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Risk assessment to improve reliability in towing system of tugboats using fuzzy based FMEA

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ABSTRACT

The towing system is one of the most crucial parts of a tug boat. The towing process in tugboats, where a lot of machines and ship equipment are involved in the process, carries many risks and potential failures. Therefore, this operation can cause serious injuries, fatal accidents, equipment damage, disruption of towing operations and loss of time and money. In this study, a comprehensive risk analysis was conducted to increase the reliability of the tugboat towing system. Firstly, the failure modes, causes and results of the towing system were determined. Then, the failure modes and effect analysis method were integrated with the rule-based fuzzy approach and risk prioritization was performed. According to the findings, the three critical failure modes among 23 failure modes were towing system rope failure, insufficient air supply to the towing system from the compressor and cracking or breaking of system components, respectively. Additionally, corrective and preventive actions were suggested for a total of eleven failure modes with high RPN values. This study aims not only to provide a theoretical contribution to the prevention of towing system-related accidents, but also to provide a practical framework that can be used in practice for all maritime stakeholders, especially tugboat owners and crews.

1. Introduction

Maritime trade has a very important position in the global economic system. In addition, the transfer of energy and raw materials between countries makes their importance more critical. Despite significant developments in maritime technology for the safe navigation of ships at sea, the desired decrease in maritime accidents has not been seen. Maritime accidents can cause serious injuries to passengers or crew. In addition, fatal accidents are also seen in some cases. The effects of maritime accidents on the environment and the economy can reach serious dimensions. For this reason, maritime safety studies have an important area in the literature with increasing interest.

Grounding and collision, two of the most important issues in marine accidents, have been on the agenda of researchers for many years. For example, Uğurlu et al. [1] created fault trees for grounding and collision in oil tankers and offered suggestions to diminish the risk of accidents. Youssef and Paik [2] conducted a

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quantitative risk analysis by collecting approximately 50 years of ship grounding accident data. Abaei et al. [3] developed a methodology to determine the grounding risk for ships using data obtained from time-dependent hydrodynamic simulations. Uğurlu et al. [4] conducted a comprehensive risk analysis for the Black Sea region using HFACS and Bayesian Networks and provided preventive recommendations. Silveira et al. [5] addressed the ship collision risk by adding an expert-based judgmental technique to the ELECTRE Tri-nC method. Abebe et al. [6] combined different machine learning algorithms with the Dempster-Shafer theory to determine the collision risk index. Ma et al. [7] proposed a methodology for ship grounding accidents that includes a Complex Network (CN), the improved K-shell algorithm, Event Tree Analysis (ETA) and the Susceptible Infected Recovered (SIR) model. Gao and Zhang [8] developed a decision-making model to prevent collision in coastal waters utilizing Automatic Identification System (AIS) data. The developed model was successfully tested and shown to be effective in collision avoidance. Zhang and Zhang [9] conducted a comprehensive study on the navigation safety of intelligent ships. The study focused on the risk perception based on different classification societies and established an index system of navigation risk factors for intelligent ships.

In addition to safety at sea studies that include such as ship collisions and grounding, risk analyses related to the main engine, auxiliary machinery systems and ship equipment in order to increase system reliability are also very important research areas. The risk assessment on the ship main engine was carried out by Ünver et al [10]. The study focused on maintenance activities. A comprehensive study on auxiliary engines was carried out by Alarcin et al. [11] using fuzzy AHP and fuzzy TOPSIS methods. The operational risk study on the marine boiler, which is one of the auxiliary engines, was presented by Ceylan and Çelik [12] using Analytic Network Process (ANP). Sezer et al. [13] offered Failure Mode Effects and Criticality Analysis (FMECA) and Dempster-Shafer theory for the risk assessment of the ballast water system. Gürgen et al. [14] presented a risk study on the steering gear with fuzzy Fault Tree Analysis (FTA). The steering gear risk assessment was also addressed by Göksu et al. [15] and the analysis was carried out with the fuzzy-Bayesian networks method in the study. Su et al. [16] suggested a virtual environment to monitor and predict real-time failures in cooling pumps. Bolbot et al. [17] created a fault tree for the risk analysis of the diesel-electric propulsion system using the Combinatorial Approach to Safety Analysis (CASA). The risk analysis related to the crankcase, which is an important part of the main engine, was presented by Ünver et al. [18]. In the study, the fault tree of the crankcase explosion was created.

Risk analysis tools are frequently used to analyze risks not only in the maritime field but also in other disciplines. For example, Arvanitoyannis and Varzakas [19] studied risk analysis in the food industry. In the study, risk assessment of salmon production was carried out using the Failure Mode and Effects Analysis (FMEA) method. Chen et al. [20] integrated the fuzzy approach into the Fine-Kinney model to assess occupational health and safety risks. Guimarães et al.[21] used the FMEA method for risk analysis in the nuclear power plant. Yüksel et al. [22] combined the spherical fuzzy entropy and Multi-Attribute Ideal-Real Comparative Assessment (MAIRCA) methods to evaluate the risks of hydroelectric energy investments and to rank the alternative investment countries, respectively. Švadlenka et al. [23] handled the risks in the Crowd-Shipping Criteria Importance Assessment (CIMAS) method and prioritized the existing risks.

It is evident from the literature that there are many tools for risk analysis. The decision on which tool to use depends on the purpose of the study, uncertainty, data type, time and resources. As mentioned above, many different methods were used for risk studies in various sectors. Each method has specific steps, advantages and limitations. When FMEA and FTA methods are compared, it is seen that the FTA method has a more complex structure. The FTA method focuses on more specific failure modes, while the FMEA method can examine the system or process more comprehensively. FTA performs deductive failure analysis by establishing logical connections between failure modes, while FMEA is an inductive failure analysis method. Visualization ability is an important advantage of the FTA method. On the other hand, FMEA uses a table format and presents the cause and effect of each failure mode in detail [24, 25]. HAZOP is a qualitative risk analysis method that focuses on deviations from operational objectives. In the HAZOP method, guide words play an important role in risk analysis. However, a comprehensive analysis is required for each failure mode in the FMEA method. [25, 26]. When basic FMEA is accompanied by criticality analysis, it becomes semiquantitative and is called Failure Modes, Effects and Criticality Analysis (FMECA). FMECA ranks the risks according to the Risk Priority Number (RPN) value and offers preventive actions for critical failure modes. However, it should be noted that scoring approaches such as RPN can also be used with the HAZOP method to rank risks [13, 27]. Risk matrix is a risk analysis tool that categorizes risks as a visual table using the probability and impact value of risks. The x-axis of the table has probability, y-axis has severity, and the risk levels are represented in different colors in the cells. The method is relatively simple and easy to understand compared to FMEA. FMEA method uses more parameters and offers detailed analysis. But, the risk matrix is not comprehensive and only provides a general overview [25].

Among various risk analysis methods, FMEA method is one of the most frequently used methods in the literature because of its easy applicability and strong analysis capability. Although FMEA is just one of many proactive strategies, its following prominent features make it a strong candidate for engineering applications: (i) It has the ability to analyse the entire system or process as well as a small part of it (ii) It can rank risks numerically according to the RPN value (iii) It offers preventive actions for critical risks (iv) It allows limited resources to be used primarily in preventing critical risks (v) It can be successfully applied in many disciplines [28].

It is possible to consider the studies carried out with the FMEA method in three categories at the maritime sector. The first category includes applications carried out with the classical FMEA method. But it has the disadvantages mentioned in Section 2. One of the important problems of this method is that it cannot handle uncertainties in the analysis process. Various approaches such as fuzzy logic, grey set theory, Z numbers and D numbers are used to handle uncertainties while performing risk assessment [29]. The most common method to handle uncertainties in the FMEA method is the fuzzy approach using linguistic values [30].The second category refers to studies using the fuzzy FMEA method. Finally, the third category refers to risk studies carried out by integrating the FMEA method with other methods or approaches.

Jae-Ohk et al. [31] conducted a risk analysis for the hatchway system of a bulk carrier using the traditional FMEA method. In the study, the hatchway system was divided into 5 subsystems, and a total of 43 failure modes were determined. Çiçek and Çelik [32] performed an application with classical FMEA for crankcase explosion in marine diesel engines. In the study, 12 potential failure modes that could cause a crankcase explosion were determined.

Due to the disadvantages of classical FMEA, in recent years, researchers have been using the fuzzy-based FMEA method instead of the classical FMEA method. Akyüz et al. [33] carried out risk analysis to assess the concentrated inspection campaign database of the Memorandum of Understanding (MoUs). The authors conducted a study specifically for the ship's fire-safety system using fuzzy FMEA with a rule-based expert. Ahmed and Gu [34] conducted a risk assessment for marine boilers. In the study conducted using the fuzzy-based FMEA method, a total of 30 potential failure modes were identified. Ceylan [35] performed a risk analysis for compressor systems on ships using the rule-based FMEA method. In the study, 33 failure modes were presented, and the analysis was performed with an inference engine having 125 If-Then rules. Göksu and Arslan [36] presented a comprehensive dynamic risk study for ship berthing/unberthing operations. In the study, a total of 25 failure modes were evaluated with seven experts and RPN values were calculated using rule-based FMEA. Ceylan et al. [37] analyzed an accident involving a bulk carrier named M/V Vitaspirit. By examining the accident report and available data, 15 root causes that could have caused the accident were obtained. Then, the rule-based fuzzy FMEA method was used to prioritize risk factors.

