A FUZZY DEMATEL MODEL PROPOSAL FOR THE CAUSE AND EFFECT OF THE FAULT OCCURRING IN THE AUXILIARY SYSTEMS OF THE SHIPS' MAIN ENGINE

(DOI No: 10.3940/rina.ijme.2018.a2.465)

A Balin, Istanbul University, Department of Transportation and Logistic, Istanbul, Turkey, **H Demirel**, Bülent Ecevit University, Department of Marine Engineering Operations, Zonguldak, Turkey, **E Celik**, Munzur University, Department of Industrial Engineering, Tunceli, Turkey and **F Alarcin**, Yildiz Technical University, Department of Marine Engineering Operations, Istanbul, Turkey

SUMMARY

The ship engine room has a structure that meets a number of needs related to administrative conditions. Even if a simple mechanical error is considered to be the addition of human errors into the complex structure of the engine room, it can lead to undetected loss. How the causes and effects of the detected faults affect the system is as important as an effective fault detection system to detect the fault and take immediate action against any possible engine failure. This study reveals the causes of problems occurring in the main engine auxiliary systems including cooling, lubricating, cooling oil and fuel systems, and the extent of these problems affecting the system. While the Decision Making Trial and Evaluation Laboratory supports to identify and analyze the error detection of auxiliary systems with respect to causal effect relation diagram, fuzzy sets deal with the uncertainty in decision-making and human judgements through the DEMATEL. Therefore, fuzzy DEMATEL approach is applied to examine the causes and the weights of the faults and their relation to each other in the auxiliary systems. When we look at the result of the proposed approach, fuel oil pump failures has more impact on the all system and air cooler problems has the second highest place among the all errors.

1. INTRODUCTION

In the engine room, all engines work in an integrated manner and must work perfectly to achieve the desired power and rotation. The engine room is designed to meet all the operational requirements of fuel, oil, exhaust, cooling, air supply and control systems which are expressed as main engine auxiliary systems designed to provide the necessary power for ship operation. Engine room is a system of high complexity systems and consists of subsystems that meet a number of needs. Diesel engines are the main source of generating power to operate the ship. Marine diesel engines are more likely to encounter sudden and unexpected failures due to long-term use. It is among the reasons for large-scale failures to ignore details or to notice small disorders. (Özsoysal, 2010).

Any simple engine failure can cause another one unless it is noticed shortly and necessary precautions are taken. These failures later become large enough to cause a loss that cannot be reversed. The important thing is to take action and take the necessary precautions before it becomes impossible to overcome these failures. Any probable engine failure can be detected easily with effective main engine failure detection. In addition to the observed symptoms and the identified failures, the frequency of failures and their cause and effect on auxiliary systems should also be taken into account in order to increase productivity and to account for possible causes of failures.

In addition to controlling the pressure and temperature of the exhaust, combustion air, oil and cooling water, checking the turbo charger with marine diesel engine would also be the occasion to detect failures (Calder, 1992). Sharma et al. (2008) has implemented a failure mode and effect analysis (FMEA) that expresses all possible failure modes and causes of the industrial system in a hierarchical structure. Çebi et al. (2009) suggested an expert diagnostics system to identify and evaluate frequent failures in ship engine auxiliaries using the PROLOG programming language. They developed an application for the ship cooling system and created action charts showing what types of faults were encountered in the event of an emergency and what they would do by changing the indicative value limits. As a result of their work, it is underlined shortening the intervention period of merchant ships and timely correcting failures that will increase operational efficiency when maneuvering on merchant ships in critical seas. Özsoysal (2010) investigated the damages and causes of exhaust failure in high speed marine diesel engines on Turkish ambulance boats. Gourgoulis (2010) worked on the turbine engine electric generators used in marine engineering for the auxiliary power supply system of the ship. The author made a failure analysis in order to solve real operating problems. Alarcin et al. (2014) applied fuzzy analytic hierarchy process (AHP) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methods that can be applied for failure detection in auxiliary systems. Balin et al. (2015) also implemented fuzzy AHP and fuzzy VIKOR methods applied for the importance of the effective use of time in determining and responding to the failures. Demirel et al. (2015) aimed to manage troubleshooting in marine engine auxiliary systems for maintenance processes for marine engineering operators using fuzzy AHP determine solution methods. Chen-Yi et al. (2007) used Fuzzy decision making trial and evaluation laboratory (FDEMATEL) to find the key factors in building the structure relations of an ideal customer's choice behavior. Wu and Lee (2007) applied FDEMATEL to segment competencies for better promoting the competency development of global managers. Furthermore, Liou et al. (2008) applied the model to establish an effective safety management system in aviation industry. Chang et al. (2011) applied FDEMATEL to find influential factors in selecting SCM suppliers. Moreover, the FDEMATEL has been successfully adopted in knowledge management (Patil and Kant, 2014), supply chain management (Govindan et al., 2015; Jeng, 2015), safety management (Zhou et al., 2013), human resource management (Chou et al., 2014), risk management (Mentes et al., 2015), emergency management (Zhou et al., 2011), critical operational hazards (Akyuz and Celik, 2015), and energy management (Luthra et al., 2016).

This paper presents an important methodological approach to mention causes and effects of the detected faults on the auxiliary systems of the ships' main engine. The proposed methodology enhances the maintenance processes for operators as well as property marine engineering. Although the method has already identified some scientific articles in different areas, there are few studies on the importance ratings of mistakes that occur mainly in auxiliary systems in the maritime industry. Therefore, this study will remedy about gap and contribute to the marine engineering area the rest of this paper is organized as follows: Section 2 presents the fundamental of the FDEMATEL approach. The case study is presented in Section 3. Finally, discussion and conclusion are presented in Section 4.

2. FUZZY DEMATEL METHOD

Decision making trial and evaluation laboratory (DEMATEL) method was proposed at Battelle Memorial Institute of Geneva Research Center for understanding and solving the real world problems (Gabus and Fontela, 1973, Gul et al., 2014; Gölcük and Baykasoğlu, 2016). It aims to reveal the direct and indirect relation between criteria, causal and effect dimensions (Dalahan et al., 2011). However, it is usually assumed that human perceptions (linguistic assessments) on decision criteria are usually evaluated subjectively. In many real cases, the human perception is uncertain and human(s) might be unwilling or unable to allocate exact numerical values to describe the preferences (Lin, 2013; Celik et al., 2015; Akyuz and Celik, 2016). While it is a good technique for evaluating problems and making decisions, fuzzy logic reflects the linguistic assessment in a healthier manner. Fuzzy logic is a robust tool for dealing with the vagueness, ambiguity and uncertainty of human perception and assessment in making decisions process that is proposed in 1965 by Lotfi A. Zadeh. Many decision making problems involve imprecision since goals, constraints, and possible actions are not known precisely in real world decision making problems, (Zadeh, 1965). Hence, it is better to convert the linguistic terms into fuzzy numbers in decision making problems (Gul et al, 2016). The FDEMATEL method can convert the relationship between the causes and effects of criteria into an intelligible structural model of the system. The FDEMATEL method has been successfully applied in many fields (Gölcük and Baykasoğlu, 2016). In recent years, the FDEMATEL method has become very popular, because it is specifically realistic to visualize the structure of complicated causal relationships with digraphs (Akyuz and Celik, 2015). The corresponding relationship between the linguistic terms and triangular fuzzy numbers is determined with respect to Table 1. The fuzzy ratings and their membership function is presented in Figure 1.

Table 1. Corresponding relationship between linguistic terms and fuzzy numbers

Linguistic terms	Triangular fuzzy numbers
No influence (No)	(0, 0, 0.25)
Very low influence (VL)	(0, 0.25, 0.5)
Low influence (L)	(0.25, 0.5, 0.75)
High influence (H)	(0.5, 0.75, 1)
Very high influence (VH)	(0.75, 1, 1)

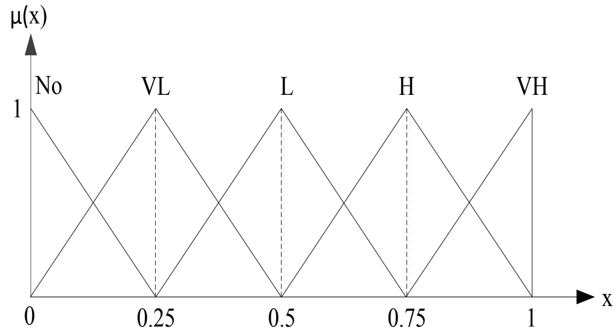

Figure 1. Fuzzy ratings and their membership function

The main steps of the method that is also presented in Figure 2 are defined as follows (Chen-Yi et al., 2007; Wu and Lee, 2007; Liou et al., 2008; Akyuz and Celik, 2015).

