

Article

Fuzzy-Fault-Tree-Based Reliability Assessment of a Marine Diesel Engine's Shutdown Mechanism: A Case Study of a Ship's Main Engine

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Abstract

The safe and uninterrupted operation of the ship's main engine is critical for maritime transportation. The shutdown mechanism, part of the main engine protection systems, prevents serious damage by automatically stopping the engine in critical situations such as low lubrication oil pressure, overspeed, high bearing temperature, and cooling system failures. However, identifying the faults that trigger the shutdown system and evaluating their risk levels is crucial for improving system reliability. In this study, shutdown events that may occur in a two-stroke low-speed marine diesel main engine were investigated using Fuzzy Fault Tree Analysis (FFTA). The shutdown event was defined as the peak event, and a total of 34 baseline events were modelled under five main branches: low lubrication oil pressure, overspeed, high thrust bearing temperature, abnormal jacket coolant inlet condition, and crankcase/cylinder oil mist formation. Fuzzy assessments based on expert opinions were defuzzified and converted into probability values and used in fault tree calculations. The results showed that the shutdown risk is largely affected by failures originating from the jacket coolant system and the lubrication oil system. Specifically, lubrication oil filter clogging and contamination/blockage in the coolant line were identified as the most critical risk factors. The findings significantly contribute to prioritizing maintenance and condition-monitoring activities aimed at improving the ship's main engine reliability through a risk-based approach.

Keywords: marine diesel engine; fuzzy fault tree analysis (FFTA); main engine shutdown; reliability analysis; maritime safety

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1. Introduction

Maritime transport plays a vital role in global trade, accounting for a substantial proportion of worldwide freight movement owing to its cost efficiency and its capacity to transport large volumes of cargo in a single voyage compared with other transportation modes [1]. The transcontinental movement of bulk solid cargo and raw materials depends heavily on international commercial freight transit by sea. Maritime transportation provides around 90% of the transportation services used to meet the needs of people worldwide [2]. However, there are several risks associated with these transportation activities, including the ship's technical state, the weather, and the crew's degree of expertise [3]. Ship propulsion systems must run safely, securely, and continuously for both operational

sustainability and financial reasons. Diesel engines are preferred in propulsion systems used in ships because of their high efficiency, relatively low maintenance requirements, and ability to perform effectively under harsh operating conditions [4–6]. Failures in the propulsion system cause various risks such as environmental risks, operational delays, and reduced maneuverability. Collisions [7], mooring operations [8], and groundings [9] during operations cause serious safety problems.

Various automation and protection systems are used to ensure the safe operation of ships. Among these systems, the shutdown function stands out as one of the most critical safety mechanisms directly affecting engine safety [10]. A key component of main engine protection systems, the shutdown system aims to prevent serious mechanical damage by automatically shutting down the main engine when critical operating parameters, such as low lubrication oil pressure, overspeed, or high coolant temperature, exceed defined safety limits. This protection function prevents major failures in the propulsion system and the resulting operational disruptions. While alarm systems are limited to alerting the operator, shutdown systems actively intervene in the control system to maintain safe operating conditions and ensure the safe shutdown of the main engine [11]. However, despite this critical protection function provided by shutdown systems, failures in the system bring significant operational risks. In particular, the failure of the shutdown function to activate when required can lead to serious [12] and potentially catastrophic consequences such as bearing seizure, piston jamming, crankcase explosion, and complete engine failure. However, unnecessary or erroneous activation of the protection system can also lead to significant operational problems. Unnecessary shutdown activations can cause unplanned main engine downtime, loss of propulsion power, flight delays, and substantial economic losses. Sudden loss of propulsion, especially in narrow waterways, during port maneuvers, and in areas with heavy traffic, poses critical risks to ship safety and navigational security [13].

With the increasing level of automation in modern ships, the structure of shutdown systems has become increasingly complex. Current systems consist of numerous sub-components such as sensors, logic control units, control modules, and actuators [14]. Furthermore, the performance of shutdown systems depends not only on the operating condition of mechanical components but also on environmental factors such as vibration, temperature variations, and humidity. Therefore, the reliability of shutdown systems should be evaluated not only from a mechanical perspective but also considering electronic components and human factors. Given their multi-component nature and the critical impact of different failure scenarios on operational safety, adopting a comprehensive risk assessment approach is crucial for identifying potential failures in advance and developing appropriate preventive and corrective strategies [15].

Maritime accidents are unavoidable when these dangers, which are categorized under several major areas, come together. To avoid unfavourable outcomes, safety is therefore regarded as one of the maritime industry's top objectives [16]. It is possible to ensure safety by accurately identifying hazards and analyzing them using the right techniques. Given its disastrous impact on property losses, the environment, and human life, marine safety stands out as one of the most important concerns facing the maritime industry. As a result, risk analysis is crucial for spotting dangers early and taking appropriate safety measures [17]. Various risk analysis methods exist in the literature. Hazard identification [18], Failure Mode and Effects Analysis [19], Event Tree Analysis [20], Bayesian Network [21], Risk Matrix [22], and Fault Tree Analysis (FTA) are a few of these. In some research employing these techniques, Sokukcu and Sakar performed dynamic risk assessment in ship collision and operational risk analyses by combining Fault Tree Analysis and Bayesian Networks [3]. Kaushik and Kumar used a Fuzzy Fault Tree and Bayesian network approach to examine the hazards associated with ship mooring operations [23]. Using a

hybrid FTA–Bayesian Network model, Göksu et al. studied blackout events caused by engine failures and system problems [24]. Using data on collision and grounding incidents involving oil tankers from 1998 to 2010, Uğurlu et al. performed a risk analysis using the FTA approach [25]. Ceylan et al. investigated biodiesel applications in diesel engines by integrating experimental engine performance and emission analyses with a fuzzy-logic-based FMEA approach to systematically assess associated operational risks [26]. Recent studies suggest that these approaches are increasingly applied within the context of maritime transport network topology, fragility–resilience interactions, and overall system resilience capacity [27]. Accordingly, maritime accidents are not only assessed through traditional cause-and-effect relationships but also evaluated in terms of how effectively the entire network can withstand unexpected disruptions and sustain operational continuity [28]. Because it rationally and methodically identifies the underlying causes of catastrophic failures that may arise in complicated and sophisticated systems, FTA is often chosen among these techniques. It allows for a better understanding of the mechanisms of hazards by presenting cause-and-effect links in a visual and hierarchical framework, in contrast to conventional risk analysis techniques. Among the significant benefits of FTA are its capacity to support both qualitative and quantitative studies, its aid in identifying crucial elements and combinations of failures, and its facilitation in prioritizing remedial and preventive measures [29–31]. Particularly in the maritime sector, where high reliability is required, it is used as an effective decision-support tool to improve system reliability and contribute to the prevention of potential accidents.

This study investigates the reliability of the shutdown protection system in a MAN B&W S50MC6 two-stroke low-speed marine diesel main engine through the application of Fuzzy Fault Tree Analysis (FFTA). Most studies in the maritime literature based on FTA and FFTA focus on different risk areas such as collision, grounding, blackout, and berthing operations. However, existing studies predominantly focus on external maritime accident scenarios, such as collisions, groundings, blackouts, and port operations, while reliability analyses of internal ship systems, particularly main engine shutdown protection mechanisms, remain relatively limited in the literature. Moreover, most available approaches do not sufficiently capture epistemic uncertainty in expert judgments when evaluating subsystem-level failure probabilities within propulsion safety systems. To address these gaps, this study extends Fuzzy Fault Tree Analysis by developing a structured reliability assessment framework specifically for the main engine shutdown protection system, integrating expert-based fuzzy probability quantification with minimal cut set and Fussell–Vesely importance measures to identify dominant failure contributors. In contrast, this study addresses the main engine shutdown function, which is critically important for the safety of ship propulsion systems. In the analysis, the main engine shutdown condition is defined as the peak event, and thirty-four basic events that could cause this condition are modelled under five main categories. The probabilities of occurrence of the basic events are quantified using a fuzzy-logic approach based on expert assessments, and the resulting values are used as inputs to the fault tree model. After that, the failure sources that seem to contribute the most to shutdown risk were identified using minimal cross-sectional sets, alongside Fussell–Vesely significance analysis. Overall, it is expected that the results will help raise the reliability of ship main engine protection systems, support planning for more effective maintenance strategies, and back risk-based decision-making in maritime safety processes.