In addition to FMEA and fuzzy FMEA applications in the maritime field, there are also studies where the FMEA method is applied together with other techniques. Helvacıoğlu and Özel [38] used the fuzzy TOPSIS method and FMEA method together for the risk assessment of the fire system in yachts. The analysis was carried out with both classical FMEA and hybrid method. Kang et al. [39] used the modified FMEA method for floating offshore wind turbines risk analysis. In another study on floating offshore wind turbines risk analysis, Li et al. [40] integrated the Analytic Hierarchy Process (AHP) method into the FMEA method. In the study, the weights of the risk indicator parameters were obtained by the AHP method. Efe [41] implemented an application with the FMEA method strengthened with Quality Function Deployment (QFD) and VIKOR methods to reduce occupational accidents in the shipbuilding sector. In the study, the weight values of the risk parameters required for the RPN calculation were obtained with intuitionistic fuzzy numbers. Yeo et al. [42] performed a risk analysis using the FMEA method and the TOPSIS method together for the Liquefied Petroleum Gas (LPG)-fueled marine engine system. As a result of a comprehensive evaluation in the study, a risk ranking was carried out for a total of 89 failure modes. Lazakis et al. [43] combined FTA with FMEA to perform a ship main engine risk assessment. In addition, a model was created for some physical indicators of the main engine, such as temperature and pressure values, with an Artificial Neural Network (ANN). Fu et al. [44] used FMEA and Functional Resonance Analysis Method (FRAM) for risk analysis application in nuclear-powered icebreakers. In addition, Monte Carlo Simulation (MCS) was used for advanced calculations. Pillay and Wang [45] applied risk analysis by dividing ocean going fishing vessel into four main systems. The researchers proposed a FMEA approach based on fuzzy rule base and grey relation theory. The same problem was later addressed by Wang et al. [46] by hybridizing extended matter-element model and AHP with FMEA method.

As seen in the studies at current literature, various risk assessment methods have been successfully applied in many areas of maritime industry. However, to the best of our knowledge, no risk assessment studies specifically addressing tugboats have been reported. Tugboats are specialized vessels equipped with high-powered engines and complex systems, among which the towing system is one of the most critical components. Risk analysis for towing systems is vital due to their pivotal role in the safe and efficient operation of tugboats. Failures in the towing system can result in severe consequences, including operational downtime, equipment damage, environmental pollution, and even loss of life. Therefore, a detailed study to identify and reduce risks in towing systems is essential to improve safety and reliability in tugboat operations.

The aim of this study is to perform a comprehensive risk assessment of tugboat towing systems. In this context, firstly, critical failure modes related to the towing system were determined. Then, a rule-based fuzzy approach was added to the FMEA method to rank the failure modes. Finally, applicable preventive actions were presented to reduce the risks. The tangible contribution of this study to the industry and literature is the presentation of preventive actions for critical failure modes related to the towing system. Thus, by taking the suggestions into consideration, loss of life and injuries can be prevented, operational costs will be reduced, and contribution will be made to the protection of the environment.

In this context, the paper was organized into five sections. The literature review and motivation of this study are provided in this section. Section 2 introduced the FMEA method and rule-based fuzzy approach. In the Section 3, the description of the problem and the application of risk analysis with the FMEA method were explained. Result and discussion were given in Section 4. The last section concluded the study and offered potential future work.

2. Failure Mode and Effect Analysis (FMEA)

The birth of FMEA was in 1949 with the US Armed Forces Military Procedures documents. For the first time, the necessary procedures for the application of FMEA were specified in this document. In the 1960s, this method was implemented for the National Aeronautics and Space Administration (NASA) programs. In the late 1970s, the method was used in the automotive sector with Ford Motor Company. As a result of these successful applications, the method was adapted to many different disciplines such as energy, banking, construction, and health in the following years [36].

FMEA reveals potential failure modes that may occur in a system, product or equipment. It also contributes to increasing system reliability by systematically analysing the effects of these failures and offering preventive actions to minimize or completely eliminate failures [39].

In the FMEA method, RPN is calculated to perform risk prioritization of failure modes. The RPN value is obtained by multiplying three parameters, Occurrence (O), Severity (S), and Detection (D), as follows [33, 36]:

$$RPN = O \cdot S \cdot D \tag{1}$$

Occurrence is an indicator of the frequency of occurrence of a failure mode. A high probability value increases the probability of the failure occurring. Severity is a parameter that shows the effect of the failure mode on the system when it occurs. The higher the severity value, the higher the final effect of the failure on the system. Detection is the ability to realize the failure mode before it occurs. This parameter is a reverse indicator. In other words, a low detection value indicates that the relevant failure can be easily detected, while a high value means that the failure is difficult to detect [39].

The *O*, *S* and *D* parameters can take integer values between 1 and 10. Therefore, the RPN value is obtained between 1 and 10,000. Failure modes with high RPN values are the ones that need to be taken into account first. Depending on the study, meanings (linguistic variables) are assigned to each score of the three parameters. This process is carried out using relevant field experts and existing literature.

Although the traditional FMEA method is used as a practical risk assessment tool for many application areas, it has some important problems. Especially in recent years, this issue has been brought to the agenda by many researchers, and instead of classical FMEA, enhanced FMEA methods are preferred. Some disadvantages of traditional FMEA mentioned in the literature are as follows [45, 47-50]:

- Different combinations of *O*, *S* and *D* parameter values may produce the same RPN value. However, the risk effects of failure modes with the same RPN value may be different.
- The importance weights of *O*, *S* and *D* parameters are equal.
- Since the RPN value is obtained by direct multiplication of three parameters, a unit change in *O*, *S* and *D* parameters has a very large or very small effect according to the RPN value.
- It is difficult to express and scale the *O*, *S* and *D* parameters numerically. It may cause problems in some cases.
- The relative importance levels of the individuals in the expert group determining the *O*, *S* and *D* values of failure modes are not taken into account.

Since classical FMEA has the disadvantages mentioned above, in this study, fuzzy logic theory was adapted to the classical FMEA method. In order to cope with the uncertainties and subjective evaluations that exist in the real world, Zadeh [51] introduced the concept of fuzzy logic in 1965. In this study, FMEA method is integrated with fuzzy approach to handle uncertainties. Fuzzy logic offers a more flexible approach instead of true-false or 0-1 in classical logic. In classical logic, the number 0 is not a member of the fuzzy set, while 1 is a full member of the fuzzy set, but in fuzzy logic, a value depends on the membership function of different orders. Therefore, linguistic terms closer to the human thought system are used in this system [36, 52, 53].

It is possible to categorize the fuzzy FMEA applications in the current literature into two categories. While the fuzzy aggregation operator approach is used in the first category, the rule-based expert system approach is used in the second category. But the fuzzy aggregation operator has the disadvantages of the classical FMEA method mentioned above.

According to Liu et al. [28], the most preferred approach in the FMEA method is the integration of the fuzzy rule base system into the FMEA. The basic working principle of the rule-based fuzzy FMEA method was visualized in Figure 1. The greatest benefit of this approach is that risk analysis can be performed with uncertain and imprecise data. It can also bring together the knowledge and experience of the team members who perform the analysis more reasonably. Therefore, the rule-based expert system approach was used for risk analysis in this study. However, it also has some limitations. The fuzzy rule-based approach includes more complex process steps compared to the classic FMEA. Appropriate membership functions must be determined for the risk factors (*O, S* and *D*) and risk level (RPN). In addition, creating a fuzzy if-then rule base is laborious and time-consuming. Team members must create enough rules. Otherwise, the accuracy of the risk level ranking is weak.

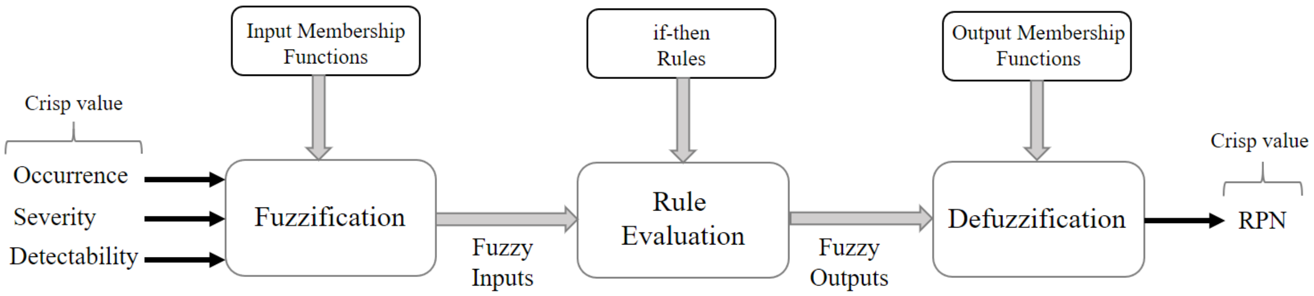
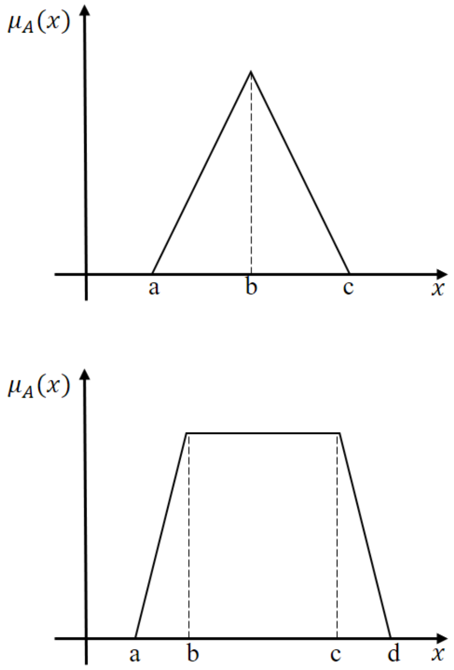