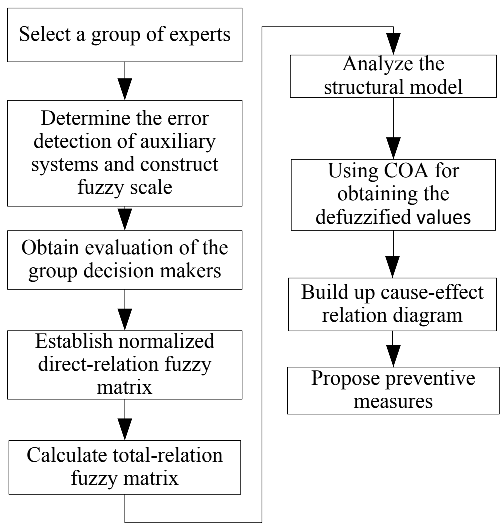

Figure 2. Flow diagram of the proposed approach

 ©2018: The Royal Institution of Naval Architects

Step 1: Select a group of experts who have enough knowledge and experience about the problem in order to obtain consistent judgements.

Step 2: Determine error and construct fuzzy scale. Then, linguistic variable is applied with five scales (no influence, very low influence, low influence, high influence, and very high influence) with respect to the linguistic terms and triangular fuzzy numbers.

Step 3: Obtain the evaluation of the group decision makers: The pair wise comparison is obtained in terms of linguistics variables. Furthermore, the fuzzy assessments are transformed into defuzzified and aggregated as a crisp value. As a result, initial direct-relation fuzzy matrix ($\tilde{E}$) of group decision makers is constructed. $\tilde{e}_{ij}$ is the fuzzy evaluation of the ith failure to jth failure, can be indicated by $\tilde{e}_{ij} = (l_{ij}, m_{ij}, u_{ij})$. Here l_{ij}, m_{ij} and u_{ij} stand for the lower, middle and upper values of the fuzzy numbers.

$$\tilde{E} = \begin{bmatrix} 0 & \cdots & \tilde{E}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{E}_{n1} & \cdots & 0 \end{bmatrix} \quad (1)$$

$$\tilde{e}_{ij} = (l_{ij}, m_{ij}, u_{ij}) \quad (2)$$

Step 4: Calculate the normalized direct-relation fuzzy matrix. Once the initial direct-relation matrix is constructed, the normalization is applied. The following calculations are done respectively.

$$\tilde{\beta}_i = \sum \tilde{e}_{ij} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij}\right) \quad (3)$$

$$\gamma = max\left(\sum_{j=1}^{n} u_{ij}\right) \quad (4)$$

where $\tilde{\beta}_i$ and γ as triangular fuzzy numbers.

Thereafter, the linear scale transformation is applied to convert the errors into comparable scales. The normalized direct-relation fuzzy matrix $(\tilde{F})$ of the group decision makers can be represented as follows.

$$\tilde{F} = \begin{bmatrix} \tilde{\tilde{F}}_{11} & \dots & \tilde{F}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{F}_{n1} & \dots & \tilde{F}_{nn} \end{bmatrix} \quad (5)$$

where $\tilde{f}_{ij} = \frac{\tilde{e}_{ij}}{\gamma} = \left(\frac{\tilde{e}_{ij}}{\gamma}, \frac{\tilde{e}_{ij}}{\gamma}, \frac{\tilde{e}_{ij}}{\gamma}\right)$

Step 5: After having established normalized direct-relation fuzzy matrix, a total-relation fuzzy matrix is calculated by ensuring of $\lim_{\omega \to \infty} F^{\omega} = 0$. Then, the crisp case of the total-relation fuzzy matrix is obtained as follows.

$$\tilde{T} = \lim_{\omega \to \infty} \left(\tilde{F} + \tilde{F}^2 + \cdots + \tilde{F}^{\omega}\right) \quad (6)$$

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \dots & \tilde{t}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \dots & \tilde{t}_{nn} \end{bmatrix} \quad (7)$$

Where $\tilde{t}_{ij=} = (l''_{ij}, m''_{ij}, u''_{ij})$

$$Matrix\left[l''_{ij}\right] = F_l \; x \; (I - F_l)^{-1} \quad (8)$$

$$Matrix\left[m''_{ij}\right] = F_m \; x \; (I - F_m)^{-1} \quad (9)$$

$$Matrix\left[u''_{ij}\right] = F_u \; x \; (I - F_u)^{-1} \quad (10)$$

Step 6: Analyze the structural model. After having calculated matrix $\tilde{T}$, $\tilde{r}_i + \tilde{c}_j$and $\tilde{r}_i - \tilde{c}_j$ are calculated. In the formula, $\tilde{r}_i$ and $\tilde{c}_j$ denote the sum of the rows and columns of matrix $\tilde{T}$. While $\tilde{r}_i + \tilde{c}_j$ presents the importance of factor i, $\tilde{r}_i - \tilde{c}_j$ presents the net effect of factor i.

Step 7: Defuzzify $\tilde{r}_i + \tilde{c}_j$ and $\tilde{r}_i - \tilde{c}_j$. Next, $\tilde{r}_i + \tilde{c}_j +$ and $\tilde{r}_i - \tilde{c}_j$ are defuzzified by using center of area defuzzification technique which is introduced by Ross (1995) in order to determine the best non-fuzzy performance value. For a convex fuzzy number $\tilde{\delta}$, a real number z^* corresponding to its centre of area can be calculated as follows (Gumus et al., 2013):

$$z^* = \frac{\int \mu_{\tilde{\delta}}(z) z dz}{\int \mu_{\tilde{\delta}}(z) dz} \quad (11)$$

The BNP value of a fuzzy number $\tilde{G} = (l_{ij}, m_{ij}, u_{ij})$ can be found with following formula.

$$BNP_{ij} = \frac{u_{ij} - l_{ij} + m_{ij} - l_{ij}}{3} + l_{ij} \quad (12)$$

Step 8: Furthermore, depict a cause-effect relation diagram. In the last step, the cause and effect relation diagram is illustrated by mapping the dataset of $r_i + c_j$ and r_i-c_j.

3. A REAL-CASE APPLICATION FOR FAILURE IN AUXILIARY SYSTEMS OF THE SHIP MAIN ENGINE

When the causes and effect of faults in the marine diesel engines are examined, it is seen that each failure is connected to a different cause depending on the operating conditions. This led to the necessity of examining the causes and effects of faults affecting the systems of ship diesel engines.

In general when technically separated engine failures based on the basic features with the intention of categorizing are examined, each of which seems to have an association with a different system. Critical heat operating value for operation of marine diesel engines, are the cooling water and oil values functioning as a major factor in engine cooling and keeps the heat from the fuel coming out of the running engine. In addition to these values, it is expressed as a factor giving important information about the heat value of exhaust gases, combustion process, combustion efficiency and power obtained from the engine.

Ships in operation, due to irregular changes in the marine diesel engine load, a comprehensive intervention to control the temperature of the oil and cooling water is required. Keeping the values of the cooling water and oil temperature at optimum levels ensures more efficient energy recovery and safer marine diesel engine operation. The formation of oil film on the cylinder wall may affected by the heat of the cylinder wall cooling water. The operating structure of the central cooling system, which is frequently encountered in marine diesel engines, is shown in Figure 3.

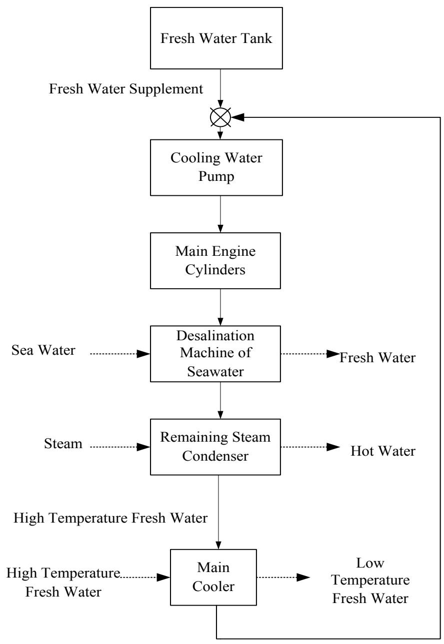

Figure 3. Structure of main engine HTFW system (Xiaoyan, 2007)

In diesel engines, fuel and governor systems must work perfectly to achieve the desired power and rotation. In order for the engines to operate safely, the rotation intervals are determined by the engine manufacturer. Exhaust heat value increases when the engine is out of range and running for longer. As the engine rotation speeds up, the emission of the exhaust gas flow increases, resulting in an increase in turbine rotation. The amount of fuel delivered from the fuel pump to the injector is controlled by the valve at a steady speed.

High-level exhaust gas temperatures, blocked filters, unwanted substances trapped in the compressor or turbine prevent the diesel engine and turbocharger from functioning properly. Fire occurs in the suction manifold due to excessive dirt and clogging of the air supply filter. Difficulties in pushing the gases generated by counter-pressure through the chimney and decrease in the inlet pressure cause the engine to fail to lift the load.