2. Materials and Methods

2.1. Ship Main Engine

This study uses a MAN B&W S50MC6 (Augsburg, Germany) two-stroke low-speed marine diesel main engine as a case study. This engine type operates directly connected to the propeller shaft and is used as the main propulsion system in ships. The continuous and safe operation of the main engine depends on the harmonious functioning of auxiliary and protection systems, such as the lubrication oil system, jacket cooling system, fuel control system, thrust bearing system, speed control system, and crankcase monitoring system. In the engine under investigation, the shutdown protection function is related to critical operating parameters that can lead to unsafe operating conditions if predetermined limit values are exceeded [32]. The main protection functions considered in this study are low lubrication oil pressure, excessive speed, high thrust bearing segment temperature, abnormal jacket coolant inlet conditions, and oil mist formation in the crankcase or cylinder area [33].

The MAN B&W S50MC6 engine was used as the reference system for defining the operational boundaries, shutdown protection functions, failure propagation paths, and logical structure of the fault tree. Accordingly, engine operating parameters such as load, rotational speed, lubricating oil pressure, jacket cooling water temperature, bearing temperature, and related monitoring signals were not treated as continuous state variables in a simulation-based calculation. Instead, these parameters were incorporated into the analysis through the predefined shutdown logic and the corresponding failure mechanisms represented in the FFTA model. Direct integration of time-dependent sensor measurements or real-time operating parameters would require a data-driven reliability model, a dynamic fault tree, a Bayesian updating framework, or a digital-twin-based condition-monitoring architecture. Such an approach would represent a different methodological design and is beyond the scope of the present expert-based FFTA risk assessment.

2.2. Shutdown Mechanism

The shutdown system used in marine diesel main engines is one of the fundamental protection functions aimed at preventing serious mechanical failures that may occur if critical operating parameters exceed safe operating limits [34–36]. Under normal operating conditions, critical parameters such as lubrication oil pressure, engine speed, thrust bearing temperature, jacket coolant status, and oil mist density are continuously monitored by alarm and monitoring systems [37]. If any of these parameters reach predefined shutdown limits, the protection system activates the automatic shutdown command, preventing the failure from escalating and leading to more severe consequences [38,39]. In this study, the main engine shutdown condition was considered as the peak event of the fault tree analysis, and the system logic was structured around five basic shutdown triggers: low lubrication oil pressure, overspeed, high thrust bearing segment temperature, abnormal jacket coolant inlet conditions, and oil mist formation in the crankcase/cylinder area. These conditions can arise from different failure mechanisms, such as pump failures, filter fouling or blockages, system leaks, control system errors, excessive fuel supply, insufficient cooling performance, mechanical damage, and oil mist accumulation reaching critical levels.

The shutdown-related instrument coding also supports the selection of these branches. The notation “Z” indicates a shutdown function, while the instrument codes PS, PT, TE, TS, and XS correspond to pressure switch, pressure transmitter, temperature element, temperature switch, and unclassified switch functions, respectively.

2.3. Fuzzy Fault Tree Analysis

FTA is a deductive safety and reliability analysis method used to model the logical relationships between an undesired top event and its contributing causes [40,41]. The method represents system failure through a hierarchical structure consisting of a top event, intermediate events, basic events, and logical gates. The AND gate is used when all input events must occur together to produce the output event, whereas the OR gate is used when any one of the input events is sufficient to produce the output event [42,43]. In conventional FTA, the occurrence probabilities of basic events are required as crisp numerical inputs [44]. However, such data are often difficult to obtain in maritime systems because component-level failure databases are limited or unavailable [8]. For this reason, maritime risk studies frequently use FFTA to convert expert linguistic judgments into numerical failure probabilities [24]. In this study, an expert-judgement-based FFTA procedure was applied to quantify the probability of main engine shutdown. Unlike multi-expert FFTA studies, the present application used the judgement of a single marine engineering expert. Therefore, the similarity aggregation, average agreement, relative agreement, and consensus coefficient calculations were not applied. The expert's score for each basic event was directly converted into the corresponding linguistic term and trapezoidal fuzzy number.

To make the methodological procedure more explicit, the mathematical basis of the FFTA calculations is presented below. In the developed fault tree, the output probability of an AND gate was calculated by multiplying the probabilities of all input events:

$$P_{AND} = \prod_{i=1}^n P_i \quad (1)$$

where (P_i) represents the probability of the (i th) input event. For an OR gate, the output probability was calculated using the complementary probability formulation:

$$P_{OR} = 1 - \prod_{i=1}^n (1 - P_i) \quad (2)$$

In the fuzzy evaluation stage, each linguistic judgement was represented by a trapezoidal fuzzy number:

$$\tilde{A} = (a, b, c, d) \quad (3)$$

Each trapezoidal fuzzy number was defuzzified using the Centre-of-Area method to obtain a crisp failure possibility value:

$$CFP = \frac{a + b + c + d}{4} \quad (4)$$

Since the obtained crisp value represents a failure possibility rather than a direct probability, the Onisawa transformation was used to convert the crisp failure possibility into a failure probability:

$$FP = \frac{1}{10^K} \quad (5)$$

$$K = \left(\frac{1 - CFP}{CFP} \right)^{\frac{1}{3}} \times 2.301 \quad (6)$$

where (FP) denotes the converted failure probability of the basic event. The converted probabilities were then propagated through the fault tree according to the AND and OR gate structures. Since the five main shutdown branches were connected to the top event through an OR gate, the top event probability was calculated as follows:

$$P(T) = 1 - \prod_{j=1}^m (1 - P_j) \quad (7)$$

where ($P(T)$) is the probability of the main engine shutdown event, (P_j) is the probability of the (j th) main intermediate event, and (m) is the number of main shutdown branches.

Finally, the Fussell–Vesely importance measure was used to determine the relative contribution of each minimal cut set to the top-event probability:

$$FV_i = \frac{P(MCS_i)}{P(T)} \quad (8)$$

where (FV_i) represents the Fussell–Vesely importance value of the $(i$ th) minimal cut set, $(P(MCS_i))$ is the probability of the corresponding minimal cut set, and $(P(T))$ is the calculated probability of the top event. The FFTA procedure used in this study consists of five main steps.

- Step 1. Construction of the fault tree diagram. The top event was defined as the main engine shutdown. The top event was then decomposed into five main intermediate events: low lubricating oil pressure, engine overspeed, high thrust bearing segment temperature, abnormal jacket cooling water inlet condition, and oil mist in the crankcase or cylinder. These events were further divided into intermediate causes and 34 basic events. The logical relationships among the events were represented using AND and OR gates.
- Step 2. Collection and conversion of expert judgments. The marine engineering expert evaluated the occurrence likelihood of each basic event using a seven-level scale from 1 to 7. These scores were converted into linguistic terms: very low, low, medium low, medium, medium high, high, and very high. Each linguistic term was then assigned to a trapezoidal fuzzy number.
- Step 3. Defuzzification and probability transformation. The trapezoidal fuzzy number assigned to each basic event was defuzzified using the Centre-of-Area method to obtain a crisp failure possibility value. Since the resulting value is a possibility rather than a probability, the Onisawa transformation was then applied to convert each crisp failure possibility into a failure probability.
- Step 4. Quantitative FFTA calculations. The converted basic event probabilities were propagated through the fault tree according to the AND and OR gate structures. Intermediate event probabilities, minimal cut set probabilities, and the top event probability were calculated using the Boolean structure of the developed fault tree.
- Step 5. Interpretation of results and importance analysis. The calculated results were interpreted by comparing the probabilities of the main shutdown branches and ranking the minimal cut sets. Fussell–Vesely importance values were used to identify the basic events and cut sets with the highest contribution to the main engine shutdown probability.