Fig. 1 The basic mechanism of rule-based fuzzy FMEA [54]

In order to perform risk assessment with the rule-based fuzzy FMEA method, firstly, the linguistic terms and their corresponding membership functions are determined. This procedure is carried out for both the input parameters *O*, *S* and *D* values and the output value RPN parameter. In the literature, the triangular and trapezoidal membership functions given in Figure 2 are frequently used for membership functions [33, 50].



$$\mu_A(x) = \begin{cases} \frac{x-a}{b-a}, & if\ a \le x \le b \\ \frac{c-x}{c-b}, & if\ b \le x \le c \\ 0 & or\ else \end{cases}$$

$$\mu_A(x) = \begin{cases} \frac{x-a}{b-a}, & if\ a \le x \le b \\ 1, & if\ b \le x \le c \\ \frac{d-x}{d-c}, & if\ c \le x \le d \\ 0 & or\ else \end{cases}$$

Fig. 2 Triangular and trapezoidal membership functions

Then the rule-based system is created. An example rule mechanism for risk assessment is shown below:

$$R_i : \boldsymbol{IF}\ o, O_i\ \boldsymbol{and}\ s, S_i\ \boldsymbol{and}\ d, D_i\ \boldsymbol{THEN}\ RPN\ is\ R_i \qquad i = 1, 2, 3 \ldots k \tag{2}$$

where R_i is the rule number; o, s, d are risk parameters; O_i, S_i, D_i are input fuzzy sets; RPN is the output value, and k is the total rule number. A fuzzy inference system is used to obtain a result according to the created rules. The most popular fuzzy inference models are Mamdani and Takagi-Sugeno models. The most popular of these is the Mamdani method. After the if-then rule is created, the membership degrees ($\mu_{Oi}(o), \mu_{Si}(s),\ \mu_{Di}(d)$) in the fuzzy set of the crisp input values (*o*, *s* and *d*) are calculated. This is called the fuzzification process. Next, the weights of rule activation are determined. For cases where each rule has multiple antecedents, the activation weight (α_i) is calculated using the AND operator as follows [33, 36]:

$$\alpha_i = \mu_{Oi}(o) \wedge \mu_{Si}(s) \wedge \mu_{Di}(d) \qquad 1 \le i \le k \tag{3}$$

After obtaining the activation weights for all rules, the output fuzzy set ($\mu_{R_i'}$) for each rule is determined using the minimum t-norm as in the following equation [33, 36]:

$$\mu_{R_i'}(RPN) = \alpha_i \wedge \mu_{R_i}(RPN) \quad (4)$$

Then, all rules are aggregated to create the final matching degree for activated rules of FMEA. Equation 5 is applied to combine the output fuzzy sets by employing the maximum (union) operation [33, 36]:

$$\mu_{R_i'}(RPN) = max_{i=1,2,\ldots k}\left(\mu_{R_i'}(RPN)\right) \quad (5)$$

The result obtained after the fuzzy inference stage is still a fuzzy value. Therefore, to convert the fuzzy result into a meaningful form, defuzzification is required. There are different methods for defuzzification, such as the center of gravity method, the center of clusters method and the height method. The center of gravity method, one of the most used methods for defuzzification, can be applied with the following equation [33, 36].

$$RPN'' = \frac{\sum_{j=1}^{l} \mu_{R'}(RPN_j) \times RPN_j}{\sum_{j=1}^{l} \mu_{R'}(RPN_j)} \quad (6)$$

where RPN'' represents the estimated value and l denotes the number of activated rules (RPN_j).

3. Towing System of Tugboats

Tugs are powerful marine vessels with towing and pushing capabilities that usually guide large ships in harbours, open seas and narrow passages. These special boats increase the maneuverability of ships, allowing them to dock at ports, leave and move safely through narrow waterways, and undertake rescue operations in hazardous situations. Despite advances in technologies for autonomous navigation, large ships still need tugboat assistance due to their limited maneuverability [55].

Tugs use their own towing system to perform the tasks expected of them. Tugboat towing systems are designed to tow or secure ships. During the towing process, a balanced system must be created between dynamic and static forces. These systems are designed to withstand the loads caused by environmental factors such as wind, waves and currents at sea. One of the most important tasks during the towing operation is to control the tension of the towing rope. In tugboats, towing winch and pulley systems are generally used to perform this task. The towing winch increases both operational efficiency and safety by allowing the winding, unwinding and tension control of the towing ropes or chains.

The basic elements of the towing system of a tugboat are the drum, brake mechanism, drive system, control unit and ropes. The drum is a cylindrical structure on which the rope or chain is wound. It ensures that the rope is collected and released properly. The brake mechanism is an important system that prevents unwanted movement of the rope or chain during pulling and works mechanically, hydraulically or electrically. The drive system is the power source that provides the movement of the towing winch and is usually powered by hydraulic, electric or diesel engines. The control unit, which provides operational control of the towing winch, is used to manage parameters such as tension, pulling force and drum speed. The materials used in pulling operations are synthetic ropes or steel ropes; synthetic ropes are light and flexible, while steel ropes are more durable.

The working principle of the towing system includes processes such as winding and unwinding the rope, tension control and load management. The drum starts the pulling operation by winding the rope and moves in the opposite direction during release. The towing winch system maintains a certain level of tension to prevent the rope from breaking and modern systems have automatic tension adjustment features. While the pulling force and load are balanced with the turning capacity of the drum, the brake systems are activated in the event of overload, ensuring safety.

Maintenance and safety precautions are vital to ensure the long-lasting and reliable operation of the system. Ropes and chains should be checked regularly for wear and tear; the brake mechanism and drive system should be lubricated and tested periodically. Electronic control units should be calibrated at regular intervals. The towing winches should be checked before operation and possible faults should be eliminated. Rope or chain tension should not be exposed to excessive load and emergency procedures, and crew training should not be disrupted. Unfortunately, accidents related to the towing system continue to occur due to reasons such as ignoring maintenance and repair activities, putting time pressure on the ship's crew to finish the towing operation, and lack of or inadequate training.

Table 1 Failure modes, causes and consequences

Code	Failure Mode	Failure Cause	Failure Consequence
FM01	Towing system rope failure	The rope is expired, the rope is deformed, the rope is not checked on time, the rope is not washed with fresh water after the maneuvering operations, improper positioning during the maneuver, the bollards or hawsehole through which the rope passes are burred, the rope has not a protective sheath, personnel lack of training/experience.	Personnel death or injury due to rope breakage, loss of directional control of the ship being pulled by the tugboat, risk of accident during the ship docking operation, risk of the broken rope piece getting tangled in the propeller of the ship or the tugboat performing the towing operation, the towing winch going off, delay in maneuvering operations, financial loss, loss of reputation.
FM02	Insufficient air supply to the towing system from the compressor	Air supply compressor failure, leakage in air lines, leakage from compressor air tank, pressure valves not performing their duties in the air system	Failure of the towing system due to failure of the pneumatic piston that moves the towing winch, loss of energy due to possible air leaks
FM03	Supply of excess air to the towing system from the compressor	Incorrect adjustment of the pressure set value from the pressure regulators, failure of the pressure valves in the air system to perform their duties.	The towing system does not work due to the pneumatic piston that moves the towing winch not working, possible risk of work accidents due to excess pressure, personnel injuries.
FM04	Low hydraulic oil pressure	The pumps that pump hydraulic oil are broken, there is a leak in the oil tank, water is mixed into the oil and therefore the oil heats up before the pressure reaches the desired level and shuts down the system, there are leaks in the oil line, the directional valves that give flow to the oil are broken and the oil returns to the main tank without creating pressure	The towing winch being off or moving in one direction because the hydromotors and directional valves in the towing system cannot perform their duties, lack of maneuverability, possible marine pollution due to oil leakage and financial losses brought about by heavy fines, work accidents due to slipping due to oil leakage, personnel injuries.
FM05	Burst/breakage of hydraulic hoses in the towing system	The replacement period of hydraulic hoses is passed, hydraulic hoses are not purchased at the appropriate pressure value, pressure regulating valves do not function and send excessive pressure to the hoses, hose maintenance and checks are not performed on time.	If it happens during the maneuver, the maneuver operation is jeopardized, the towing system is damaged, oil leakage, personnel injuries, loss of money.
FM06	No energy supply to the towing system	Malfunction of the electrical panel controlling the towing system, failure to perform preventive maintenance on the electrical system on time, malfunction of the PLCs that drive the system, poor contact in the electrical cables, short circuiting of the system, oxidation in the electrical cables,	Towing winches being off, personnel injuries due to electrical leaks, financial losses
FM07	Failure of the solenoid valve	The solenoid valves on the towing winch are broken, the solenoid valves are not maintained on time, the oil flow logs under the solenoid valves do not function.	Towing system lacks maneuverability (movement in one direction), financial losses
FM08	Abnormal piston noise/piston wear	Insufficient hydraulic oil pressure from the pumps, broken/deformed piston rings, foreign matter inside the pistons, worn piston shaft	Damage to towing system parts, reduction in operating efficiency
FM09	The towing winch linings are excessively thin	Failure to check the brake linings on time, burrs on the brake pad bed, use of improper brake linings	Danger of the towing winch losing its rope during maneuvering operation, the tugboat missing the ship and the ship hitting the pier due to reduced braking capability
FM10	Hydraulic pump noise	Insufficient oil reaching the pump, high oil viscosity, pump wear, excessive oil pressure, excessive rpm, excessively low oil tank level, clogged oil tank pipes, personnel lack of training/experience	Damage to hydraulic system parts, occupational disease caused by noise level of working personnel, reduction in pump efficiency