In the paper the main elements of the criteria for the selection and evaluation of machine operating systems were identified as a result of extensive exploration and consultation with three groups, including a professor from Naval Architecture and Ship Engineering. They were asked to rate the adequacy, appropriateness, and eligibility of the criteria and dimensions and to verify their "content validity" in terms of the functioning of the machine evaluation. The reasons for failures in the main engine systems were created from previous records and the daily maintenance books, and they were integrated with the staff experience. Failures are encoded as C_i where i is the number of related failure.

High heat level in all exhaust cylinders of the engine:

C_1: Fuel oil quality: It is important to determine the preheating temperature. Because the preheating is directly influence the combustion quality, it may cause increased cylinder wear related to liners and rings. Fuel oils are generally contaminated by water, sludge etc. and thus, the fuel oil must be wholly cleaned for solid as well as liquid contaminants via operators before sending it to the main engine or the auxiliary engines.

C_2: Fuel injector problems: Fuel injector has a critical role in atomization of fuel and combustion. If any part of the injector damaged or broke this results in the loss of power and efficiency. After that, The engine is also affected adversely in long term. Pressure and temperature should be monitored properly and necessary changes must be done on time.

C_3: Fuel oil pump failures: Fuels used incorrectly temperature and pressure cause these failures. After, power and efficiency decrease and suddenly engine can stop. The characteristics of the fuel must be noted and maintenance must be done regularly.

C_4: Fuel oil leakage in cylinders: Fuel oil leakage in cylinders generally occurs due to the injector problems. The leakage effects the combustion quality badly and can damage the turbine equipment. The injector maintenance must be done and the pressures and the temperatures must be checked properly.

C_5: Air fan is not working properly: If air fan is not working properly, the necessary amount of air for combustion does not enter the cylinders. Thus, the fuel cannot be burned completely. As a result, exhaust temperature increases and turbine equipment can be damaged. The amount of air for combustion must be checked periodically and the necessary precautions must be done on time.

 ©2018: The Royal Institution of Naval Architects

Fluctuation in engine rotations:
C_6: Dirty fuel oil filter: In this case, fuel at a desired pressure is not sent to engine. Fuel pump may be damaged and the engine power decreases. The fuel filter should be cleaned regularly.

C_7: Fuel oil pump pressure: Higher or lower pressure than normal damage the oil pump and effect badly all the circuit. In addition, this can disrupt the other equipments and leads to affect combustion adversely. Therefore, the pump pressure should be checked regularly.

C_8: Fuel oil temperature: The temperature of the fuel affects its viscosity. This decreases the combustion quality and may lead to damage the engine. The temperature of the fuel must be controlled by operators.

C_9: Mechanical failure in the turbocharger: One of the most important problems in turbocharging is surging. This situation causes mechanical damages such as rotor and/or compressor blades. Any abnormality in the fuel system must be evaluated and fouling in the gas/air system must be timely cleaned by operators

C_{10}: Wrong adjustment of governor: This situation negatively effects the injected fuel quantity and the injection time. As a result, combustion quality decreases and the desired speed and power cannot be obtained. Injected fuel quantity and the injection time must be evaluated periodically.

Sudden shut down of the engine during normal operation:
C_{11}: Low level fuel oil tank: In this case, enough fuel may not be taken from storage tank or fuel is exhausted. Thus, the engine may be stopped suddenly. The level of the fuel tank should be checked regularly.

C_{12}: Insufficient intake air: Blower or dirty filter causes this situation. In this case, the desired combustion is not be obtained and engine performance decreases. Filters should be cleaned on time and periodic maintenance of blower should be noted.

C_{13}: Oil pressure: Oil pressure effects all the circuit. Pump failure, dirty filter and a leak on the circuit or the engine can cause the oil pressure failure. Without the required oil pressure, it is not ensured that whether the adequate cooling of the engine is satisfied. As a result, engine may damaged. The oil pressure must be checked regularly via operators.

C_{14}: Oil leakage: Oil leakage cause the decline in the oil pressure. As a result, adequate lubrication is not occur and the engine may be damaged. The oil level and pressure must be checked regularly via operators

C_{15}: Insufficient cooling water: A leak on the system or the end of the water in the cooling water tank can cause insufficient cooling water. Engine overheats without sufficient cooling water and engine may damaged. Cooling water level tanks, cooling water pressure and temperature must be checked regularly by operators.

Rise in the oil level in crankcase while the engine is working:
C_{16}: Cooling water leakage: A hole, crack on the system or worn O-rings can cause cooling water leakage. In this case, the amount of cooling water and pressure decrease. Thus, it is not ensured that whether the adequate cooling of the engine is satisfied and the engine may be damaged. Cooling water tank levels and pressure should be checked regularly.

C_{17}: Shut off valve on oil tank open: This situation causes a rise in the oil level in crankcase while the engine is working and engine is affected adversely. Oil tank level should be checked and noted.

C_{18}: Fuel oil leakage: All of the fuel pumps are connected with drain pipes to a common drain tank which involves a level switch. If there is a problem in pipes or any other equipments, oil level in crankcase rise and engine may be damaged. The drain pipes of all fuel pumps and oil levels should be checked regularly.

Fire in the Scavenging area:
C_{19}: Dirty scavenging manifold inlet: Dirty scavenging manifold inlet increases the fire in the scavenging area. This situation damage the engine. Scavenging manifold inlet should be cleaned periodically.

C_{20}: Abrasive oil ring and piston: In this case, abrasive oil ring and piston negatively affect scavenging area and increase the temperature. Increasing temperature in the system causes power loss Lubrication, maintenance of oil ring and piston should be done on time.

C_{21}: Air cooler problem: In this case, air cooler does not not work properly or stop suddenly. When the system temperatures increase and engine efficiency affect negatively. Air cooler filters and temperature levels should be checked regularly.

Surge in the turbocharger:
C_{22}: Exhaust valve burns: Especially, false opening of exhaust valve causes this case. As a result, surge occur in the turbocharger and this damages the system mechanically. Exhaust valve timing should be examined and applied carefully.

C_{23}: Insufficient turbocharger oil: Insufficient turbocharger oil causes surge in the turbocharger. Without the required lubrication, engine performance decreases. Oil level in turbocharger should be checked periodically.

C_{24}: Low level oil in the governor: Low level oil in the governor negatively affects the combustion quality and may cause surge in the turbocharger. This situation decreases the engine power. Oil level in the governor should be controlled periodically.

C_{25}: Scavenging pressure high: High scavenging pressure may cause mechanical failure in the turbocharger. If scavenge air system work properly, there is no surge in the turbocharger. Scavenge air system should be checked periodically.

3.1 APPLICATION OF THE PROPOSED APPROACH

After determining the key dimensions of the criteria for evaluation and selection of machine operation systems, then, experts assess the relation among the hazards through the use of fuzzy linguistic scale.

According to the three marine experts, Table 2 presents the linguistic assessment of the three marine experts' decisions. For example, C_1 is evaluated with respect to C_2 as High (H), Very High (VH) and High (H) by three experts, respectively. (shown in Table 2, row 1 and column 2). The all evaluations for failure with respect to all failure are presented in the same manner, in Table 2. Then, the initial direct-fuzzy matrix is constructed using linguistic variables that are presented in Table 1. Table 3 presents the aggregated fuzzy initial-direct matrix. In this step, the aggregation of the row 1 (C_1) and column 2 (C_2) is obtained as follows:

$$e_{C1,\,C2}=\frac{(0.5,\,0.75,\,1)+(0.75,\,1,\,1)+(0.5,\,0.75,\,1)}{3}$$

$$e_{C1,\,C2}=\frac{(1.75,\,2.5,\,3)}{3}=(0.58,\,0.83,\,1)$$

In the same manner, all calculations are applied for obtaining initial direct-fuzzy matrix. After having constructed initial direct-fuzzy matrix, normalized direct-relation fuzzy matrix is obtained by using the equations (3 - 5) respectively. The normalized initial direct-relation fuzzy matrix is presented in Table 4. Next, total-relation fuzzy matrix can be computed by using equations (6-10) that is provided Table 5. As a consequences of outcomes, the fuzzy values of $\tilde{r}_i, \tilde{c}_j,\ \tilde{r}_i+\tilde{c}_j, \tilde{r}_i\text{-}\tilde{c}_j$ are computed as presented in Table 6. Then, defuzzification process is applied to convert the fuzzy numbers into crisp numbers. The crisp values of the $r_i,\ c_j,\ r_i+c_j, r_i\text{-}c_j$ are presented in Table 7. According to the crisp numbers, the cause-effect relation diagram is build up. In the last step of the proposed approach, the cause and effect relationship diagram is figured based on the above outcomes.