3. Application

3.1. Construction of the Fault Tree Diagram

FTA was applied in this study to model the causal structure leading to the shutdown of a two-stroke marine diesel main engine. In accordance with the general structure of FTA, the analysis process began with the identification of the peak event, which was then systematically decomposed into intermediate events, intermediate causes, and root events using logic gates. The peak event represents an undesirable outcome at the system level, while root events represent the lowest-level causes that are not further decomposed within the scope of the analysis. The AND gate used in the fault tree shows that all input events must occur simultaneously for the output event to occur, while the OR gate indicates that the occurrence of any one of the input events is sufficient to trigger the output event. In this study, the “Main Engine Shutdown” event was chosen as the peak event because it represents a critical loss in the ship’s propulsion capability and can directly affect ship safety, maneuverability, and operational continuity. In the fault tree model, the top event is specifically defined as the activation or demand of the automatic main engine protective shutdown function caused by critical

monitored operating conditions exceeding predefined shutdown limits. The model focuses on the initiating failure mechanisms and protection-related signals that may lead the safety system to command a main engine shutdown. Physical degradation mechanisms, such as lubricating oil filter blockage, jacket cooling water leakage, cooling water flow restriction, bearing wear, or abnormal oil mist formation, are included together with shutdown-relevant detection or control conditions when they directly contribute to the protective shutdown logic. The system boundary covers the MAN B&W S50MC6 main engine shutdown-related protection functions and the associated subsystems that can generate a shutdown demand. These include the lubricating oil pressure system, speed control and fuel admission system, thrust bearing temperature protection, jacket cooling water inlet condition, and crankcase/cylinder oil mist monitoring. The model does not include the reliability of the shutdown actuator after the shutdown command is generated, false or spurious trips caused solely by sensor malfunction, bridge maneuvering consequences, propulsion recovery actions, or wider ship-level accident scenarios following shutdown. The fault tree was developed based on the shutdown functions and protection logic of the MAN B&W S50MC6 two-stroke marine diesel engine, together with expert evaluation from the perspective of marine engineering operation. The top event was decomposed into five main intermediate events: low lubricating oil pressure, engine overspeed, high thrust bearing segment temperature, abnormal jacket cooling water inlet condition, and oil mist in the crankcase or cylinder. These five events were connected to the top event by an OR gate, since any one of these shutdown conditions can independently initiate the main engine shutdown process.

The first intermediate event, low lubricating oil pressure, was decomposed into three intermediate causes: lubricating oil supply failure, local lubricating oil pressure loss, and pressure drop not recovered. Lubricating oil supply failure was modelled with an AND gate because the failure of the main lubricating oil pump does not necessarily lead to a shutdown unless the standby lubricating oil pump also fails to start. Local lubricating oil pressure loss was modelled with an OR gate, since lubricating oil filter blockage, lubricating oil leakage, low lubricating oil tank or sump level, or incorrect valve position in the lubricating oil line can individually contribute to pressure loss. The pressure drop not recovered event was modelled with an AND gate because both the occurrence of a lubricating oil pressure drops alarm or signal and the failure to restore lubricating oil pressure are required for this branch to progress toward shutdown. The second intermediate event, engine overspeed, was divided into speed control failure, excessive fuel admission, and load rejection response failure. Speed control failure was connected to governor malfunction, actuator or fuel-regulating linkage failure, or incorrect speed commands from the control system through an OR gate. Excessive fuel admission was also represented by an OR gate, as either the fuel pump rack being stuck in the high-fuel position or fuel pump mechanical failure may lead to excessive fuel delivery. Load rejection response failure was represented by an AND gate, since sudden propeller or load loss becomes critical when it is combined with an inadequate speed-control response. The third intermediate event, high thrust bearing segment temperature, was decomposed into lubrication and heat removal failure, thrust bearing segment degradation, and excessive thrust load not compensated. Lubrication and heat removal failures were modelled with an AND gate because insufficient lubricating oil supply to the thrust bearing and insufficient lubricating oil cooling of the thrust bearing jointly represent a critical thermal condition. Thrust bearing segment degradation was represented by an OR gate, since either segment wear or segment damage may increase bearing temperature. Excessive thrust load not compensated was modelled with an AND gate, because excessive propeller thrust becomes critical when the lubrication or cooling system cannot compensate for the increased load. The fourth intermediate event, abnormal jacket cooling water inlet condition, was divided into cooling water supply failure, cooling water inventory loss, and cooling water flow path restriction. Cooling water supply failure was modelled with an AND gate because failure of the main jacket cooling water pump

alone may not lead to the shutdown condition if the standby pump successfully starts. Cooling water inventory loss was modelled with an OR gate, since jacket cooling water leakage or low expansion/deaerating tank level can individually reduce the available cooling water inventory. Cooling water flow path restriction was also represented by an OR gate, as an incorrectly positioned or closed cooling water valve, clogging or fouling in the cooling water flow path, or an air lock in the jacket cooling water line can individually disturb the inlet cooling condition. The fifth intermediate event, oil mist in the crankcase or cylinder, was decomposed into bearing heating-induced oil mist, piston/cylinder friction-induced oil mist, and mechanical damage or critical oil mist detection. Bearing heating-induced oil mist was modelled with an AND gate because lubricating oil supply failure, causing bearing heating and bearing surface overheating, jointly define the mechanism leading to oil mist generation. Piston/cylinder friction-induced oil mist was also modelled with an AND gate, since abnormal piston or cylinder friction must develop into local overheating in the piston or cylinder region to form a critical oil mist condition. Mechanical damage or critical oil mist detection was represented by an OR gate, as mechanical damage in the crankshaft, connecting rod, or crosshead assembly, or the detection of critical oil mist concentration, can independently contribute to this shutdown branch.

The intermediate events shown in Figure 1, such as Speed Control Failure, Lubrication and Heat Removal Failure, and Cooling Water Supply Failure, do not directly represent the primary failure events being evaluated. These events describe functional failure conditions that may occur in the shutdown mechanism and allow for the logical grouping of the relevant primary events. The probabilities of these intermediate events were not directly assigned by the expert; instead, they were calculated using the probabilities of the relevant primary events through the Boolean structure of the fault tree and AND/OR gate relationships. For example, the Speed Control Failure event is derived from the combined effects of governor failure, actuator or fuel adjustment linkage mechanism failure, and an incorrect speed command from the control system. Similarly, the Lubrication and Heat Removal Failure event is modelled based on the simultaneous occurrence of insufficient lubrication and insufficient heat removal conditions. This approach allows for a more physically understandable interpretation of the fault tree and provides a transparent basis for subsequent probability calculations.

