole process. This order of importance continues in the form of C28 (There is a problem with cylinder cooling), C1 (seizure of piston) and C32 (The piston rings are completely worn). Other fault codes have relatively moderate-low influence on the DG operations since their r_i-c_j value as well as r_i values in the operations are not high enough.

3.4.2. Effect Factors

Although the influence factors of failures in diesel generators are influenced by other factors, they need to be investigated with great care because these effects can have very serious consequences in a chained way. With the guidance of the cause-effect relation diagram, results show that C33 (Fuel injection advance has problem) has the highest r_i+c_j value (3.92) among all effect factors. Moreover, it is degree of influential impact index (r_i) and influenced impact index (c_j) values (1.92; 2.02) are the quite high degree among the all process. The r_i-c_j value of C33 is close to the average value compared to other factors in the effect group, not very low. For this reason, it is understood that C33 has a significant effect on the other factors. Thereafter, C8 (Fuel injection is not occurring. There is a problem with the injectors) and C9 (The fuel has poor quality) have the second highest r_i+c_j values (3.56) among effect factors in the whole process. However, when C9's r_i-c_j value is investigated it can be seen that it is very low (-1.81) which means that it can easily be affected by the other factors. Also, when the cause- effect diagram data is examined, it is seen that C25 (The filter of the corresponding station is blocked for low pressure of cooling oil or water) comes in the third place (3.18) in terms of r_i+c_j values. As can be seen in the cause effect diagram, the rest of the factors have relatively moderate r_i+c_j values. Their r_i-c_j values are comparatively low which indicates a powerful influenced degree.

4. Conclusion

Safety and security measures at sea must be practiced to protect the environment, machines, and especially human life. In marine engines, planned maintenance and repair are therefore very important. If planned maintenance-repair is not done, many faults can be encountered. Rarely, unexpected failures can occur despite scheduled maintenance. A breakdown can sometimes have multiple causes and a breakdown can trigger another. For this reason, it is essential to know the ship auxiliary engine systems and their relation to each other. In this study, some failures in DGs have been analyzed. The first start of the DG, stopping of DG, the fuel system, the lubrication and cooling systems, the faults in some physical equipment etc. have been investigated. In terms of results, it is understood that, when the causes and effects are examined in case of faults in the DG, the fuel system and the combustion, lubrication and cooling systems are relatively more important in terms of the reasons. From the point of effects, it is seen that the most important ones are fuel injection advance, fuel injection, fuel quality and filtration. This study will help marine engineers, especially oceangoing engineers to understand the causes of common problems in DGs and their relationship to each other. For future work, by understanding the relation between problems occurring in DGs, it may be possible to develop wonderful preventive systems such as the prediction of failures. The obtained results of the research will contribute to ship safety at sea and prevention of hazardous machinery effects.

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