The following Tables are contained in the Appendices at the end of this Paper:

Table 2. Linguistic assessment of the three marine experts
Table 3. The fuzzy direct-influence matrix
Table 4. Normalized initial direct-relation fuzzy matrix
Table 5. Total-relation fuzzy matrix
Table 6. Fuzzy values of $\tilde{r}_i, \tilde{c}_j,\ \tilde{r}_i+\tilde{c}_j, \tilde{r}_i\text{-}\tilde{c}_j$
Table 7. Crisp values of $r_i,\ c_j,\ r_i+c_j, r_i\text{-}c_j$

3.2 FINDINGS

By considering the calculation of the $r_i,\ c_j,\ r_i+c_j, r_i-c_j$, the Figure 4 presents the cause-effect relation diagram. The finding group can be considered as cause and effect group. While the effect group is under the axis, the cause group remains on the axis.

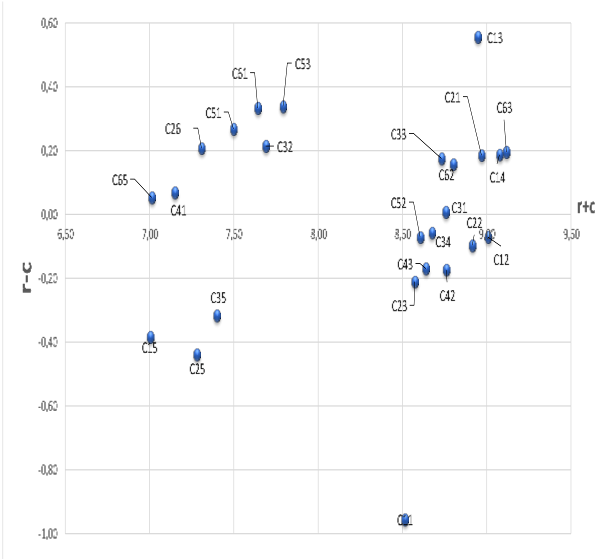

Figure 4. Cause-effect relation diagram

In order to evaluate error detection of auxiliary systems of ship main engines, it is significant to concentrate on the cause factor (error) analysis which have net and great impact on the all system. According to the Figure 4, C_3 (Fuel oil pump failures) has the highest r_i-c_j value among the all error in cause group. It means that C_3 has more impact on the all system. In addition, C_3 has the highest r_i value (4.75) among the causal factors from the view of influential impact degree. It shows that C_3 has major impact on the other errors. C_{21} (Air cooler problem) has the second highest r_i-c_j value since it ranks second place among the all errors. The third most critical factors among the entire process is C_{22} (Exhaust valve burns) while its r_i-c_j value (0.33) ranks third place among the process.

Since effect factors are simply influenced by the other factors and, it may be still necessary to analyze effect factors (errors) which can lead to severe results in error detection of auxiliary systems of ship main engines. In the light of cause-effect relation diagram, apparently C_2 (Fuel injector problems) has the highest r_i+c_j value (9.01) among the all system. The r_i-c_j value (-0,07) of C_2 is very low when compared to other factors in effect group. Hence, C_2 has the significant impact on the other factors. Next, C_7 (fuel oil pump pressure) and C_{17} (shut

 ©2018: The Royal Institution of Naval Architects

off valve on oil tank open) have the second and third highest $r_i + c_j$ values (respectively 8.91 and 8.76) in the all system. On the other hand, their $r_i - c_j$ values are very low (-0,10 and 0,17-) that means they are very easily influenced by the other factors. The rest of factors have moderate $r_i + c_j$ values as it can be seen in diagram.

3.3 PREVENTIVE MEASURES PROPOSAL

In the light of the above findings, C_2, C_3, C_7, C_{17} C_{21}, C_{22}, H_5, H_4 and H_{11} are critical factors in the course of error detection the auxiliary systems of the ships' main engine. Preventive measures are presented in the view of marine experts who have enough experience on the auxiliary systems of the ships' main engine for a long year. Considering the marine experts' wide experience and knowledge, the preventive measures proposed by them are the most effective measures to avoid similar errors for auxiliary systems of the ships' main engines in the future. For all failures, operators have a critical role because of checking all the changes in the system. Therefore, practical and technical training of operators are most important for the prevention of failures. Table 8 provides the preventive measures against the critical error.

Table 8. Preventive measures.

Failure code	Preventive measures
C_3	Making regular maintenance of pump, cleaning of fuel and evaluating properties of the fuel carefully.
C_2	Monitoring of pressure and temperature changes regularly and making timely maintenance of the injector.
C_7	Considering the abrupt pump pressure changes and inspection of the fuel quality regularly.
C_{17}	Making regular maintenance of valve and checking the oil level periodically.
C_{21}	Cleaning the air cooler filters regularly and monitoring the system temperatures.
C_{22}	Applying exhaust valve timing carefully and making regular maintenance of valve.

4. CONCLUSIONS

The entire system must operate in an integrated manner in the Ship Engine room. Therefore, any failure in any system will quickly affect the entire system. A small mistake can sometimes become a non-compensating vital danger and adversely affect the entire system. Any Engine failures must always be solved by the engine operators as quickly as possible. For this reason, the causes and the weights of the faults and their relation to each other in the motor auxiliaries need to be addressed well.

As a result of the proposed approach, C_3 (Fuel oil pump failures) has more impact on the all system. On the other hand, while C_{21} (Air cooler problem) has the second highest place among the all errors, C_{22} (Exhaust valve burns) is the third most critical factors among the entire process. In the light of the above findings, C_2, C_3, C_7, C_{17} C_{21}, C_{22}, H_5, H_4 and H_{11} is obtained as crucial factors for the error detection of auxiliary systems of a ships' main engines.

The proposed hybrid method can be extended to interval type-2 fuzzy sets. The study is also thought to be a good reference for maintenance processes for ship engine officers.

5. REFERENCES

1. AKYUZ, E., & CELIK, E. (2015). *A fuzzy DEMATEL method to evaluate critical operational hazards during gas freeing process in crude oil tankers*. Journal of Loss Prevention in the Process Industries, 38, 243-253.
2. AKYUZ, E., & CELIK, E. (2016). *A modified human reliability analysis for cargo operation in single point mooring (SPM) off-shore units*. Applied Ocean Research, 58, 11-20.
3. ALARCIN, F., BALIN, A., & DEMIREL, H. (2014). *Fuzzy AHP and Fuzzy TOPSIS integrated hybrid method for auxiliary systems of ship main engines*. Journal of Marine Engineering & Technology,13(1), 3-11.
4. BALIN, A., DEMIREL, H., & ALARCIN, F. (2015). *A hierarchical structure for ship diesel engine trouble-shooting problem using fuzzy AHP and fuzzy VIKOR hybrid methods*. Brodogradnja, 66(1), 54-65.
5. CELIK, E., GUL, M., AYDIN, N., GUMUS, A. T., & GUNERI, A. F. (2015). *A comprehensive review of multi criteria decision making approaches based on interval type-2 fuzzy sets*. Knowledge-Based Systems, 85, 329-341.
6. CHANG, B., CHANG, C. W., & WU, C. H. (2011). *Fuzzy DEMATEL method for developing supplier selection criteria*. Expert systems with Applications, 38(3), 1850-1858.
7. DALALAH, D., HAYAJNEH, M., & BATIEHA, F. (2011). *A fuzzy multi-criteria decision making model for supplier selection*. Expert systems with applications, 38(7), 8384-8391.
8. DEMIREL, H., UNLÜGENÇOĞLU K., ALARCIN, F. & BALIN, A (2015). *Application of Fuzzy Analytical Hierarchy Proses for Error Detection of Auxiliary Systems of Ship Main Diesel Engines*. International Journal Maritime Engineering, 157, 105-111.
9. GABUS, A., & FONTELA, E., (1973). *Perceptions of the world problematique: communication procedure, communicating with those bearing collective responsibility*. Battelle Geneva Research Centre, Switzerland, Geneva.