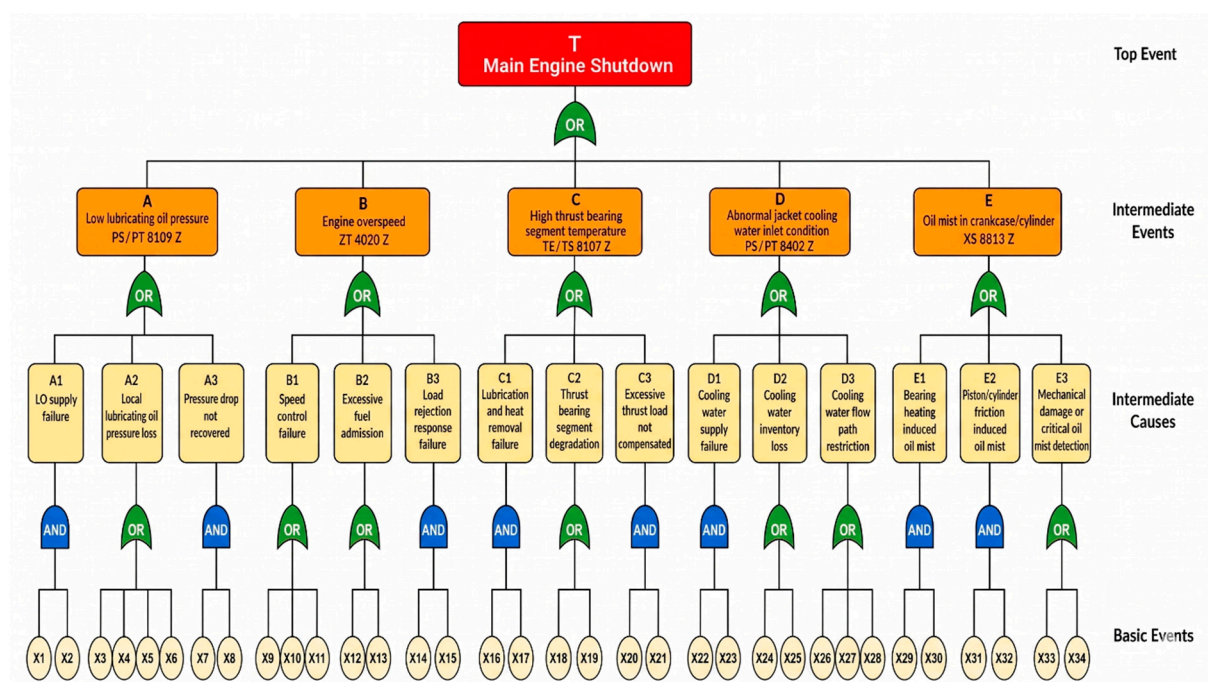


Figure 1. Fault tree diagram of the study.

The fault tree built has five main events, about 15 intermediate causes, and 34 fundamental events. All basic events are positioned at the lowest level of the fault tree, thereby facilitating Boolean reduction, the identification of minimal cut sets, and systematic probability calculations. However, this way of modelling does not really stop the FTA logic—those fundamental events can be placed at different levels if the analyst prefers a certain decomposition level. Moreover, structuring all fundamental events at the lowest level of the fault tree and consistently maintaining this modelling approach provides a more systematic framework for applying fuzzy-logic-based probability transformations and offers a more reliable analytical infrastructure for significance analyses performed in later stages. To make the fault tree structure more transparent, the rationale for the decomposition of the shutdown mechanism and the selection of AND/OR gates is summarized in Table 1. In this model, OR gates were used when any single input event was sufficient to generate the corresponding intermediate event. AND gates were used when the intermediate event could occur only through the simultaneous occurrence of two conditions, such as redundancy failure, failure of recovery action, or the combination of an initiating disturbance with an inadequate control response. The model is based on the functional protection logic of the main engine shutdown system and expert reasoning regarding marine diesel engine operation. Since shutdown set points may vary depending on vessel configuration, monitoring system settings, and manufacturer-specific alarm/shutdown arrangements, the model represents functional shutdown conditions rather than fixed numerical trip thresholds.

Table 1. Technical rationale for the selected intermediate events and gate logic.

Fault Tree Element/Gate	Technical Rationale
Top event	Main engine protective shutdown demand/OR: The top event was defined as the activation or demand of the automatic protective shutdown function. Since any one of the five main shutdown conditions can independently generate a shutdown demand, the main branches were connected to the top event by an OR gate.
A	Low lubricating oil pressure/OR: Low lubricating oil pressure may occur through different mechanisms, including lubricating oil supply failure, local pressure loss, or failure to recover pressure after a pressure drop. Since each mechanism can independently lead to a shutdown-relevant low-pressure condition, an OR gate was used.
A1	Lubricating oil supply failure/AND: The main lubricating oil pump failure alone does not necessarily cause shutdown if the standby pump starts correctly. Therefore, this branch was modelled with an AND gate, because the condition becomes critical only when the main pump fails, and the standby pump also fails to start.
A2	Local lubricating oil pressure loss/OR: Filter blockage, lubricating oil leakage, low sump/tank level, or incorrect valve position can each independently cause local pressure loss. Therefore, these events were connected by an OR gate.
A3	Pressure drops do not recover/AND: A temporary pressure drop becomes shutdown-relevant when a pressure drop signal/alarm occurs, and adequate lubricating oil pressure cannot be restored. Since both conditions are required, an AND gate was used.
B	Engine overspeed/OR: Engine overspeed may result from speed control failure, excessive fuel admission, or inadequate response to load rejection. Since each mechanism can independently create an overspeed shutdown condition, an OR gate was selected.
B1	Speed control failure/OR: Governor malfunction, actuator or fuel regulating linkage failure, and incorrect speed command from the control system can each independently disturb speed control. Therefore, an OR gate was used.
B2	Excessive fuel admission/OR: A stuck fuel pump rack or fuel pump mechanical failure can independently cause excessive fuel delivery. Therefore, these events were connected by an OR gate.

B3	Load rejection response failure/AND: Sudden propeller/load loss does not necessarily cause shutdown if the speed control system responds properly. It becomes critical when load rejection occurs together with inadequate speed control response. Therefore, an AND gate was used.
C	High thrust bearing segment temperature/OR: High thrust bearing temperature may result from lubrication and heat removal failure, thrust bearing segment degradation, or excessive thrust load not compensated. Since each mechanism can independently contribute to a shutdown-relevant temperature rise, an OR gate was used.
C1	Lubrication and heat removal failure/AND: A critical thermal condition in the thrust bearing requires both insufficient lubricating oil supply and insufficient heat removal. Therefore, this branch was modelled with an AND gate.
C2	Thrust bearing segment degradation/OR: Thrust bearing segment wear or damage can independently increase friction and bearing temperature. Therefore, an OR gate was selected.
C3	Excessive thrust load not compensated/AND: Excessive thrust load becomes shutdown-relevant when the lubrication or cooling system cannot compensate for the increased mechanical and thermal load. Since both conditions are required, an AND gate was used.
D	Abnormal jacket cooling water inlet condition/OR: Abnormal jacket cooling water inlet condition may arise from cooling water supply failure, cooling water inventory loss, or cooling water flow path restriction. Since any one of these mechanisms can independently disturb the inlet cooling condition, an OR gate was used.
D1	Cooling water supply failure/AND: The main jacket cooling water pump failure alone may not cause shutdown if the standby pump starts correctly. This condition becomes critical only when the main pump fails, and the standby pump also fails to start. Therefore, an AND gate was used.
D2	Cooling water inventory loss/OR: Jacket cooling water leakage or low expansion/deaerating tank level can independently reduce cooling water availability. Therefore, an OR gate was selected.
D3	Cooling water flow path restriction/OR: An incorrectly positioned or closed valve, clogging/fouling in the cooling water line, or an air lock can each independently restrict flow and disturb jacket cooling water inlet conditions. Therefore, these events were connected by an OR gate.
E	Oil mist in crankcase/cylinder/OR: Oil mist-related shutdown demand may arise from bearing heating, piston/cylinder friction-induced overheating, or mechanical damage/critical oil mist detection. Since any of these conditions can generate an oil mist-related shutdown demand, an OR gate was used.
E1	Bearing heating-induced oil mist/AND: Bearing-related oil mist formation requires a lubrication-related heating mechanism and actual bearing surface overheating. Since both conditions are required, an AND gate was used.
E2	Piston/cylinder friction-induced oil mist/AND: Abnormal piston/cylinder friction becomes oil mist-relevant when it develops into local overheating in the piston/cylinder region. Therefore, an AND gate was selected.
E3	Mechanical damage or critical oil mist detection/OR: Mechanical damage in the crankshaft, connecting rod, or crosshead assembly may contribute directly to oil mist generation, while critical oil mist concentration detection can independently generate a shutdown demand. Therefore, an OR gate was used.