FM11	Air or foam in the oil in the towing system	Excessive resistance in the suction line	Decrease in towing system operation efficiency
FM12	Failure of the towing system remote control system	Breakage/deterioration of the joystick controlling the bridge towing system, loss of signaling of the remote control system	Due to manual control, there may be delays of seconds in the maneuvering operation and disruptions in the operation.
FM13	System overheating	No cooling water source, blocked or contaminated oil cooler, excessive oil viscosity, abnormal internal leakage within one or more components, excessive load on pump, valve or motor	Damage to towing system parts, reduction in operating efficiency
FM14	Engine speed of towing winch is lower than the specified value	Pump wear, engine speed too low, engine wear, oil temperature too high, excessive ambient temperature, pump clearance, control valve leakage, engine overload, personnel lack of training/experience	Damage to towing winch parts, reduction in operating efficiency
FM15	No rotation of the motor shaft	Pump operating in the wrong direction or not operating at all, motor pulley not being held in place, operating at extremely low pressure, personnel lack of training/experience	Damage to capstan system parts, limited maneuverability
FM16	Motor shaft ratios are in the reverse direction	Incorrect connection of the oil line to the engine components during maintenance and repair, lack of personnel training/experience	Decrease in work efficiency, loss of time
FM17	Damage/breakage of bollards connected to the towing system	Excessive force applied to the bollard due to weather conditions, incorrect tensioning of maneuvering ropes by personnel, bollards made of inappropriate materials, inappropriate maneuvering angles, personnel lack of training/experience	Inability to perform ship docking maneuvers using the towing system, operational financial losses, personnel injuries
FM18	Limited rotation of the towing winch	Corrosion of mechanical parts due to sea water and corrosive environment, inadequate cleaning during maintenance, lack of fresh water washing after each operation, lack of personnel training/experience	Limited maneuvering operation or no maneuvering operation due to limited rotation of the system, noisy operation
FM19	Malfunction of the alarm system	Failure to perform maintenance and repair activities at the appropriate time, system failure due to excessive heat or cold, electronic card failure, signaling errors.	Damage to the towing system, limited maneuverability, financial loss as a result of personnel continuing to operate the system without knowing the fault.
FM20	Emergency stop error	Emergency stop button malfunction, lack of training/experience of personnel	Personnel injuries and risk of accidents during maneuvers due to situations such as rope jamming
FM21	Wear of mechanical components	Wear of mechanical parts such as gears, pulleys, bearings due to lack of timely preventive maintenance, inadequate lubrication, lack of personnel training/experience	Failure of the towing winch parts to operate the towing system, financial loss
FM22	Software error	Incorrect system programming, failure to update	The towing winch does not work properly or moves in the opposite direction, reducing maneuverability
FM23	Cracking or breaking of system components	Failure to perform preventive maintenance on time, system overheating, vibration	Cracks or breaks in mechanical parts prevent the system from working properly, financial loss

4. Application

A methodology consisting of four main stages was designed for the application phase of this study. In the first stage, the problem was discussed in detail. At this stage, the appropriate expert group experienced in tugboat towing system was determined. In the FMEA method, instead of a single expert, using a team of 5 to 9 people with various opinions and experiences to determine failure modes and effects increases the reliability of the analysis [56]. In this study, a team of 7 people with approximately 14 years of experience in tugboats and at least a bachelor's degree was established. After the brainstorming phase, 23 failure modes were determined based on technical documentation and individual experiences. Table 1 shows the failure modes, causes and effects determined by experienced experts on towing systems in tugboats. Then, the scales and definitions of the *O*, *S* and *D* values for the RPN calculation were established and given in Tables 2, 3, and 4, respectively.

Table 2 Rating for occurrence parameter [46]

Score	Probability of failure occurrence	Definition of the occurrence score
1	Nearly impossible	<1:1,500,000
2	Remote	1:150,000
3	Low	1:15,000
4	Relatively low	1:2,000
5	Moderate	1:400
6	Moderately	1:80
7	High	1:20
8	Repeated failures	1:8
9	Very high	1:3
10	Extremely	>1:2

Table 3 Rating for detection parameter [26, 46, 57]

Score	Probability of failure detection	Definition of the detection score
1	Almost certain	It is almost certain to detect a possible cause and the subsequent failure mode with the controls.
2	Very high	Very high chance the controls will detect a potential cause and subsequent failure mode
3	High	High chance the controls will detect a potential cause and subsequent failure mode
4	Moderately high	Moderately high chance the controls will detect a potential cause and subsequent failure mode
5	Moderately	Moderate chance the controls will detect a potential cause and subsequent failure mode
6	Low	Low chance the controls will detect a potential cause and subsequent failure mode
7	Very low	Very low chance the controls will detect a potential cause and subsequent failure mode
8	Remote	Remote chance the controls will detect a potential cause and subsequent failure mode
9	Very remote	Very remote chance the controls will detect a potential cause and subsequent failure mode
10	Almost impossible	It is almost impossible to detect a possible cause and the subsequent failure mode with the controls.

Table 4 Rating for severity parameter [26, 34]

Score	Effect	Definition of the severity score
1	None	No effect on the system
2	Very minor	Very minor effect on the system performance. The system does not require repair
3	Minor	Minor effect on the system performance. The system can require repair
4	Very low	Very low effect on the system performance. The system can require repair and maintenance
5	Moderate	Moderate effect on system performance. The system requires repair. Safe operation can be performed.
6	Significant	System performance is degraded. The safety level of the system is low. Failure may cause moderate injury, property damage, or system damage.
7	Major	System performance is severely affected. The safety level of the system is quite low. Failure causes injury, property damage, or system damage
8	Extreme	The system is inoperable with loss of primary function. Failure can involve hazardous outcomes
9	Very extreme	Failure involves hazardous outcomes. Potential safety, health or environmental issues. Failure will occur with a warning
10	Serious	Failure is hazardous and occurs without warning. Failure is serious enough to cause injury, property damage, or system damage. Failure will occur without warning.

The second main stage included the survey section. The *O*, *S* and *D* values for each failure mode were collected by an expert team using the scores given in Tables 2, 3 and 4. In the last section of the second main stage, the aggregation process was performed for the *O*, *S* and *D* values collected as crisp values. The simple aggregation tool frequently used in literature is the arithmetic mean method. However, in the FMEA method, the experience and knowledge of each person in the risk assessment team is often different from each other. Therefore, in order to eliminate this subjective assessment and to include different perspectives in the assessment in a reasonable way, a certain importance level is determined for each expert. In order to assign a relative importance level to experts, a score method based on knowledge and experience or multi-criteria decision-making methods can be used [46, 58]. In this study, the first method was adopted. In this context, three main headings were determined as education level, professional title and work experience to determine the relative weights of the experts and the scores were shown in Table 5.

Table 5 Classification of expert and corresponding scores

Parameter	Category	Score
Educational level	B. Sc.	1
	M.Sc.	2
	Ph.D.	3
Professional position	Ship crew	1
	Marine engineer or officer	2
	Chief engineer or Master	3
Sea Experience (year)	<5	1
	5-10	2
	>10	3

Table 6 shows the group of experts in this study and the relative weight of each expert based on the scores given in Table 5.

Table 6 Experts and their weight

Expert	Professional position	Sea Experience (years)	Educational level	Total score	Weight of expert
E1	Officer	16	B. Sc.	6	0.1463
E2	Officer	13	B. Sc.	5	0.1219
E3	Officer	13	B. Sc.	5	0.1219
E4	Marine engineer	22	M.Sc.	8	0.1951
E5	Officer	14	B. Sc.	5	0.1219
E6	Master	14	B. Sc.	6	0.1463
E7	Marine engineer	4	M.Sc.	6	0.1463

Finally, the corresponding *O*, *S* and *D* values for each failure mode were calculated as follows:

$$FM_{ij} = \sum_{k=1}^{l} w_k \cdot FM_{ij}^{k} \tag{7}$$

where i is the failure mode ($i = 1,2, \dots m$), j is the risk parameter (*O, S* and *D*), k is the number of experts ($k = 1,2, \dots l$) and w_k is the weight of the *k*th expert.

The third stage includes the process of calculating RPN. The RPN value is obtained by rule-based fuzzy inference. For this procedure, the "Fuzzy Logic Toolbox" in the MATLAB program was used. The interface of the toolbox is shown in Figure 3. The structure of the Mamdani fuzzy inference system is designed to have 3 inputs and 1 output. While the inputs are *O*, *S* and *D*, the output value is the RPN value. A 5-level structure was adopted for input values. While a trapezoidal fuzzy number was used for occurrence, a triangular fuzzy number was used for severity and detection. The parameters *O*, *S* and *D* are determined according to the former experiences of the team members. Although the occurrence is generally seen as a quantitative parameter, expert judgments are more uncertain, and the trapezoidal membership function is more attractive to better model this situation. Severity and detection are considered more qualitative. However, experts usually provide a clearer and more reliable judgment about the severity or detectability of the effect of a failure mode. Therefore, using the triangle membership function for severity and detection increases the realism and consistency of the model. A triangular fuzzy structure consisting of 10 levels was used for the output parameter RPN. Similar structure has been successfully implemented in many studies [33, 36, 37]. The input and output membership function are given in Figure 4 and 5.