10. GÖLCÜK, İ., & BAYKASOĞLU, A. (2016). *An analysis of DEMATEL approaches for criteria interaction handling within ANP*. Expert Systems with Applications, 46, 346-366.
11. GOURGOULIS, D. (2010). *Troubleshooting of marine steam turbo electro generators using engine control room simulator*, Journal of Maritime Research, 7(1), 13-26.
12. GOVINDAN, K., KHODAVERDI, R., & VAFADARNIKJOO, A. (2015). *Intuitionistic fuzzy based DEMATEL method for developing green practices and performances in a green supply chain*. Expert Systems with Applications, 42(20), 7207-7220.
13. GUL, M., GUNERI, A. F., & DERIN, B. (2014). *Evaluation of service quality criteria for a private medical center by using SERVQUAL and DEMATEL methods*. Sigma, 32, 240-253.
14. GUL, M., CELIK, E., AYDIN, N., GUMUS, A. T., & GUNERI, A. F. (2016). *A state of the art literature review of VIKOR and its fuzzy extensions on applications*. Applied Soft Computing, 46, 60-89.
15. GUMUS, A.T., YAYLA, A.Y., CELIK, E., & YILDIZ, A., (2013). *A combined fuzzy-ahp and fuzzy-gra methodology for hydrogen energy storage method selection in Turkey*. Energies 6 (6), 3017e3032.
16. HSU, C. Y., CHEN, K. T., TZENG, G. H., 2007. *FMCDM with fuzzy DEMATEL approach for customers' choice behavior model*. International Journal of Fuzzy Syst. 9 (4), 236-246.
17. JENG, D. J. F. (2015). *Generating a causal model of supply chain collaboration using the fuzzy DEMATEL technique*. Computers & Industrial Engineering, 87, 283-295.
18. LIN, R. J. (2013). *Using fuzzy DEMATEL to evaluate the green supply chain management practices*. Journal of Cleaner Production, 40, 32-39.
19. LIOU, J.J., YEN, L., & TZENG, G.H., (2008). *Building an effective safety management system for airlines*. J. Air Transp. Manag. 14 (1), 20-26.
20. LUTHRA, S., GOVINDAN, K., KHARB, R. K., & MANGLA, S. K. (2016). *Evaluating the enablers in solar power developments in the current scenario using fuzzy DEMATEL: An Indian perspective*. Renewable and Sustainable Energy Reviews, 63, 379-397.
21. MENTES, A., AKYILDIZ, H., YETKIN, M., & TURKOGLU, N. (2015). *A FSA based fuzzy DEMATEL approach for risk assessment of cargo ships at coasts and open seas of Turkey*. Safety Science, 79, 1-10.
22. ÖZSOYSAL, O. A. (2010). *Siphoning sea water back into the engine in fast boats*, Journal of Marine Science and Technology, 18(4), 496-503.
23. PATIL, S. K., & KANT, R. (2014). *A hybrid approach based on fuzzy DEMATEL and FMCDM to predict success of knowledge management adoption in supply chain*. Applied Soft Computing, 18, 126-135.
24. SHARMA, R.K., KUMAR, D., & KUMAR, P. (2005). *Systematic failure mode effect analysis (FMEA) using fuzzy linguistic modelling*, International Journal of Quality & Reliability Management, 22, 986 – 1004
25. ROSS, T.J., (1995). *Fuzzy Logic with Engineering Applications*. McGraw-Hill, Inc, USA.
26. CEBI, S., CELIK, M., KAHRAMAN, C., & ER, I. D. (2009). *An expert system auxiliary machinery troubleshooting: Shipamtsolver*, Expert Systems with Applications, 36, 7219-7227.
27. UNLUGENCOGLU, K. (2012). *Development and application of simulator algorithm in accordance with ship main engine auxiliary systems*. MSc Thesis, Yildiz Technical University, İstanbul, Turkey.
28. WU, W.W., & LEE, Y.T., (2007). *Developing global managers' competencies using the fuzzy DEMATEL method*. Expert Systems with Applications, 32 (2), 499-507.
29. ZADEH, L.A., (1965). *Fuzzy sets*. Information and Control 8, 338–353.
30. ZHOU, Q., HUANG, W., & ZHANG, Y., (2011). *Identifying critical success factors in emergency management using a fuzzy DEMATEL method*. Safety Science, 49 (2), 243e252.
31. ZHOU, S., SUN, J., LI, K. P., & YANG, X. (2013). *Development of a Root Cause Degree Procedure for measuring intersection safety factors*. Safety Science, 51(1), 257-266.

 ©2018: The Royal Institution of Naval Architects

APPENDICES

Table 2. Linguistic assessment of the three marine experts

	C1	C2	C3	C4	C22	C23	C24	C25
C1	(No, No, No)	(H, VH, H)	(H, VH, VH)	(VH, VH, H)	(H, H, VH)	(L, L, L)	(VL, L, L)	(VL, VL,
C2	(H, VH, H)	(No, No, No)	(H, L, H)	(H, VL, VL)	(L, VL, VL)	(H, H, H)	(VH, H, H)	(L, L, L)
C3	(VL, VH, VH)	(H, VH, H)	(No, No, No)	(L, L, H)	(L, VL, VL)	(H, H, H)	(VH, VH, VH)	(L, VL, L)
C4	(VH, VH, VH)	(H, VH, VL)	(H, VL, H)	(No, No, No)	(VL, L, L)	(VH, VH, VH)	(VH, VH, VH)	(L, L, L)
C5	(VL, VH, VL)	(VL, VL, L)	(L, VL, VL)	(VH, L, VL)	(VH, VH, VH)	(VL, VL, VL)	(VL, VL, VL)	(H, VH, VH)
C6	(VH, H, H)	(VH, VH, H)	(H, H, H)	(VH, VH, VH)	(VL, VL, VL)	(H, H, H)	(H, H, H)	(VL, VL,
C7	(VH, H, H)	(VH, VH, VH)	(VH, VH, VH)	(VH, VH, VH)	(VL, L, L)	(VH, VH, VH)	(H, VH, VH)	(VL, L, L)
C8	(H, H, H)	(H, VH, VH)	(L, L, L)	(H, H, H)	(VL, VL, VL)	(VH, H, H)	(H, H, VH)	(VL, VL,
C9	(L, VL, VL)	(L, L, L)	(L, VL, VL)	(VL, L, L)	(L, L, L)	(L, L, L)	(L, L, L)	(L, VL, VL)
C10	(L, L, L)	(VH, H, H)	(VL, VL, VL)	(H, H, VH)	(L, L, L)	(VL, L, L)	(VH, H, H)	(L, VL, VL)
C11	(VH, VH, VH)	(VL, L, VL)	(VH, H, H)	(VH, VH, VH)	(VL, VL, VL)	(VH, VH, VH)	(VH, VH, VH)	(L, L, L)
C12	(L, L, L)	(H, H, H)	(VL, VL, VL)	(VL, VL, VL)	(H, VH, VH)	(L, L, L)	(L, VL, VL)	(H, H, H)
C13	(VH, VH, VH)	(H, VH, VH)	(VH, VH, VH)	(VH, H, H)	(VL, VL, VL)	(VH, VH, VH)	(VH, VH, H)	(VL, VL,
C14	(VH, VH, VH)	(VH, H, H)	(VH, H, H)	(VH, H, H)	(VL, L, L)	(VH, H, H)	(VH, VH, VH)	(VL, VL,
C15	(L, L, L)	(VL, VL, VL)	(VL, VL, VL)	(VL, VL, VL)	(H, H, H)	(L, L, VL)	(VL, L, VL)	(L, L, L)
C16	(L, VL, VL)	(VL, VL, VL)	(VL, L, L)	(VL, VL, L)	(L, L, L)	(VL, VL, VL)	(VL, L, L)	(L, L, L)
C17	(VH, VH, VH)	(H, H, H)	(VH, VH, H)	(VH, H, H)	(VL, VL, L)	(VL, VL, L)	(VH, VH, VH)	(VL, L, L)
C18	(VH, VH, VH)	(VH, VH, VH)	(VH, VH, VH)	(VH, VH, VH)	(VL, L, VL)	(L, L, L)	(VH, VH, VH)	(VL, VL,
C19	(L, L, VL)	(L, L, L)	(VL, VL, VL)	(VL, VL, VL)	(H, H, VH)	(H, H, VH)	(L, L, L)	(H, H, H)
C20	(VH, VH, VH)	(H, H, H)	(H, VH, VH)	(VH, VH, VH)	(VL, VL, VL)	(L, VL, VL)	(H, H, H)	(L, L, L)
C21	(H, H, H)	(VH, VH, VH)	(VL, L, L)	(L, L, L)	(H, VH, VH)	(H, H, H)	(VL, VL, L)	(H, VH, VH)
C22	(H, H, H)	(L, VL, L)	(VL, VL, VL)	(L, L, L)	(No, No, No)	(VH, L, VL)	(VL, H, L)	(VL, H, H)
C23	(VH, H, H)	(H, H, H)	(H, H, H)	(H, VH, VH)	(VH, VH, L)	(No, No, No)	(VL, VH, VH)	(L, H, VL)
C24	(VH, VH, VH)	(H, H, H)	(VH, VH, VH)	(H, H, H)	(VL, L, H)	(L, VH, VH)	(No, No, No)	(VL, L, H)
C25	(VL, L, L)	(L, VL, VL)	(VL, L, VL)	(VL, L, L)	(VL, H, H)	(L, H, VL)	(VL, VL, VL)	(No, No, No)