Figure 1 presents the constructed fault tree diagram for the main engine shutdown event. The corresponding Boolean representation of the top event is given as follows: $T = A + B + C + D + E$, where T denotes main engine shutdown, A denotes low lubricating oil pressure, B denotes engine overspeed, C denotes high thrust bearing segment temperature, D denotes abnormal jacket cooling water inlet condition, and E denotes oil mist in the

crankcase or cylinder. The detailed Boolean expressions of these intermediate events are as follows:

$$A = (X_1 \cdot X_2) + (X_3 + X_4 + X_5 + X_6) + (X_7 \cdot X_8) \quad (9)$$

$$B = (X_9 + X_{10} + X_{11}) + (X_{12} + X_{13}) + (X_{14} \cdot X_{15}) \quad (10)$$

$$C = (X_{16} \cdot X_{17}) + (X_{18} + X_{19}) + (X_{20} \cdot X_{21}) \quad (11)$$

$$D = (X_{22} \cdot X_{23}) + (X_{24} + X_{25}) + (X_{26} + X_{27} + X_{28}) \quad (12)$$

$$E = (X_{29} \cdot X_{30}) + (X_{31} \cdot X_{32}) + (X_{33} + X_{34}) \quad (13)$$

Accordingly, the top event can be expressed as follows:

$$T = [(X_1 \cdot X_2) + (X_3 + X_4 + X_5 + X_6) + (X_7 \cdot X_8)] + [(X_9 + X_{10} + X_{11}) + (X_{12} + X_{13}) + (X_{14} \cdot X_{15})] \\ + [(X_{16} \cdot X_{17}) + (X_{18} + X_{19}) + (X_{20} \cdot X_{21})] + [(X_{22} \cdot X_{23}) + (X_{24} + X_{25}) + (X_{26} + X_{27} + X_{28})] \\ + [(X_{29} \cdot X_{30}) + (X_{31} \cdot X_{32}) + (X_{33} + X_{34})] \quad (14)$$

Boolean forms the basis for the subsequent FFTA calculation, in which expert linguistic judgments are converted into fuzzy numbers, defuzzified into crisp failure possibility values, transformed into failure probabilities, and finally propagated through the fault tree to obtain the probability of the top event and the importance values of the minimal cut sets.

3.2. Collection and Conversion of Expert Judgments

The probability values of the basic events could not be obtained from an operational failure database. Therefore, the basic event probabilities were derived from expert judgement under the FFTA framework. This procedure follows the approach used in maritime FFTA studies, where linguistic expert evaluations are first converted into fuzzy numbers and then transformed into probability values for use in fault tree calculations.

In this study, the assessment was obtained from one marine engineering expert with operational experience on two-stroke marine diesel engines. Since only one expert participated in the evaluation, the similarity aggregation procedure was not applied. Therefore, the expert's linguistic judgement for each basic event was directly assigned to its corresponding trapezoidal fuzzy number. In other words, the aggregated fuzzy judgement for each basic event was accepted as the fuzzy number corresponding to the single expert score:

$$\tilde{R}_{AG,i} = \tilde{R}_i^{(1)} = (a_i, b_i, c_i, d_i), i = 1, 2, \dots, 34 \quad (15)$$

where $\tilde{R}_{AG,i}$ denotes the aggregated fuzzy judgement assigned to the (ith) basic event, $\tilde{R}_i^{(1)}$ represents the fuzzy judgement of the single expert for the same basic event, and a_i, b_i, c_i, d_i is the corresponding trapezoidal fuzzy number. Since only one expert participated in the evaluation process, the aggregated fuzzy judgement was taken as equal to the fuzzy judgement provided by that expert. In this representation, (a_i) and (d_i) indicate the lower and upper bounds of the expert judgement, while (b_i) and (c_i) define the interval in which the judgement has the highest degree of membership. A trapezoidal fuzzy number is a four-parameter fuzzy set used to represent imprecise or linguistic assessments in numerical form. In this study, it was preferred because the occurrence probabilities of the basic events could not be obtained from a reliable operational failure database. Therefore, expert judgments expressed through linguistic terms such as “low”, “medium”, and “high” were represented by trapezoidal fuzzy numbers. This representation allows the uncertainty and vagueness inherent in expert-based risk evaluations to be incorporated into the FFTA model before defuzzification and probability transformation.

The expert evaluated the occurrence likelihood of each basic event using a seven-level scale. The numerical scores were converted into linguistic terms as follows: 1 = very low, 2 = low, 3 = medium-low, 4 = medium, 5 = medium-high, 6 = high, and 7 = very high. The corresponding trapezoidal fuzzy numbers were adopted from the linguistic scale used in previous FFTA applications. Linguistic scale and corresponding trapezoidal fuzzy numbers were seen in Table 2.

Table 2. Linguistic scale and corresponding trapezoidal fuzzy numbers.

Score	Linguistic Term	Abbreviation	Trapezoidal Fuzzy Number
1	Very low	VL	(0.0, 0.0, 0.1, 0.2)
2	Low	L	(0.1, 0.2, 0.2, 0.3)
3	Medium low	ML	(0.2, 0.3, 0.4, 0.5)
4	Medium	M	(0.4, 0.5, 0.5, 0.6)
5	Medium high	MH	(0.5, 0.6, 0.7, 0.8)
6	High	H	(0.7, 0.8, 0.8, 0.9)
7	Very high	VH	(0.8, 0.9, 1.0, 1.0)

The expert scores assigned to the 34 basic events are presented in Table 3. These values constitute the input data for the fuzzy quantification stage.

Table 3. Expert scores and corresponding fuzzy numbers for basic events.

Code	Expert Score	Linguistic Term	Trapezoidal Fuzzy Number
X1	3	ML	(0.2, 0.3, 0.4, 0.5)
X2	2	L	(0.1, 0.2, 0.2, 0.3)
X3	7	VH	(0.8, 0.9, 1.0, 1.0)
X4	5	MH	(0.5, 0.6, 0.7, 0.8)
X5	3	ML	(0.2, 0.3, 0.4, 0.5)
X6	4	M	(0.4, 0.5, 0.5, 0.6)
X7	6	H	(0.7, 0.8, 0.8, 0.9)
X8	6	H	(0.7, 0.8, 0.8, 0.9)
X9	1	VL	(0.0, 0.0, 0.1, 0.2)
X10	3	ML	(0.2, 0.3, 0.4, 0.5)
X11	1	VL	(0.0, 0.0, 0.1, 0.2)
X12	3	ML	(0.2, 0.3, 0.4, 0.5)
X13	3	ML	(0.2, 0.3, 0.4, 0.5)
X14	5	MH	(0.5, 0.6, 0.7, 0.8)
X15	2	L	(0.1, 0.2, 0.2, 0.3)
X16	3	ML	(0.2, 0.3, 0.4, 0.5)
X17	4	M	(0.4, 0.5, 0.5, 0.6)
X18	2	L	(0.1, 0.2, 0.2, 0.3)
X19	2	L	(0.1, 0.2, 0.2, 0.3)
X20	2	L	(0.1, 0.2, 0.2, 0.3)
X21	4	M	(0.4, 0.5, 0.5, 0.6)
X22	6	H	(0.7, 0.8, 0.8, 0.9)
X23	3	ML	(0.2, 0.3, 0.4, 0.5)
X24	6	H	(0.7, 0.8, 0.8, 0.9)
X25	4	M	(0.4, 0.5, 0.5, 0.6)
X26	6	H	(0.7, 0.8, 0.8, 0.9)
X27	7	VH	(0.8, 0.9, 1.0, 1.0)
X28	5	MH	(0.5, 0.6, 0.7, 0.8)
X29	3	ML	(0.2, 0.3, 0.4, 0.5)
X30	2	L	(0.1, 0.2, 0.2, 0.3)

X31	3	ML	(0.2, 0.3, 0.4, 0.5)
X32	2	L	(0.1, 0.2, 0.2, 0.3)
X33	1	VL	(0.0, 0.0, 0.1, 0.2)
X34	2	L	(0.1, 0.2, 0.2, 0.3)

After assigning the corresponding trapezoidal fuzzy number to each basic event, the defuzzification process was applied to obtain the crisp failure possibility value. For a trapezoidal fuzzy number $\tilde{R} = (r^1, r^2, r^3, r^4)$, the Centre-of-Area method was used as follows:

$$CFP = \frac{1}{3} \times \left(\frac{(r_4 + r_3)^2 - r_4 r_3 - (r_1 + r_2)^2 + r_1 r_2}{r_4 + r_3 - r_2 - r_1} \right) \quad (16)$$

where CFP denotes the crisp failure possibility of the relevant basic event. The resulting CFP values were then converted into failure probability values by using the Onisawa transformation, which is commonly applied in FFTA studies to transform fuzzy possibility into probability.

$$FP = \frac{1}{10^K}, CFP \neq 0; FP = 0, CFP = 0 \quad (17)$$

$$K = \left(\frac{1 - CFP}{CFP} \right)^{\frac{1}{3}} \times 2.301 \quad (18)$$

where FP represents the failure probability of the basic event. The obtained FP values were used as the quantitative inputs for the AND and OR gate calculations in the constructed fault tree.