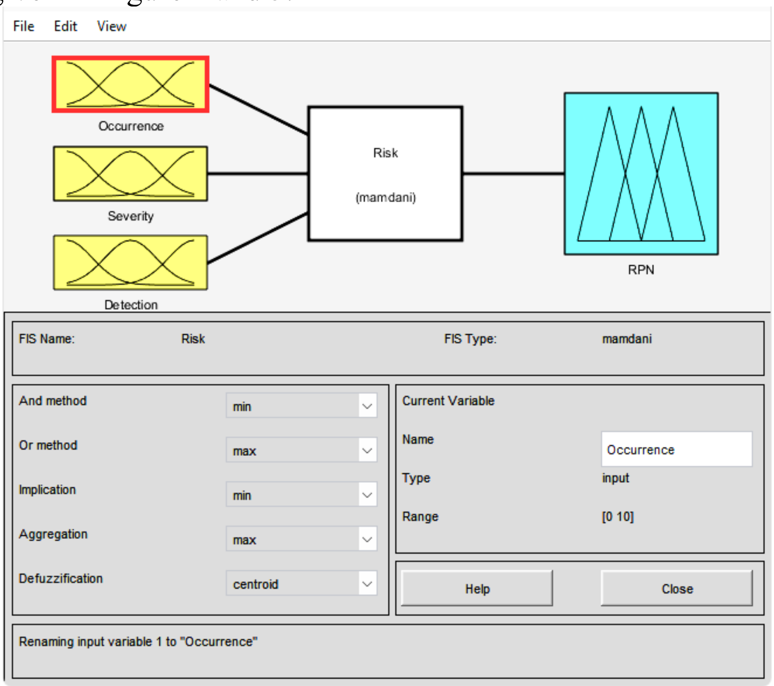


Fig. 3 Matlab interface of fuzzy inference model

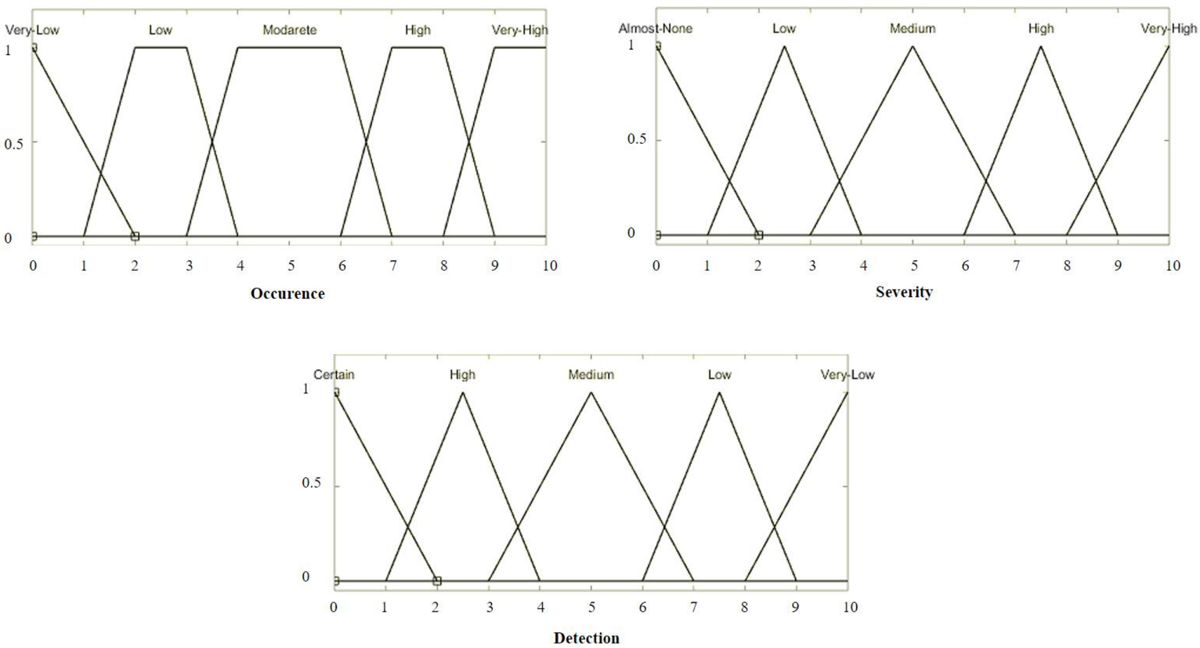


Fig. 4 The membership function for occurrence, severity and detection

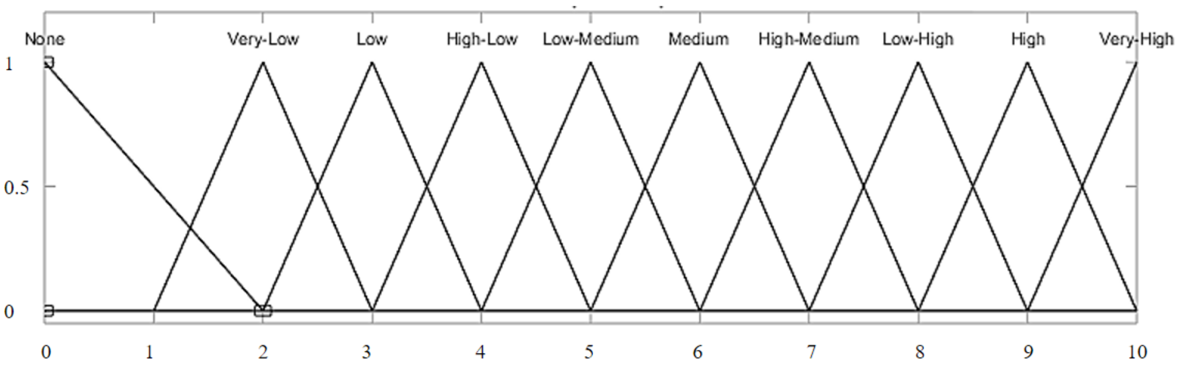


Fig. 5 The membership function for RPN

One of the most important steps of the third stage is the creation of the rule base. Since there are 5 different situations for each of the 3 inputs, a total of 125 rules were created that take into account all possibilities. The 3D surface graphs for the rules Occurrence-Severity, were shown in Figure 6. Additionally, a color-coded version of all the rules is included in Appendix A to facilitate easier interpretation and highlight the relative rankings of each parameter. The rule set was developed through an expert-driven brainstorming session, integrating both academic literature and real-world experience. In the last step of the third stage, the RPN value was obtained for the *O*, *S* and *D* values collected by the experts using the created fuzzy inference system. The centroid method was used for the defuzzification procedure.

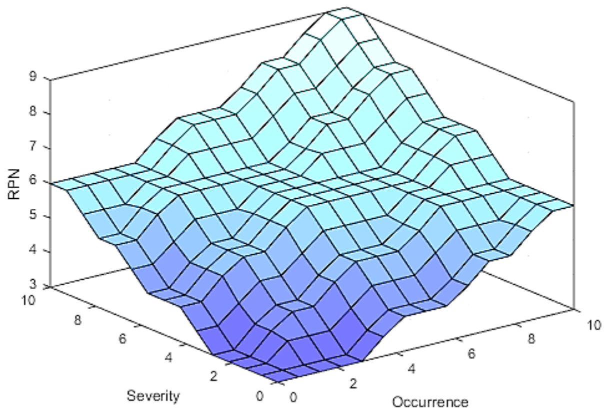


Fig. 6 The relationship between RPN, severity and occurrence

The final main stage of the application phase involves identifying risky failure modes and providing preventive recommendations. In this section, failure modes are prioritized and some preventive actions are suggested to reduce or prevent the risk of these failure modes. Figure 7 shows the flow chart containing the steps followed in the application section.

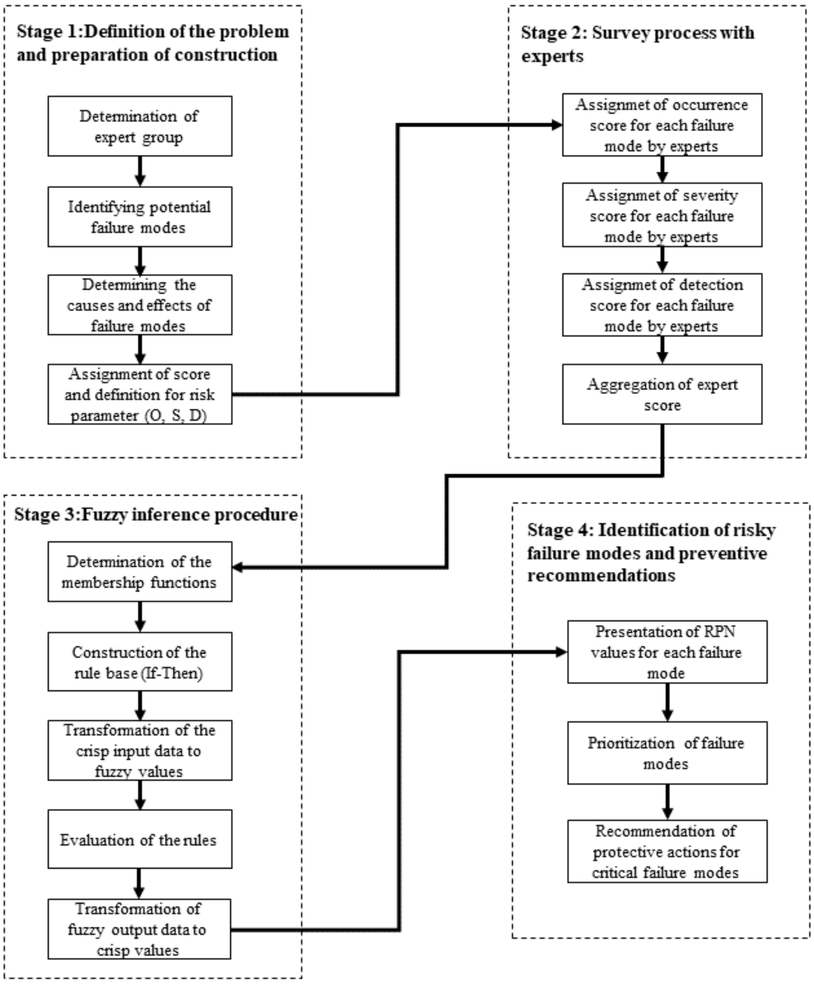


Fig. 7 Flow chart of the methodology

5. Results and Discussions

The *O*, *S* and *D* values of the failure modes determined for the towing system of a tugboat were evaluated by seven experts experienced in tugboats and were shown in Table 7. Then, an aggregation process was performed to obtain a single result for the group. In this study, the data were reduced to a single *O*, *S* and *D* with a weighted average by taking into account the weight value of each expert given in Table 6. For example, the average value for the *O* parameter of FM01 was calculated as follows; $O_{FM01} = (0.1463 \times 5) + (0.1219 \times 5) + (0.1219 \times 5) + (0.1951 \times 6) + (0.1219 \times 5) + (0.1463 \times 5) + (0.1463 \times 7) = 5.49$ The average *O*, *S* and *D* and fuzzy RPN values for each failure mode are shown in Table 8.