Table 3. The fuzzy direct-influence matrix

	C1	C2	C3	C4	C22	C23	C24	C25
C1	(0, 0, 0.25)	(0.58, 0.83, 1)	(0.67, 0.92, 1)	(0.67, 0.92, 1)	(0.58, 0.83, 1)	(0.25, 0.5, 0.75)	(0.17, 0.42, 0.67)	(0, 0.25, 0.5)
C2	(0.58, 0.83, 1)	(0, 0, 0.25)	(0.42, 0.67, 0.92)	(0.17, 0.42, 0.67)	(0.08, 0.33, 0.58)	(0.5, 0.75, 1)	(0.58, 0.83, 1)	(0.25, 0.5, 0.75)
C3	(0.5, 0.75, 0.83)	(0.58, 0.83, 1)	(0, 0, 0.25)	(0.33, 0.58, 0.83)	(0.08, 0.33, 0.58)	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.17, 0.42, 0.67)
C4	(0.75, 1, 1)	(0.42, 0.67, 0.83)	(0.33, 0.58, 0.83)	(0, 0, 0.25)	(0.17, 0.42, 0.67)	(0.75, 1, 1)	(0.75, 1, 1)	(0.25, 0.5, 0.75)
C5	(0.25, 0.5, 0.67)	(0.08, 0.33, 0.58)	(0.08, 0.33, 0.58)	(0.33, 0.58, 0.75)	(0.75, 1, 1)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.67, 0.92, 1)
C6	(0.58, 0.83, 1)	(0.67, 0.92, 1)	(0.5, 0.75, 1)	(0.75, 1, 1)	(0, 0.25, 0.5)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0, 0.25, 0.5)
C7	(0.58, 0.83, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.17, 0.42, 0.67)	(0.75, 1, 1)	(0.67, 0.92, 1)	(0.17, 0.42, 0.67)
C8	(0.5, 0.75, 1)	(0.67, 0.92, 1)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0, 0.25, 0.5)	(0.58, 0.83, 1)	(0.58, 0.83, 1)	(0, 0.25, 0.5)
C9	(0.08, 0.33, 0.58)	(0.25, 0.5, 0.75)	(0.08, 0.33, 0.58)	(0.17, 0.42, 0.67)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.08, 0.33, 0.58)
C10	(0.25, 0.5, 0.75)	(0.58, 0.83, 1)	(0, 0.25, 0.5)	(0.58, 0.83, 1)	(0.25, 0.5, 0.75)	(0.17, 0.42, 0.67)	(0.58, 0.83, 1)	(0.08, 0.33, 0.58)
C11	(0.75, 1, 1)	(0.08, 0.33, 0.58)	(0.58, 0.83, 1)	(0.75, 1, 1)	(0, 0.25, 0.5)	(0.75, 1, 1)	(0.75, 1, 1)	(0.25, 0.5, 0.75)
C12	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.67, 0.92, 1)	(0.25, 0.5, 0.75)	(0.08, 0.33, 0.58)	(0.5, 0.75, 1)
C13	(0.75, 1, 1)	(0.67, 0.92, 1)	(0.75, 1, 1)	(0.58, 0.83, 1)	(0, 0.25, 0.5)	(0.75, 1, 1)	(0.67, 0.92, 1)	(0, 0.25, 0.5)
C14	(0.75, 1, 1)	(0.58, 0.83, 1)	(0.58, 0.83, 1)	(0.58, 0.83, 1)	(0.17, 0.42, 0.67)	(0.58, 0.83, 1)	(0.75, 1, 1)	(0, 0.25, 0.5)
C15	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.5, 0.75, 1)	(0.17, 0.42, 0.67)	(0.08, 0.33, 0.58)	(0.25, 0.5, 0.75)
C16	(0.08, 0.33, 0.58)	(0, 0.25, 0.5)	(0.17, 0.42, 0.67)	(0.08, 0.33, 0.58)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0.17, 0.42, 0.67)	(0.25, 0.5, 0.75)
C17	(0.75, 1, 1)	(0.5, 0.75, 1)	(0.67, 0.92, 1)	(0.58, 0.83, 1)	(0.08, 0.33, 0.58)	(0.08, 0.33, 0.58)	(0.75, 1, 1)	(0.17, 0.42, 0.67)
C18	(0.75, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.75, 1, 1)	(0.08, 0.33, 0.58)	(0.25, 0.5, 0.75)	(0.75, 1, 1)	(0, 0.25, 0.5)
C19	(0.17, 0.42, 0.67)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.58, 0.83, 1)	(0.58, 0.83, 1)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)
C20	(0.75, 1, 1)	(0.5, 0.75, 1)	(0.67, 0.92, 1)	(0.75, 1, 1)	(0, 0.25, 0.5)	(0.08, 0.33, 0.58)	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)
C21	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.17, 0.42, 0.67)	(0.25, 0.5, 0.75)	(0.67, 0.92, 1)	(0.5, 0.75, 1)	(0.08, 0.33, 0.58)	(0.67, 0.92, 1)
C22	(0.5, 0.75, 1)	(0.17, 0.42, 0.67)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0.33, 0.58, 0.75)	(0.25, 0.5, 0.75)	(0.33, 0.58, 0.83)
C23	(0.58, 0.83, 1)	(0.5, 0.75, 1)	(0.5, 0.75, 1)	(0.67, 0.92, 1)	(0.58, 0.83, 0.92)	(0, 0, 0.25)	(0.5, 0.75, 0.83)	(0.25, 0.5, 0.75)
C24	(0.75, 1, 1)	(0.5, 0.75, 1)	(0.75, 1, 1)	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)	(0.58, 0.83, 0.92)	(0, 0, 0.25)	(0.25, 0.5, 0.75)
C25	(0.17, 0.42, 0.67)	(0.08, 0.33, 0.58)	(0.08, 0.33, 0.58)	(0.17, 0.42, 0.67)	(0.33, 0.58, 0.83)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0, 0.25)