3.3. Defuzzification and Conversion of Failure Possibilities into Probabilities

The trapezoidal fuzzy number assigned to each basic event was first converted into a crisp failure possibility value by using the Centre-of-Area method. For each basic event, the corresponding fuzzy number $\tilde{R} = (r^1, r^2, r^3, r^4)$ was defuzzified as follows:

$$CFP = \frac{1}{3} \times \left(\frac{(r_4 + r_3)^2 - r_4 r_3 - (r_1 + r_2)^2 + r_1 r_2}{r_4 + r_3 - r_2 - r_1} \right) \quad (19)$$

where CFP denotes the crisp failure possibility value. Since CFP is a possibility value rather than a probability value, it was converted into failure probability by using the Onisawa transformation, as is commonly applied in FFTA studies.

$$FP = \left\{ \frac{1}{10^K} \text{ if } CFP \neq 0; 0 \text{ if } CFP = 0 \right\} \quad (20)$$

$$K = ((1 - CFP)/CFP)^{(1/3)} \times 2.301 \quad (21)$$

The obtained crisp failure possibility and failure probability values for the 34 basic events are presented in Table 4.

Table 4. Defuzzified failure possibilities and converted failure probabilities of basic events.

Code	Score	Linguistic Term	CFP	FP
X1	3	ML	0.3500	1.485×10^{-3}
X2	2	L	0.2000	2.225×10^{-4}
X3	7	VH	0.9222	9.793×10^{-2}
X4	5	MH	0.6500	1.343×10^{-2}
X5	3	ML	0.3500	1.485×10^{-3}
X6	4	M	0.5000	5.000×10^{-3}
X7	6	H	0.8000	3.552×10^{-2}
X8	6	H	0.8000	3.552×10^{-2}
X9	1	VL	0.0778	5.663×10^{-6}
X10	3	ML	0.3500	1.485×10^{-3}

X11	1	VL	0.0778	5.663×10^{-6}
X12	3	ML	0.3500	1.485×10^{-3}
X13	3	ML	0.3500	1.485×10^{-3}
X14	5	MH	0.6500	1.343×10^{-2}
X15	2	L	0.2000	2.225×10^{-4}
X16	3	ML	0.3500	1.485×10^{-3}
X17	4	M	0.5000	5.000×10^{-3}
X18	2	L	0.2000	2.225×10^{-4}
X19	2	L	0.2000	2.225×10^{-4}
X20	2	L	0.2000	2.225×10^{-4}
X21	4	M	0.5000	5.000×10^{-3}
X22	6	H	0.8000	3.552×10^{-2}
X23	3	ML	0.3500	1.485×10^{-3}
X24	6	H	0.8000	3.552×10^{-2}
X25	4	M	0.5000	5.000×10^{-3}
X26	6	H	0.8000	3.552×10^{-2}
X27	7	VH	0.9222	9.793×10^{-2}
X28	5	MH	0.6500	1.343×10^{-2}
X29	3	ML	0.3500	1.485×10^{-3}
X30	2	L	0.2000	2.225×10^{-4}
X31	3	ML	0.3500	1.485×10^{-3}
X32	2	L	0.2000	2.225×10^{-4}
X33	1	VL	0.0778	5.663×10^{-6}
X34	2	L	0.2000	2.225×10^{-4}

The highest converted failure probabilities were obtained for X3 and X27. X3, representing lubricating oil filter blockage, and X27, representing clogging or fouling in the cooling water flow path, both received the highest expert score and therefore produced the highest CFP and FP values. The lowest converted failure probabilities were obtained for X9, X11, and X33, which were evaluated as very low by the expert. These FP values were then used as the quantitative inputs for the fault tree. In the next calculation stage, the AND gates were evaluated by multiplication of the relevant input probabilities, while the OR gates were evaluated by the complementary probability formulation:

$$P_{AND} = \prod_{i=1}^n P_i \quad (22)$$

$$P_{OR} = 1 - \prod_{i=1}^n (1 - P_i) \quad (23)$$

Thus, the converted basic event probabilities provide a direct numerical basis for calculating the intermediate event probabilities, minimal cut set probabilities, the top event probability, and the Fussell–Vesely importance values.

3.4. Calculation of Top Event Probability

The failure probability values obtained for the basic events were propagated through the fault tree by considering the AND and OR gate structures defined in Section 3.1. For an AND gate, the output probability was calculated by multiplying the input event probabilities. For an OR gate, the complementary probability formulation was used. This calculation logic is consistent with the FFTA calculation procedure used in previous maritime applications, where the converted basic event probabilities are propagated through the tree to calculate the top event and minimal cut set probabilities.

$$P_{AND} = \prod_{i=1}^n P_i \quad (24)$$

$$P_{OR} = 1 - \prod_{i=1}^n (1 - P_i) \quad (25)$$

The intermediate event probabilities were calculated according to the Boolean structure of the developed fault tree. The obtained results are presented in Table 5.

Table 5. Calculated probabilities of intermediate events.

Event	Description	Boolean Expression	Probability
A1	LO supply failure	$X_1 \cdot X_2$	3.304×10^{-7}
A2	Local lubricating oil pressure loss	$X_3 + X_4 + X_5 + X_6$	1.158×10^{-1}
A3	Pressure drops not recovered	$X_7 \cdot X_8$	1.262×10^{-3}
A	Low lubricating oil pressure	$A1 + A2 + A3$	1.169×10^{-1}
B1	Speed control failure	$X_9 + X_{10} + X_{11}$	1.496×10^{-3}
B2	Excessive fuel admission	$X_{12} + X_{13}$	2.967×10^{-3}
B3	Load rejection response failure	$X_{14} \cdot X_{15}$	2.988×10^{-6}
B	Engine overspeed	$B1 + B2 + B3$	4.462×10^{-3}
C1	Lubrication and heat removal failure	$X_{16} \cdot X_{17}$	7.424×10^{-6}
C2	Thrust bearing segment degradation	$X_{18} + X_{19}$	4.450×10^{-4}
C3	Excessive thrust load not compensated	$X_{20} \cdot X_{21}$	1.113×10^{-6}
C	High thrust bearing segment temperature	$C1 + C2 + C3$	4.535×10^{-4}
D1	Cooling water supply failure	$X_{22} \cdot X_{23}$	5.274×10^{-5}
D2	Cooling water inventory loss	$X_{24} + X_{25}$	4.034×10^{-2}
D3	Cooling water flow path restriction	$X_{26} + X_{27} + X_{28}$	1.417×10^{-1}
D	Abnormal jacket cooling water inlet condition	$D1 + D2 + D3$	1.763×10^{-1}
E1	Bearing heating-induced oil mist	$X_{29} \cdot X_{30}$	3.304×10^{-7}
E2	Piston/cylinder friction-induced oil mist	$X_{31} \cdot X_{32}$	3.304×10^{-7}
E3	Mechanical damage or critical oil mist detection	$X_{33} + X_{34}$	2.282×10^{-4}
E	Oil mist in crankcase/cylinder	$E1 + E2 + E3$	2.289×10^{-4}

The top event was calculated by applying the OR gate formulation to the five main intermediate events: $T = A + B + C + D + E$

$$P(T) = 1 - [(1 - P(A))(1 - P(B))(1 - P(C))(1 - P(D))(1 - P(E))]$$

$$P(T) = 2.764 \times 10^{-1}$$

Accordingly, the calculated probability of the main engine shutdown top event was 2.764×10^{-1} . Among the five main intermediate events, D, abnormal jacket cooling water inlet condition, produced the highest probability value, followed by A, low lubricating oil pressure. The remaining three branches had considerably lower calculated probabilities.