Table 7 O, S and D scores assigned by experts

	E1			E2			E3			E4			E5			E6			E7		
	O	**S**	**D**	**O**	**S**	**D**	**O**	**S**	**D**	**O**	**S**	**D**	**O**	**S**	**D**	**O**	**S**	**D**	**O**	**S**	**D**
FM01	5	8	5	5	10	6	5	9	5	6	7	2	5	9	5	5	8	1	7	9	3
FM02	5	6	6	5	6	4	5	6	6	4	7	2	5	6	6	6	6	2	6	5	5
FM03	2	7	4	2	5	4	2	6	4	3	7	2	2	6	4	4	5	2	2	4	4
FM04	4	5	5	4	5	4	4	5	5	4	7	2	4	5	5	5	4	2	4	5	5
FM05	3	6	3	3	6	3	3	6	3	4	8	3	3	6	3	8	8	3	3	7	4
FM06	2	5	2	3	5	2	3	5	2	5	9	3	4	5	3	7	5	3	5	6	4
FM07	2	7	2	2	5	2	3	6	2	6	7	4	4	6	2	7	7	5	5	6	4
FM08	2	6	3	2	6	3	3	6	3	6	8	4	4	5	3	6	6	4	3	5	2
FM09	3	7	2	2	7	4	3	7	2	6	8	1	3	7	2	8	8	1	4	5	1
FM10	4	5	3	2	4	3	3	5	3	6	7	2	4	5	3	7	8	1	5	4	2
FM11	2	4	5	2	4	5	2	4	5	3	7	3	2	4	4	6	8	3	2	4	1
FM12	3	5	2	3	5	2	3	5	2	5	6	5	3	5	2	6	8	2	2	4	1
FM13	2	4	3	2	4	3	2	4	3	4	7	4	2	4	3	7	6	2	3	5	2
FM14	4	5	2	2	5	2	3	5	2	3	7	4	3	5	2	4	6	2	2	4	2
FM15	3	5	3	2	5	2	3	5	2	2	9	4	3	5	3	4	5	3	2	4	2
FM16	2	7	3	2	7	2	2	8	2	2	9	4	2	7	3	3	7	3	1	5	1
FM17	4	8	2	3	7	2	3	8	2	4	9	2	3	8	3	4	9	1	1	9	3
FM18	3	7	1	3	7	1	3	7	1	3	8	3	3	7	1	7	9	1	6	7	2
FM19	2	5	2	2	4	2	2	5	2	4	6	5	2	5	2	5	9	1	5	6	2
FM20	2	8	1	2	6	1	2	7	1	2	7	4	2	6	1	6	9	2	3	6	2
FM21	4	7	3	3	7	3	3	7	3	3	6	2	4	6	3	8	9	2	4	5	2
FM22	3	5	2	3	6	2	3	5	2	4	8	5	4	6	2	3	4	6	4	5	7
FM23	4	6	3	3	6	2	3	6	2	5	8	4	4	5	2	8	9	3	4	7	4

Table 8 The average value of O, S and D parameters

Code	Failure Mode	O	S	D
FM01	Towing system rope failure	5.49	8.44	3.66
FM02	Insufficient air supply to the towing system from the compressor	5.10	6.05	4.24
FM03	Supply of excess air to the towing system from the compressor	2.49	5.78	3.32
FM04	Low hydraulic oil pressure	4.15	5.24	3.85
FM05	Burst/breakage of hydraulic hoses in the towing system	3.93	6.83	3.15
FM06	No energy supply to the towing system	4.24	5.93	2.76
FM07	Failure of the solenoid valve	4.32	6.37	3.12
FM08	Abnormal piston noise/piston wear	3.88	6.12	3.20
FM09	The towing winch linings are excessively thin	4.34	7.05	1.76
FM10	Hydraulic pump noise	4.61	5.56	2.37
FM11	Air or foam in the oil in the towing system	2.78	5.17	3.61
FM12	Failure of the towing system remote control system	3.68	5.49	2.44
FM13	System overheating	3.27	5.02	2.90
FM14	Engine speed of towing winch is lower than the specified value	3.02	5.39	2.39
FM15	No rotation of the motor shaft	2.68	5.63	2.80
FM16	Motor shaft ratios are in the reverse direction	2.00	7.22	2.66
FM17	Damage/breakage of bollards connected to the towing system	3.20	8.37	2.12
FM18	Limited rotation of the towing winch	4.02	7.49	1.54
FM19	Malfunction of the alarm system	3.27	5.80	2.44
FM20	Emergency stop error	2.73	7.05	1.88
FM21	Wear of mechanical components	4.15	6.68	2.51
FM22	Software error	3.46	5.68	3.90
FM23	Cracking or breaking of system components	4.54	6.85	2.98

When the average value of the *O* parameter, which shows the frequency of occurrence, was examined, the most frequently occurring failure mode was determined as FM01 with a value of 5.49. The least *O* value was obtained in FM016 with a value of 2.00. In terms of the *S* parameter, which shows the effect that will occur when an accident occurs, the highest effect value was obtained in FM01 with a value of 8.44, while FM13 had the least effect score with a value of 5.02. When an evaluation was performed in terms of the *D* parameter, the most difficult failure mode to detect was determined as FM02 with a value of 4.24. The easiest failure mode to detect was determined as FM018 with a score of 1.54.

Table 9 shows the RPN values and rankings obtained by both classic FMEA and fuzzy FMEA methods. The results showed that FM01, FM02, FM19 and FM15 had the same ranking with both methods. The rankings of other failure modes had changed. FM01 and FM02 are ranked first and second in both methods, respectively. This result shows that both methods are consistent in finding most critical risk on the tugboat's towing system. In addition, the 19th and 23rd ranked failure modes with both methods were obtained as FM19 and FM15, respectively. Therefore, both methods were consistent in detecting the lowest risk failure mode. However, the rankings for the remaining 21 failure modes had changed. This result showed that the rule-based fuzzy FMEA method had a significant effect on the results.

Table 9 Comparison of risk priorities of failure modes with classical FMEA and fuzzy FMEA methods

Failure Code	Classic RPN	Priority	Fuzzy RPN	Priority	Failure Code	Classic RPN	Priority	Fuzzy RPN	Priority
FM01	169.43	1	6.4	1	FM06	60.65	11	5	12
FM02	130.86	2	6	2	FM10	51.90	14	5	12
FM23	83.79	6	5.88	3	FM08	53.74	13	4.97	15
FM04	47.70	16	5.81	4	FM20	92.52	3	4.9	16
FM09	47.66	17	5.8	5	FM12	38.39	22	4.65	17
FM21	85.80	4	5.74	6	FM11	38.97	21	4.54	18
FM05	84.38	5	5.69	7	FM19	46.27	19	4.33	19
FM18	46.30	18	5.61	8	FM13	56.72	12	4.31	20
FM07	69.32	10	5.44	9	FM03	42.40	20	4.26	21
FM22	75.86	8	5.39	10	FM14	76.81	7	4.03	22
FM17	49.30	15	5.32	11	FM15	36.16	23	4	23
FM16	69.61	9	5	12					

In classic FMEA, since the weights of the *O*, *S*, and *D* parameters and uncertainties are not taken into account, significant differences were obtained in the ranking of failure modes, especially in the medium-risk group with close RPN values. In classic FMEA, RPN is calculated by multiplying each risk factor (*O, S* and *D*) by crisp values ranging from 1 to 10, while fuzzy FMEA uses fuzzy membership functions that take into account the uncertainty of expert opinions. In addition, a more flexible structure is obtained for risk parameters by creating a rule base. Therefore, fuzzy FMEA evaluates small differences better and allows decision makers to manage limited resources correctly for the implementation of preventive activities. As a result, the rule-based fuzzy FMEA method stands out in handling uncertainty and produces more reliable results.

The rule-based fuzzy FMEA results showed that the highest risk failure mode was FM01 (Towing system rope failure) with an RPN value of 6.4. Ropes have a certain lifespan and if regular checks are not performed, deformed ropes may break. In addition, the rope is not washed with fresh water after maneuvering operations and improper positioning during maneuvering are among the most important reasons for rope failure. Rope failure has very serious consequences. Personnel injuries or deaths may occur due to rope breakage. Serious accidents may occur during ship docking operation and financial losses may occur.

The second risky failure mode was determined as FM02 (Insufficient air supply to the towing system from the compressor) with an RPN value of 6. This error occurs when the compressor malfunctions due to lack of regular and careful compressor maintenance. In addition, leaks in the air lines or compressor air tank and failure of the pressure valves in the air system also cause insufficient air to come from the compressor. If this occurs, the pneumatic piston that moves the towing winch system may not work and the towing operation may stop as a result.