©2018: The Royal Institution of Naval Architects

Table 4. Normalized initial direct-relation fuzzy matrix

Normaliz	C1	C2	C3	C4	C22	C23	C24	C25
C1	(0, 0, 0.01)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0.01, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0, 0.01, 0.02)
C2	(0.03, 0.04, 0.05)	(0, 0, 0.01)	(0.02, 0.03, 0.04)	(0.01, 0.02, 0.03)	(0, 0.02, 0.03)	(0.02, 0.03, 0.05)	(0.03, 0.04, 0.05)	(0.01, 0.02, 0.03)
C3	(0.02, 0.03, 0.04)	(0.03, 0.04, 0.05)	(0, 0, 0.01)	(0.02, 0.03, 0.04)	(0, 0.02, 0.03)	(0.02, 0.03, 0.05)	(0.03, 0.05, 0.05)	(0.01, 0.02, 0.03)
C4	(0.03, 0.05, 0.05)	(0.02, 0.03, 0.04)	(0.02, 0.03, 0.04)	(0, 0, 0.01)	(0.01, 0.02, 0.03)	(0.03, 0.05, 0.05)	(0.03, 0.05, 0.05)	(0.01, 0.02, 0.03)
C5	(0.01, 0.02, 0.03)	(0, 0.02, 0.03)	(0, 0.02, 0.03)	(0.02, 0.03, 0.03)	(0.03, 0.05, 0.05)	(0, 0.01, 0.02)	(0, 0.01, 0.02)	(0.03, 0.04, 0.05)
C6	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0.02, 0.03, 0.05)	(0.03, 0.05, 0.05)	(0, 0.01, 0.02)	(0.02, 0.03, 0.05)	(0.02, 0.03, 0.05)	(0, 0.01, 0.02)
C7	(0.03, 0.04, 0.05)	(0.03, 0.05, 0.05)	(0.03, 0.05, 0.05)	(0.03, 0.05, 0.05)	(0.01, 0.02, 0.03)	(0.03, 0.05, 0.05)	(0.03, 0.04, 0.05)	(0.01, 0.02, 0.03)
C8	(0.02, 0.03, 0.05)	(0.03, 0.04, 0.05)	(0.01, 0.02, 0.03)	(0.02, 0.03, 0.05)	(0, 0.01, 0.02)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0, 0.01, 0.02)
C9	(0, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0, 0.02, 0.03)
C10	(0.01, 0.02, 0.03)	(0.03, 0.04, 0.05)	(0, 0.01, 0.02)	(0.03, 0.04, 0.05)	(0.01, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0.03, 0.04, 0.05)	(0, 0.02, 0.03)
C11	(0.03, 0.05, 0.05)	(0, 0.02, 0.03)	(0.03, 0.04, 0.05)	(0.03, 0.05, 0.05)	(0, 0.01, 0.02)	(0.03, 0.05, 0.05)	(0.03, 0.05, 0.05)	(0.01, 0.02, 0.03)
C12	(0.01, 0.02, 0.03)	(0.02, 0.03, 0.05)	(0, 0.01, 0.02)	(0, 0.01, 0.02)	(0.03, 0.04, 0.05)	(0.01, 0.02, 0.03)	(0, 0.02, 0.03)	(0.02, 0.03, 0.05)
C13	(0.03, 0.05, 0.05)	(0.03, 0.04, 0.05)	(0.03, 0.05, 0.05)	(0.03, 0.04, 0.05)	(0, 0.01, 0.02)	(0.03, 0.05, 0.05)	(0.03, 0.04, 0.05)	(0, 0.01, 0.02)
C14	(0.03, 0.05, 0.05)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0.01, 0.02, 0.03)	(0.03, 0.04, 0.05)	(0.03, 0.05, 0.05)	(0, 0.01, 0.02)
C15	(0.01, 0.02, 0.03)	(0, 0.01, 0.02)	(0, 0.01, 0.02)	(0, 0.01, 0.02)	(0.02, 0.03, 0.05)	(0.01, 0.02, 0.03)	(0, 0.02, 0.03)	(0.01, 0.02, 0.03)
C16	(0, 0.02, 0.03)	(0, 0.01, 0.02)	(0.01, 0.02, 0.03)	(0, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0, 0.01, 0.02)	(0.01, 0.02, 0.03)	(0.01, 0.02, 0.03)
C17	(0.03, 0.05, 0.05)	(0.02, 0.03, 0.05)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0, 0.02, 0.03)	(0, 0.02, 0.03)	(0.03, 0.05, 0.05)	(0.01, 0.02, 0.03)
C18	(0.03, 0.05, 0.05)	(0.03, 0.05, 0.05)	(0.03, 0.05, 0.05)	(0.03, 0.05, 0.05)	(0, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0.03, 0.05, 0.05)	(0, 0.01, 0.02)
C19	(0.01, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0, 0.01, 0.02)	(0, 0.01, 0.02)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.05)	(0.01, 0.02, 0.03)	(0.02, 0.03, 0.05)
C20	(0.03, 0.05, 0.05)	(0.02, 0.03, 0.05)	(0.03, 0.04, 0.05)	(0.03, 0.05, 0.05)	(0, 0.01, 0.02)	(0, 0.02, 0.03)	(0.02, 0.03, 0.05)	(0.01, 0.02, 0.03)
C21	(0.02, 0.03, 0.05)	(0.03, 0.05, 0.05)	(0.01, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0.03, 0.04, 0.05)	(0.02, 0.03, 0.05)	(0, 0.02, 0.03)	(0.03, 0.04, 0.05)
C22	(0.02, 0.03, 0.05)	(0.01, 0.02, 0.03)	(0, 0.01, 0.02)	(0.01, 0.02, 0.03)	(0, 0, 0.01)	(0.02, 0.03, 0.03)	(0.01, 0.02, 0.03)	(0.02, 0.03, 0.04)
C23	(0.03, 0.04, 0.05)	(0.02, 0.03, 0.05)	(0.02, 0.03, 0.05)	(0.03, 0.04, 0.05)	(0.03, 0.04, 0.04)	(0, 0, 0.01)	(0.02, 0.03, 0.04)	(0.01, 0.02, 0.03)
C24	(0.03, 0.05, 0.05)	(0.02, 0.03, 0.05)	(0.03, 0.05, 0.05)	(0.02, 0.03, 0.05)	(0.01, 0.02, 0.03)	(0.03, 0.04, 0.04)	(0, 0, 0.01)	(0.01, 0.02, 0.03)
C25	(0.01, 0.02, 0.03)	(0, 0.02, 0.03)	(0, 0.02, 0.03)	(0.01, 0.02, 0.03)	(0.02, 0.03, 0.04)	(0.01, 0.02, 0.03)	(0, 0.01, 0.02)	(0, 0, 0.01)

Table 5. Total-relation fuzzy matrix

	C1	C2	C3	C4	C22	C23	C24	C25
C1	(0.01, 0.07, 0.37)	(0.04, 0.1, 0.4)	(0.04, 0.1, 0.37)	(0.04, 0.1, 0.39)	(0.03, 0.08, 0.34)	(0.02, 0.08, 0.37)	(0.02, 0.08, 0.37)	(0.01, 0.05, 0.31)
C2	(0.05, 0.12, 0.46)	(0.02, 0.08, 0.42)	(0.04, 0.1, 0.42)	(0.03, 0.09, 0.42)	(0.01, 0.07, 0.36)	(0.04, 0.1, 0.43)	(0.04, 0.11, 0.44)	(0.02, 0.07, 0.36)
C3	(0.05, 0.12, 0.47)	(0.05, 0.12, 0.47)	(0.02, 0.08, 0.41)	(0.04, 0.11, 0.45)	(0.01, 0.07, 0.38)	(0.04, 0.11, 0.45)	(0.05, 0.13, 0.46)	(0.02, 0.07, 0.37)
C4	(0.06, 0.14, 0.47)	(0.04, 0.11, 0.45)	(0.03, 0.1, 0.42)	(0.02, 0.08, 0.41)	(0.02, 0.08, 0.37)	(0.05, 0.12, 0.44)	(0.05, 0.13, 0.45)	(0.02, 0.08, 0.37)
C5	(0.02, 0.08, 0.35)	(0.01, 0.06, 0.34)	(0.01, 0.06, 0.32)	(0.02, 0.07, 0.34)	(0.04, 0.08, 0.31)	(0.01, 0.06, 0.33)	(0.01, 0.06, 0.33)	(0.04, 0.08, 0.3)
C6	(0.05, 0.12, 0.47)	(0.05, 0.12, 0.46)	(0.04, 0.11, 0.43)	(0.05, 0.12, 0.45)	(0.01, 0.07, 0.37)	(0.04, 0.11, 0.44)	(0.04, 0.11, 0.45)	(0.01, 0.06, 0.36)
C7	(0.05, 0.12, 0.45)	(0.05, 0.12, 0.44)	(0.05, 0.12, 0.41)	(0.05, 0.12, 0.43)	(0.02, 0.07, 0.36)	(0.05, 0.12, 0.42)	(0.05, 0.12, 0.43)	(0.01, 0.07, 0.35)
C8	(0.04, 0.11, 0.44)	(0.04, 0.11, 0.43)	(0.03, 0.09, 0.39)	(0.04, 0.1, 0.42)	(0.01, 0.06, 0.34)	(0.04, 0.1, 0.41)	(0.04, 0.11, 0.42)	(0.01, 0.06, 0.33)
C9	(0.01, 0.07, 0.36)	(0.02, 0.07, 0.36)	(0.01, 0.06, 0.33)	(0.01, 0.07, 0.35)	(0.02, 0.06, 0.31)	(0.02, 0.07, 0.35)	(0.02, 0.07, 0.35)	(0.01, 0.05, 0.29)
C10	(0.02, 0.09, 0.4)	(0.04, 0.09, 0.4)	(0.01, 0.06, 0.35)	(0.04, 0.09, 0.39)	(0.02, 0.06, 0.33)	(0.02, 0.07, 0.37)	(0.04, 0.1, 0.39)	(0.01, 0.05, 0.31)
C11	(0.06, 0.13, 0.44)	(0.02, 0.09, 0.42)	(0.05, 0.11, 0.41)	(0.05, 0.12, 0.43)	(0.01, 0.07, 0.35)	(0.05, 0.12, 0.42)	(0.05, 0.12, 0.43)	(0.02, 0.07, 0.35)
C12	(0.02, 0.09, 0.41)	(0.03, 0.09, 0.41)	(0.01, 0.07, 0.36)	(0.01, 0.07, 0.38)	(0.04, 0.09, 0.35)	(0.02, 0.08, 0.39)	(0.01, 0.08, 0.38)	(0.03, 0.08, 0.34)
C13	(0.06, 0.13, 0.45)	(0.05, 0.12, 0.44)	(0.05, 0.12, 0.41)	(0.05, 0.12, 0.43)	(0.01, 0.07, 0.35)	(0.05, 0.12, 0.42)	(0.05, 0.12, 0.43)	(0.01, 0.06, 0.34)
C14	(0.05, 0.13, 0.44)	(0.04, 0.11, 0.43)	(0.04, 0.11, 0.41)	(0.05, 0.11, 0.42)	(0.01, 0.07, 0.35)	(0.04, 0.11, 0.42)	(0.05, 0.12, 0.42)	(0.01, 0.06, 0.34)
C15	(0.02, 0.08, 0.38)	(0.01, 0.06, 0.36)	(0.01, 0.06, 0.33)	(0.01, 0.06, 0.35)	(0.03, 0.07, 0.33)	(0.01, 0.07, 0.35)	(0.01, 0.07, 0.35)	(0.02, 0.06, 0.31)
C16	(0.01, 0.07, 0.38)	(0.01, 0.07, 0.36)	(0.01, 0.07, 0.35)	(0.01, 0.07, 0.36)	(0.02, 0.06, 0.32)	(0.01, 0.06, 0.35)	(0.02, 0.07, 0.36)	(0.02, 0.06, 0.31)
C17	(0.05, 0.13, 0.44)	(0.04, 0.11, 0.43)	(0.05, 0.11, 0.41)	(0.04, 0.11, 0.42)	(0.01, 0.07, 0.35)	(0.02, 0.08, 0.4)	(0.05, 0.12, 0.42)	(0.01, 0.07, 0.34)
C18	(0.06, 0.13, 0.43)	(0.05, 0.12, 0.42)	(0.05, 0.12, 0.4)	(0.05, 0.12, 0.41)	(0.01, 0.07, 0.34)	(0.03, 0.09, 0.4)	(0.05, 0.12, 0.41)	(0.01, 0.06, 0.33)
C19	(0.02, 0.08, 0.4)	(0.02, 0.08, 0.4)	(0.01, 0.06, 0.36)	(0.01, 0.07, 0.37)	(0.03, 0.08, 0.35)	(0.04, 0.09, 0.39)	(0.02, 0.08, 0.39)	(0.03, 0.07, 0.34)
C20	(0.05, 0.12, 0.44)	(0.04, 0.11, 0.43)	(0.05, 0.11, 0.41)	(0.05, 0.12, 0.42)	(0.01, 0.06, 0.35)	(0.02, 0.08, 0.4)	(0.04, 0.11, 0.42)	(0.02, 0.07, 0.35)
C21	(0.04, 0.1, 0.43)	(0.05, 0.11, 0.42)	(0.02, 0.08, 0.38)	(0.02, 0.09, 0.4)	(0.04, 0.09, 0.36)	(0.03, 0.09, 0.4)	(0.01, 0.08, 0.39)	(0.04, 0.09, 0.35)
C22	(0.04, 0.1, 0.42)	(0.02, 0.08, 0.4)	(0.01, 0.07, 0.37)	(0.02, 0.08, 0.39)	(0.01, 0.05, 0.32)	(0.03, 0.08, 0.39)	(0.02, 0.08, 0.39)	(0.02, 0.07, 0.34)
C23	(0.05, 0.12, 0.46)	(0.04, 0.11, 0.45)	(0.04, 0.1, 0.42)	(0.05, 0.12, 0.44)	(0.03, 0.09, 0.38)	(0.02, 0.07, 0.4)	(0.04, 0.11, 0.43)	(0.02, 0.07, 0.36)
C24	(0.06, 0.14, 0.47)	(0.04, 0.12, 0.46)	(0.05, 0.12, 0.43)	(0.04, 0.12, 0.45)	(0.02, 0.08, 0.38)	(0.04, 0.11, 0.44)	(0.02, 0.08, 0.41)	(0.02, 0.08, 0.37)
C25	(0.02, 0.08, 0.37)	(0.01, 0.07, 0.36)	(0.01, 0.06, 0.34)	(0.01, 0.07, 0.36)	(0.02, 0.07, 0.32)	(0.02, 0.07, 0.35)	(0.01, 0.06, 0.35)	(0.01, 0.04, 0.28)