The minimal cut sets were then obtained from the Boolean expression of the fault tree. Each minimal cut set represents the smallest combination of basic events that can lead to the top event. In this study, 26 minimal cut sets were identified. The probability of each minimal cut set was calculated using the relevant basic event probabilities. The contribution of each cut set to the top event was then assessed using the Fussell–Vesely importance measure:

$$FV - I_i = \frac{P(MCS_i)}{P(T)} \quad (26)$$

The calculated minimal cut set probabilities and FV-I values are given in Table 6.

Table 6. Minimal cut set probabilities and Fussell–Vesely importance values.

Rank	Minimal Cut Set	Probability	FV-I
1	X_3	9.793×10^{-2}	0.3543
2	X_{27}	9.793×10^{-2}	0.3543

3	X ₂₄	3.552×10^{-2}	0.1285
4	X ₂₆	3.552×10^{-2}	0.1285
5	X ₄	1.343×10^{-2}	0.0486
6	X ₂₈	1.343×10^{-2}	0.0486
7	X ₆	5.000×10^{-3}	0.0181
8	X ₂₅	5.000×10^{-3}	0.0181
9	X ₅	1.485×10^{-3}	0.0054
10	X ₁₀	1.485×10^{-3}	0.0054
11	X ₁₂	1.485×10^{-3}	0.0054
12	X ₁₃	1.485×10^{-3}	0.0054
13	X ₇ ·X ₈	1.262×10^{-3}	0.0046
14	X ₁₈	2.225×10^{-4}	0.0008
15	X ₁₉	2.225×10^{-4}	0.0008
16	X ₃₄	2.225×10^{-4}	0.0008
17	X ₂₂ ·X ₂₃	5.274×10^{-5}	0.0002
18	X ₁₆ ·X ₁₇	7.424×10^{-6}	0.00003
19	X ₉	5.663×10^{-6}	0.00002
20	X ₁₁	5.663×10^{-6}	0.00002
21	X ₃₃	5.663×10^{-6}	0.00002
22	X ₁₄ ·X ₁₅	2.988×10^{-6}	0.00001
23	X ₂₀ ·X ₂₁	1.113×10^{-6}	0.000004
24	X ₁ ·X ₂	3.304×10^{-7}	0.000001
25	X ₂₉ ·X ₃₀	3.304×10^{-7}	0.000001
26	X ₃₁ ·X ₃₂	3.304×10^{-7}	0.000001

The highest FV-I values were obtained for X₃ and X₂₇. X₃ represents lubricating oil filter blockage, while X₂₇ represents clogging or fouling in the cooling water flow path. These two basic events were followed by X₂₄, jacket cooling water leakage, and X₂₆, an incorrectly positioned or closed cooling water valve. Therefore, the numerical FFTA results indicate that the main engine shutdown risk is mainly governed by the lubricating oil pressure branch and the jacket cooling water inlet condition branch.

3.5. Results and Discussion

The quantitative FFTA results show that the probability of the top event, main engine shutdown, was calculated as 2.764×10^{-1} . Among the five main shutdown branches, the highest probability was obtained for abnormal jacket cooling water inlet condition, with a value of 1.763×10^{-1} . This was followed by low lubricating oil pressure, with a probability of 1.169×10^{-1} . This branch was followed by the low lubrication oil pressure branch with a probability value of 1.169×10^{-1} . In contrast, the probability values of the branches for overspeed, high thrust bearing segment temperature, and oil mist formation in the crank-case/cylinder area were calculated to be significantly lower. This finding indicates that the shutdown risk is primarily driven by failures originating from the coolant system and the lubrication oil system. In Figure 2, it is clear how the abnormal jacket coolant inlet condition and the low lubrication oil pressure dominate the calculated shutdown probability, while the contributions from overspeed, thrust bearing temperature, and oil mist formation branches stay relatively limited.

The fact that the abnormal jacket coolant inlet condition branch has the highest probability value should not be interpreted as meaning that this failure group is more critical than lubrication oil system failures under all operating conditions. This result is a consequence of the expert assessments used in the developed FFTA model and the logical structure of the fault tree. In particular, the high probability of occurrence assigned to the fundamental events associated with clogging, contamination, and flow restrictions in the

coolant circuit increased the contribution of this branch to the shutdown probability. Therefore, the resulting ranking reflects the probabilistic effects calculated within the scope of the model, not the physical severity of the failure mechanisms.

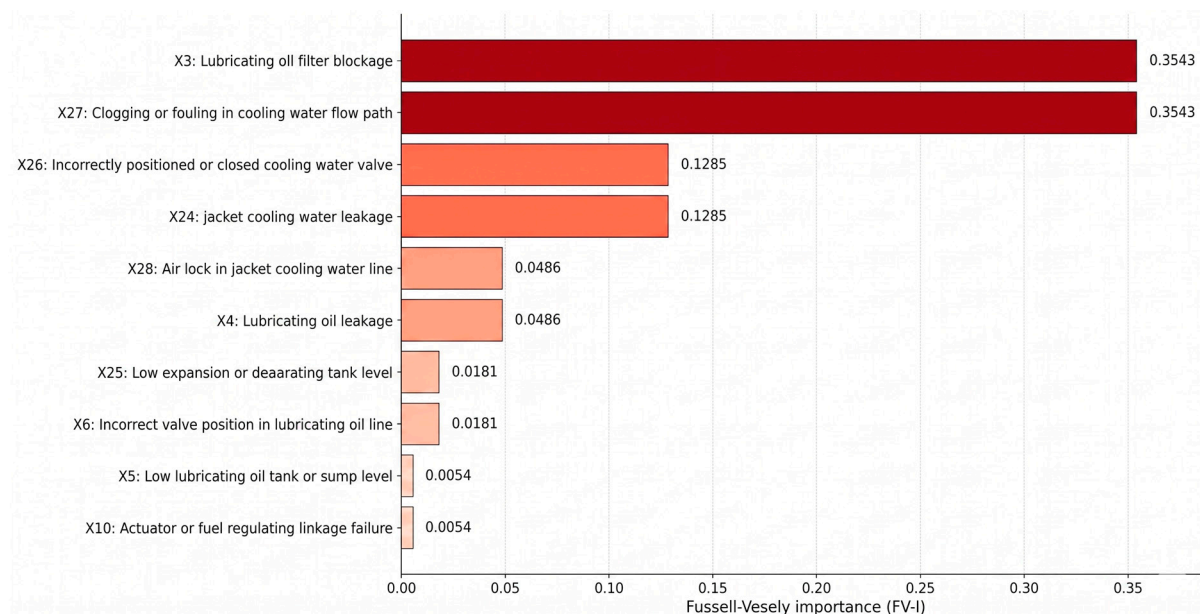


Figure 2. Calculated probabilities of the top event and main shutdown branches.

The probability of the abnormal jacket coolant inlet condition branch was largely due to restrictions occurring in the coolant flow path. Within this branch, X27, representing contamination or blockage in the coolant line, and X26, representing a mispositioned or closed coolant valve, were identified as the primary events contributing the most. This finding demonstrates that the operability of the jacket coolant circuit is highly sensitive to flow-restricting mechanisms. Therefore, conditions such as heat exchanger fouling, line blockages, valve positioning errors, and airlock formation should be considered critical operational problems that directly affect coolant inlet conditions and can trigger the shutdown logic. The second most contributing branch to the peak event was low lubrication oil pressure. Within this branch, X3, representing lubrication oil filter blockage, stood out as the primary event with the highest probability value, followed by lubrication oil leakage (X4) and incorrect valve positioning in the lubrication oil line (X6). The results show that failure mechanisms causing local pressure loss are more effective than the simultaneous failure of the main and backup lubrication oil pumps. Furthermore, the fact that combinations of X1·X2 and X7·X8 AND gates produce lower probability values is due to the need for these events to occur simultaneously.