FM23 (Cracking or breaking of system components) was determined as the third risky failure mode with an RPN value of 5.88. The most important factors affecting this failure mode can be summarized as not performing preventive maintenance on time, overheating of the system and vibration. When there is cracking or breaking in the system components, it prevents the towing system from working properly and can cause serious financial losses.

FM04 (Low hydraulic oil pressure) was calculated as the fourth risky failure mode with an RPN value of 5.81. There are many factors that can cause low hydraulic oil pressure. One of the most common reasons is the failure of the hydraulic pumps. Leaks in the oil tank or line are also important reasons. The system shutting down before the pressure in the oil reaches the desired level as a result of water mixing into the oil can also cause low hydraulic oil pressure. In addition, failure of the directional valves that provide flow to the oil and the resulting return of the oil to the main tank without creating pressure are also factors that cause this failure mode. Low hydraulic oil pressure can directly affect the towing system, causing the towing winch to move in one direction or the system to be completely inoperable. In cases where oil leaks occur, work accidents can occur. In addition, oil leaks can reach the sea and cause marine pollution, and financial losses due to heavy fines can be experienced.

The fifth risky failure mode was determined as FM09 (The towing winch linings are excessively thin) with an RPN value of 5.8. The factors that are effective in the occurrence of this failure mode can be summarized as the linings not being checked on time and not being changed when they should be, the lining bed being burred and the use of inappropriate linings. In such a case, the braking ability is reduced and problems such as the towing winch losing the rope during the manoeuvring operation or the tugboat losing the ship may be encountered. In addition, there is also the risk of the ship hitting the pier. Therefore, serious financial losses may be experienced.

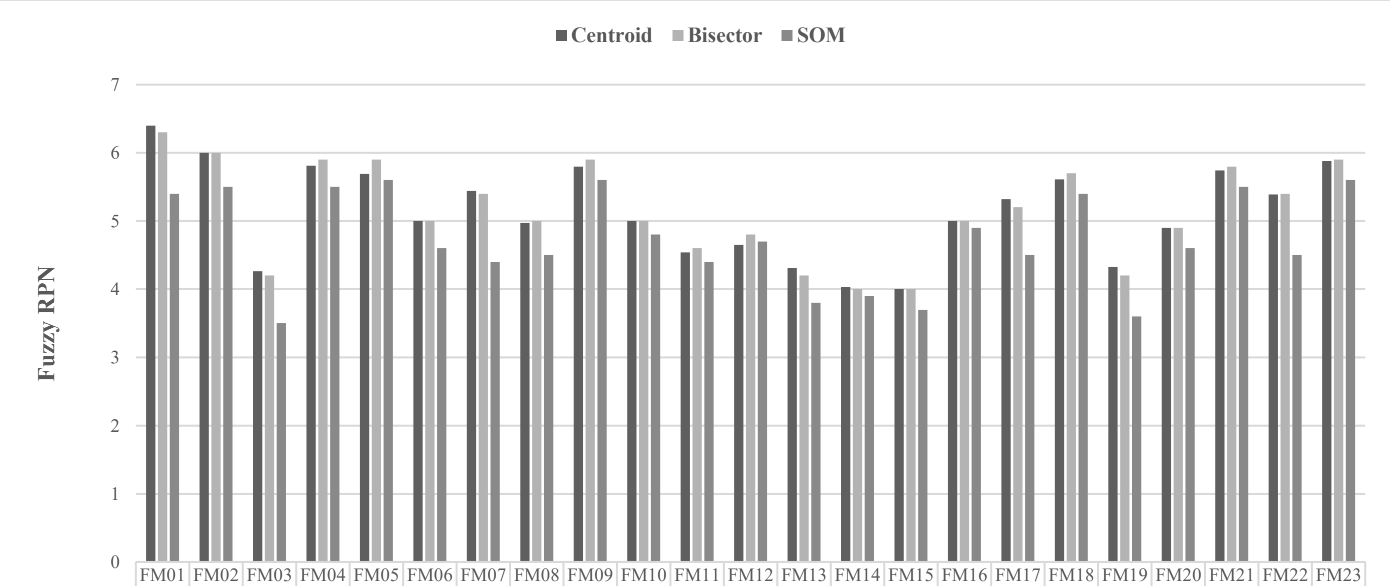
When the RPN values calculated with the fuzzy FMEA method were considered, the total number of failure modes with RPN values greater than five was eleven. These were considered critical failure modes and preventive actions were suggested. Table 10 shows the suggested actions for high-risk failure modes.

Table 10 Preventive actions for risky failure modes

Code	Failure Mode	Preventive Actions
FM01	Towing system rope failure	Regular visual and physical checks of the rope, preference for high-strength and abrasion-resistant ropes suitable for working conditions, periodic replacement of the rope by recording its service life.
FM02	Insufficient air supply to the towing system from the compressor	Periodic measurement, monitoring and recording of compressor output flow and pressure values, regular cleaning or replacement of compressor inlet filters, addition of water separator equipment to remove moisture accumulated in the air line, and integration of a spare air source into the compressor system.
FM23	Cracking or breaking of system components	Regularly checking system components with non-destructive testing methods such as ultrasonic and magnetic particle testing, using reinforced materials in areas with a high risk of cracking, integrating shock absorbers and damping systems to reduce vibration impact, and using load limit control devices to prevent overloads.
FM04	Low hydraulic oil pressure	Regularly checking the oil level and adding appropriate hydraulic oil if necessary, regularly cleaning and changing filters, periodically performing pump performance tests and having spare pump systems.
FM09	The towing winch linings are excessively thin	Using thickness measuring devices to regularly check the wear level of brake linings, creating a brake lining replacement program at certain intervals, depending on the frequency of use, and replacing the brake lining production material with wear-resistant options
FM21	Wear of mechanical components	Periodic lubrication of mechanical parts and use of appropriate lubricants, application of anti-wear coating materials, and replacement of mechanical components at certain intervals in accordance with the design life.
FM05	Burst/breakage of hydraulic hoses in the towing system	Regular visual and physical inspection of hoses, use of safety valves and flow control devices against excessive pressure, and selection of hoses with appropriate durability for the working environment.
FM18	Limited rotation of the towing winch	Regular lubrication and cleaning of the moving parts of the towing winch, periodic checking and, if necessary, replacement of components in the rotation mechanism, and use of limiters that ensure that torque values remain within the design limits.
FM07	Failure of the solenoid valve	Regularly checking the electrical connections and coil resistances of solenoid valves, improving filtering systems to prevent contamination inside the valve, and applying protective coating against corrosion caused by environmental conditions.
FM22	Software error	Regularly updating the software and implementing backup procedures, performing debugging and test simulations on the software, and training ship personnel on software use.
FM17	Damage/breakage of bollards connected to the towing system	Producing bollards from materials suitable for the design load capacity and preventing overloads, detecting structural damage with periodic visual inspection and ultrasonic tests, and strengthening the connection points of bollards.

In order to avoid any trouble with the rope in the towing system, the most basic precaution to be taken is to regularly perform visual and physical checks of the rope. In addition, choosing high-strength and abrasion-resistant ropes suitable for working conditions in the towing system will significantly reduce the possibility of rope breakage. Recording the service life of the rope and periodically changing it is also a prevention process that should not be overlooked. The simplest and cheapest method to prevent insufficient air from the compressor to the towing system is to periodically measure, monitor and record the compressor output flow and pressure values. In addition, regular cleaning and, if necessary, replacement of compressor inlet filters is another process that should be taken into consideration. Finally, solutions such as adding water separator equipment to remove moisture accumulated in the air line and integrating a spare air source into the compressor system can also be considered. The basic precaution against the third riskiest failure mode, cracking or breaking of system components, is to regularly check the system components with non-destructive testing methods such as ultrasonic and magnetic particle testing. Another precaution to be taken is to use reinforced materials, especially in areas with a high risk of cracking. In addition, the integration of shock absorber and damper systems to reduce vibration and impact, and the use of load limit control devices to prevent overloads can also be considered to protect towing system components. Recommended preventive actions for the remaining failure modes with high RPN values can be seen in Table 10.

In this study, risk analysis was performed by adopting model parameters widely used in the literature. However, membership functions, rule base, and inference model affect RPN calculation and then failure mode ranking. In the last part of this study, sensitivity analysis was performed using various defuzzification methods. For the sensitivity analysis, three different methods were considered: Centroid, Bisector and Smallest of Maximum (SOM), and the RPN value was recalculated for each failure mode. While the Centroid method takes into account the center of gravity of the fuzzy set, the Bisector method calculates according to the x-coordinate of the vertical line dividing the area into two equal parts. The SOM method selects the smallest x value corresponding to the maximum value of the membership function [59]. RPN values calculated with the Centroid, Bisector and SOM methods were given in Figure 8. Results showed that while the Centroid and Bisector methods generally produced close results, whereas lower RPN values were obtained with the SOM method.