©2018: The Royal Institution of Naval Architects

Table 6. Fuzzy values of $\tilde{r}_i, \tilde{c}_j,\ \tilde{r}_i + \tilde{c}_j, \tilde{r}_i - \tilde{c}_j$

	$\tilde{r}_i$	$\tilde{c}_j$	$\tilde{r}_i + \tilde{c}_j$	$\tilde{r}_i - \tilde{c}_j$
C1	(0.55, 1.9, 8.89)	(0.95, 2.66, 10.6)	(1.5, 4.56, 19.48)	(-10.05, -0.75, 7.94)
C2	(0.8, 2.37, 10.24)	(0.83, 2.43, 10.35)	(1.63, 4.8, 20.59)	(-9.55, -0.07, 9.41)
C3	(0.91, 2.58, 10.76)	(0.73, 2.24, 9.62)	(1.64, 4.82, 20.38)	(-8.71, 0.34, 10.03)
C4	(0.91, 2.58, 10.41)	(0.82, 2.42, 10.09)	(1.73, 5, 20.5)	(-9.18, 0.16, 9.58)
C5	(0.37, 1.57, 7.99)	(0.5, 1.81, 8.77)	(0.87, 3.39, 16.76)	(-8.4, -0.24, 7.49)
C6	(0.83, 2.43, 10.47)	(0.79, 2.36, 10.03)	(1.62, 4.79, 20.5)	(-9.2, 0.07, 9.68)
C7	(0.83, 2.42, 9.98)	(0.82, 2.42, 10.28)	(1.65, 4.84, 20.26)	(-9.45, 0.01, 9.15)
C8	(0.66, 2.12, 9.76)	(0.77, 2.33, 10.07)	(1.44, 4.45, 19.83)	(-9.41, -0.21, 8.98)
C9	(0.36, 1.57, 8.33)	(0.53, 1.88, 9.17)	(0.9, 3.45, 17.5)	(-8.8, -0.31, 7.8)
C10	(0.5, 1.82, 8.95)	(0.44, 1.71, 8.5)	(0.94, 3.53, 17.46)	(-8, 0.11, 8.51)
C11	(0.83, 2.43, 9.88)	(0.81, 2.39, 9.93)	(1.64, 4.82, 19.8)	(-9.09, 0.05, 9.07)
C12	(0.58, 1.96, 9.31)	(0.49, 1.81, 8.91)	(1.07, 3.77, 18.22)	(-8.33, 0.16, 8.82)
C13	(0.87, 2.49, 10)	(0.76, 2.3, 9.77)	(1.63, 4.79, 19.77)	(-8.91, 0.19, 9.24)
C14	(0.77, 2.32, 9.83)	(0.76, 2.31, 10.03)	(1.54, 4.63, 19.86)	(-9.26, 0.02, 9.07)
C15	(0.43, 1.69, 8.51)	(0.56, 1.92, 9.1)	(0.98, 3.61, 17.61)	(-8.67, -0.23, 7.95)
C16	(0.45, 1.73, 8.65)	(0.42, 1.66, 8.54)	(0.87, 3.39, 17.19)	(-8.09, 0.06, 8.23)
C17	(0.76, 2.3, 9.82)	(0.85, 2.46, 10.08)	(1.61, 4.76, 19.91)	(-9.33, -0.17, 8.98)
C18	(0.78, 2.34, 9.58)	(0.8, 2.38, 10.03)	(1.59, 4.72, 19.61)	(-9.24, -0.04, 8.77)
C19	(0.55, 1.91, 9.19)	(0.46, 1.74, 8.65)	(1.01, 3.65, 17.84)	(-8.1, 0.18, 8.73)
C20	(0.72, 2.23, 9.84)	(0.76, 2.3, 9.95)	(1.49, 4.53, 19.8)	(-9.23, -0.07, 9.08)
C21	(0.64, 2.08, 9.47)	(0.49, 1.81, 8.88)	(1.14, 3.89, 18.35)	(-8.23, 0.27, 8.98)
C22	(0.58, 1.97, 9.41)	(0.49, 1.79, 8.69)	(1.07, 3.76, 18.1)	(-8.11, 0.18, 8.93)
C23	(0.79, 2.36, 10.29)	(0.75, 2.28, 9.93)	(1.54, 4.64, 20.22)	(-9.14, 0.07, 9.54)
C24	(0.93, 2.62, 10.42)	(0.84, 2.45, 10.09)	(1.77, 5.07, 20.51)	(-9.16, 0.16, 9.58)
C25	(0.43, 1.68, 8.49)	(0.4, 1.63, 8.41)	(0.83, 3.31, 16.9)	(-7.98, 0.05, 8.09)

Table 7. Crisp values of $r_i,\ c_j,\ r_i + c_j, r_i - c_j$

	r_i	c_j	$r_i + c_j$	$r_i - c_j$
C1	3.78	4.73	8.51	-0.96
C2	4.47	4.54	**9.01**	**-0.07**
C3	4.75	4.20	**8.95**	**0.56**
C4	4.63	4.44	9.08	0.19
C5	3.31	3.69	7.00	-0.38
C6	4.58	4.39	8.97	0.19
C7	4.41	4.51	**8.91**	**-0.10**
C8	4.18	4.39	8.57	-0.21
C9	3.42	3.86	7.28	-0.44
C10	3.76	3.55	7.31	0.21
C11	4.38	4.37	8.76	0.01
C12	3.95	3.74	7.69	0.21
C13	4.45	4.28	8.73	0.17
C14	4.31	4.37	8.67	-0.06
C15	3.54	3.86	7.40	-0.32
C16	3.61	3.54	7.15	0.07
C17	4.29	4.47	**8.76**	**-0.17**
C18	4.23	4.40	8.64	-0.17
C19	3.88	3.61	7.50	0.27
C20	4.27	4.34	8.60	-0.07
C21	4.06	3.73	**7.79**	**0.34**
C22	3.99	3.65	**7.64**	**0.33**
C23	4.48	4.32	8.80	0.16
C24	4.66	4.46	9.12	0.20
C25	3.53	3.48	7.01	0.05