	FM01	FM02	FM03	FM04	FM05	FM06	FM07	FM08	FM09	FM10	FM11	FM12	FM13	FM14	FM15	FM16	FM17	FM18	FM19	FM20	FM21	FM22	FM23
Centroid	6.4	6	4.26	5.81	5.69	5	5.44	4.97	5.8	5	4.54	4.65	4.31	4.03	4	5	5.32	5.61	4.33	4.9	5.74	5.39	5.88
Bisector	6.3	6	4.2	5.9	5.9	5	5.4	5	5.9	5	4.6	4.8	4.2	4	4	5	5.2	5.7	4.2	4.9	5.8	5.4	5.9
SOM	5.4	5.5	3.5	5.5	5.6	4.6	4.4	4.5	5.6	4.8	4.4	4.7	3.8	3.9	3.7	4.9	4.5	5.4	3.6	4.6	5.5	4.5	5.6

Fig. 8 Comparative analysis of defuzzification methods in fuzzy RPN calculations

Table 11 showed the risk ranking according to the fuzzy RPN values calculated with the Centroid, Bisector and SOM methods. The Centroid and Bisector methods resulted in a close ranking, whereas the SOM method caused significant changes in the ranking. The most dramatic result was obtained for the highest-risk failure mode. While FM01 was ranked 1st in the Centroid and Bisector methods, it fell to 7th place in the

SOM method. FM05, FM09 and FM23 shared the first place with the same RPN value in the SOM method. These results show that the selected defuzzification method has an effect on the risk ranking. However, the Centroid method tends to be preferred in maritime applications because it produces more balanced results based on the entire fuzzy set area.

Table 11 The effect of defuzzification methods on risk ranking

Failure code	Centroid method	Bisector method	SOM method	Failure Code	Centroid method	Bisector method	SOM method
FM01	1	1	7	FM13	20	19	20
FM02	2	2	4	FM14	22	22	19
FM03	21	19	23	FM15	23	22	21
FM04	4	3	4	FM16	12	12	9
FM05	7	3	1	FM17	11	11	14
FM06	12	12	12	FM18	8	8	7
FM07	9	9	17	FM19	19	19	22
FM08	15	12	14	FM20	16	16	12
FM09	5	3	1	FM21	6	7	4
FM10	12	12	10	FM22	10	9	14
FM11	18	18	17	FM23	3	3	1

6. Conclusions

Ships are complex systems consisting of many machines and equipment. Therefore, there is a high probability of many potential failures. Risk analyses help us to identify these failures in advance and determine which failures have high risks. Finally, various precautions can be taken with a proactive approach before the relevant failures occur. Tugboats are special marine vehicles with powerful engines and high maneuverability. Tugboats are responsible for the docking or departing of ships to the port, maneuvering of ships in narrow waterways, rescue and fire extinguishing operations. The most important system specific to this special boat is the towing system. In this study, a comprehensive risk analysis was carried out for the towing system of tugboats. In this context, a total of 23 failure modes were determined by experienced experts. For each failure mode, *O, S* and *D* values were evaluated by experts and then the average calculation was performed. The obtained data was processed in the rule-based fuzzy FMEA method and the RPN value was calculated for each failure mode.

The results showed that the three risky failure modes were FM01 (Towing system rope failure), FM02 (Insufficient air supply to the towing system from the compressor) and FM23 (Cracking or breaking of system components), respectively. Then, FM04 (Low hydraulic oil pressure) and FM09 (The towing winch linings are excessively thin) were determined as failure modes with high RPN values. Although each of them occurs for different reasons, their results can be summarized as disruption or complete stoppage of the towing operation, personnel injuries or deaths and financial losses. Based on the results, specific preventive activities were determined for failure modes with high RPN values. In general, control and recording stand out as the most basic preventive activities. In addition, regular maintenance and repair activities and appropriate equipment/material selection are also among the important preventive activities. Based on the risk analysis findings, we propose several key regulatory recommendations to enhance the safety and reliability of towing system of tugboats:

- Establishing mandatory inspection intervals for critical towing system components such as ropes, hydraulic lines, and compressor units.
- Requiring minimum standards for crew training focused on towing system operation, emergency handling, and maintenance awareness.
- Encouraging the use of redundancy features and monitoring equipment, such as backup air sources, oil pressure sensors, and overload protection systems.

In this study, the risk assessment was carried out by considering the equipment and machines that constitute the towing system. In the future studies, a dynamic risk analysis can be performed for the towing operation by taking into account environmental conditions and human factors, such as weather, sea conditions, and operator fatigue. Simulation or digital twin technologies to model and predict towing system performance under real-time operational conditions can be integrated. A more comprehensive sensitivity analysis that takes into account model parameters such as the fuzzy inference method, membership function and rules can be conducted to investigate the risk prioritization outcomes effects of these parameters. Prioritization of risk control measures can be performed by taking into account effectiveness, cost and ease of implementation criteria with multi-criteria decision-making tools (e.g., AHP or fuzzy TOPSIS). In addition, tugboats have other important systems such as fuel system, navigation system, hydraulic system, and this study can be an inspiration for risk analysis of other systems of tugboats.

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Appendix A. Colored fuzzy rules

Rule No	Occurrence	Severity	Detection	Risk (RPN level)	Rule No	Occurrence	Severity	Detection	Risk (RPN level)
1	Very low	Almost none	Certain	None	64	Moderate	Medium	Low	Medium
2	Very low	Almost none	High	Very low	65	Moderate	Medium	Very low	High medium
3	Very low	Almost none	Medium	Low	66	Moderate	High	Certain	Low medium
4	Very low	Almost none	Low	Low	67	Moderate	High	High	Medium
5	Very low	Almost none	Very low	High low	68	Moderate	High	Medium	Medium
6	Very low	Low	Certain	Very low	69	Moderate	High	Low	High medium
7	Very low	Low	High	Low	70	Moderate	High	Very low	Low high
8	Very low	Low	Medium	Low	71	Moderate	Very high	Certain	Medium
9	Very low	Low	Low	High low	72	Moderate	Very high	High	Medium
10	Very low	Low	Very low	Low medium	73	Moderate	Very high	Medium	High medium
11	Very low	Medium	Certain	Low	74	Moderate	Very high	Low	Low high
12	Very low	Medium	High	Low	75	Moderate	Very high	Very low	High
13	Very low	Medium	Medium	High low	76	High	Almost none	Certain	Low
14	Very low	Medium	Low	Low medium	77	High	Almost none	High	High low
15	Very low	Medium	Very low	Medium	78	High	Almost none	Medium	Low medium
16	Very low	High	Certain	Low	79	High	Almost none	Low	Medium
17	Very low	High	High	High low	80	High	Almost none	Very low	Medium
18	Very low	High	Medium	Low medium	81	High	Low	Certain	High low
19	Very low	High	Low	Medium	82	High	Low	High	Low medium
20	Very low	High	Very low	Medium	83	High	Low	Medium	Medium
21	Very low	Very high	Certain	High low	84	High	Low	Low	Medium
22	Very low	Very high	High	Low medium	85	High	Low	Very low	High medium
23	Very low	Very high	Medium	Medium	86	High	Medium	Certain	Low medium
24	Very low	Very high	Low	Medium	87	High	Medium	High	Medium
25	Very low	Very high	Very low	High medium	88	High	Medium	Medium	Medium
26	Low	Almost none	Certain	Very low	89	High	Medium	Low	High medium
27	Low	Almost none	High	Low	90	High	Medium	Very low	Low high
28	Low	Almost none	Medium	Low	91	High	High	Certain	Medium
29	Low	Almost none	Low	High low	92	High	High	High	Medium
30	Low	Almost none	Very low	Low medium	93	High	High	Medium	High medium
31	Low	Low	Certain	Low	94	High	High	Low	Low high
32	Low	Low	High	Low	95	High	High	Very low	High
33	Low	Low	Medium	High low	96	High	Very high	Certain	Medium
34	Low	Low	Low	Low medium	97	High	Very high	High	High medium
35	Low	Low	Very low	Medium	98	High	Very high	Medium	Low high
36	Low	Medium	Certain	Low	99	High	Very high	Low	High
37	Low	Medium	High	High low	100	High	Very high	Very low	High
38	Low	Medium	Medium	Low medium	101	Very high	Almost none	Certain	High low
39	Low	Medium	Low	Medium	102	Very high	Almost none	High	Low medium
40	Low	Medium	Very low	Medium	103	Very high	Almost none	Medium	Medium
41	Low	High	Certain	High low	104	Very high	Almost none	Low	Medium
42	Low	High	High	Low medium	105	Very high	Almost none	Very low	High medium
43	Low	High	Medium	Medium	106	Very high	Low	Certain	Low medium
44	Low	High	Low	Medium	107	Very high	Low	High	Medium
45	Low	High	Very low	High medium	108	Very high	Low	Medium	Medium
46	Low	Very high	Certain	Low medium	109	Very high	Low	Low	High medium
47	Low	Very high	High	Medium	110	Very high	Low	Very low	Low high
48	Low	Very high	Medium	Medium	111	Very high	Medium	Certain	Medium
49	Low	Very high	Low	High medium	112	Very high	Medium	High	Medium
50	Low	Very high	Very low	Low high	113	Very high	Medium	Medium	High medium
51	Moderate	Almost none	Certain	Low	114	Very high	Medium	Low	Low high
52	Moderate	Almost none	High	Low	115	Very high	Medium	Very low	High
53	Moderate	Almost none	Medium	High low	116	Very high	High	Certain	Medium
54	Moderate	Almost none	Low	Low medium	117	Very high	High	High	High medium
55	Moderate	Almost none	Very low	Medium	118	Very high	High	Medium	Low high
56	Moderate	Low	Certain	Low	119	Very high	High	Low	High
57	Moderate	Low	High	High low	120	Very high	High	Very low	High
58	Moderate	Low	Medium	Low medium	121	Very high	Very high	Certain	High medium
59	Moderate	Low	Low	Medium	122	Very high	Very high	High	Low high
60	Moderate	Low	Very low	Medium	123	Very high	Very high	Medium	High
61	Moderate	Medium	Certain	High low	124	Very high	Very high	Low	High
62	Moderate	Medium	High	Low medium	125	Very high	Very high	Very low	Very high
63	Moderate	Medium	Medium	Medium					