The engine overspeed branch produced a lower probability compared with the lubricating oil and cooling water branches. The main contributors within this branch were X10 (actuator or fuel regulating linkage failure), X12 (fuel pump rack stuck in high-fuel position), and X13 (fuel pump mechanical failure). The load rejection response failure combination, X14 · X15, had a lower probability because it requires both a sudden propeller/load loss and failure of the speed control response. This outcome is consistent with the structure of the model, where overspeed shutdown is not only associated with fuel admission faults but also with the failure of the control response to suppress rapid speed rises. The high thrust bearing segment temperature branch had a comparatively low probability. Although thrust bearing temperature is a critical protection parameter, most of the related cut sets in this branch were either low-probability single events or AND-gate combinations. X18, thrust bearing segment wear, and X19, thrust bearing segment damage,

were the dominant contributors within this branch. The combinations X16 · X17 and X20 · X21 remained lower because they require concurrent lubrication/cooling inadequacy or excessive thrust load with insufficient compensation.

Among the five main shutdown branches, the lowest probability value was calculated for the branch representing oil mist formation in the crankcase/cylinder area. Within this branch, the most significant contributing event was X34, representing the detection of a critical level of oil mist concentration. In contrast, the combinations X29·X30 and X31·X32 produced significantly lower probability values due to being modelled with AND gates and requiring the simultaneous occurrence of the relevant events. However, caution should be exercised when evaluating this result, as the oil mist detector is not a direct cause of physical failure but rather a final-stage indicator representing the detection of a potentially dangerous situation to the safety system. Nevertheless, since the peak event was defined as “shutdown” in this study, this event was preserved in the fault tree. This is because a shutdown can occur not only because of physical failure mechanisms but also through signals from protection systems. The importance of the ranking of the minimal cross-sectional clusters also supports the obtained results. The highest contribution values, FV-I = 0.3543, were calculated for events X3 and X27 in the Fussell–Vesely significance analysis. These events were followed by X24 (jacket coolant leak) and X26 (mispositioned or closed coolant valve), both with a FV-I value of 0.1285. These results show that the minimal cross-section clusters that contribute most to the shutdown risk are not homogeneously distributed across the entire fault tree; rather, they are concentrated in the lubrication oil pressure and jacket coolant inlet condition branches. As highlighted in previous FFTA applications in the maritime sector, the importance of ranking minimal cross-section clusters offers a more robust and explanatory approach to identifying critical baseline events compared to examining only the probability of the peak event. The top ten minimal cross-section clusters shown in Figure 3, ranked by Fussell–Vesely importance values, clearly demonstrate that lubrication oil filter clogging, coolant line contamination, and coolant line blockages are the dominant risk factors determining the probability of shutdown.

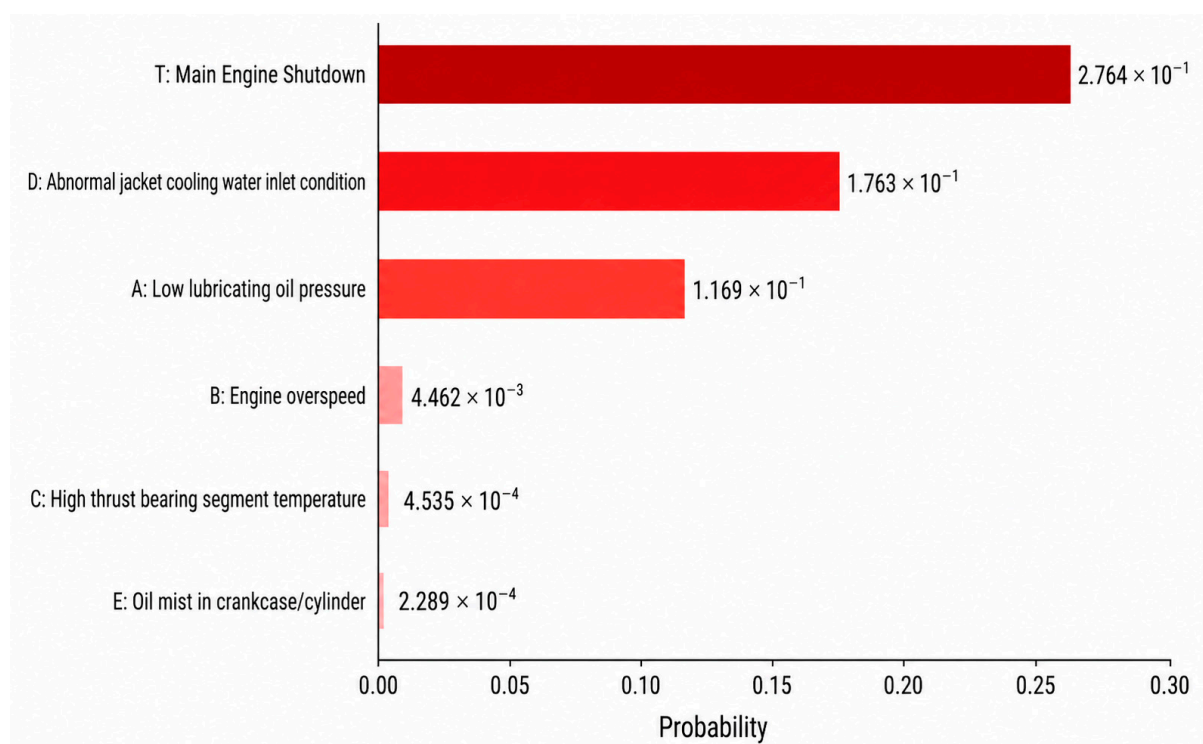


Figure 3. Top 10 minimal cut sets according to Fussell–Vesely importance values.

When examining the importance ranking of minimal cross-sectional sets, it is observed that cross-sectional sets consisting mostly of a single primary event occupy the top positions in the list, while multiple-event combinations modelled with AND gates have lower importance values due to the necessity of simultaneous occurrence. This finding indicates that maintenance and inspection activities aimed at reducing the risk of main engine shutdown should be directed towards critical areas, such as maintaining the effectiveness of lubrication oil filters, preventing lubrication oil and jacket coolant leaks, regularly verifying valve positions, and preventing contamination and blockages in the coolant circuit. Within the scope of the FFTA model based on expert assessments, these factors stand out as the primary risk elements contributing most significantly to shutdown events. Furthermore, the results show that minimal cross-sectional sets consisting of single events have a significant advantage in the importance ranking, while event combinations defined with AND gates produce lower probability values. This can be considered a theoretically expected result stemming from the Boolean logic of the fault tree, where the simultaneous occurrence of multiple events reduces the total probability of occurrence.

3.6. Sensitivity Analysis

Since the quantitative inputs of the FFTA model were obtained from expert-based linguistic assessments, a sensitivity analysis was performed to examine the robustness of the calculated top-event probability and the ranking of the most significant basic events. The main objective of this analysis was to determine whether reasonable variations in expert estimates would substantially change the dominant shutdown branches and the most important minimal cut sets. A one-at-a-time sensitivity analysis was applied. In this procedure, the expert score of each basic event was varied by one linguistic level while keeping all other basic event scores constant. Each basic event score was increased by +1 and decreased by −1 within the limits of the seven-level linguistic scale. For boundary values, one-sided variation was applied; that is, events originally scored as 1 were only increased to 2, while events originally scored as 7 were only decreased to 6. A total of 63 sensitivity scenarios were generated. For each scenario, the corresponding trapezoidal fuzzy number, crisp failure possibility, and converted failure probability were updated according to the same defuzzification and Onisawa transformation procedure used in the baseline model. The updated probabilities were then propagated through the fault tree using the same AND and OR gate logic. The percentage change in the top event probability was calculated as follows:

$$\Delta P(T)(\%) = \left(\frac{P_{s(T)} - P_{0(T)}}{P_{0(T)}} \right) \times 100 \quad (27)$$

where $\Delta P(T)$ denotes the baseline top event probability and $P_{s(T)}$ represents the top event probability obtained under the relevant sensitivity scenario. In the baseline case, the probability of the main engine shutdown top event was calculated as (2.764×10^{-1}) . Under the one-at-a-time sensitivity scenarios, the top event probability ranged between (2.263×10^{-1}) and (3.232×10^{-1}) . This corresponds to a maximum decrease of 18.11% and a maximum increase of 16.94% compared with the baseline result. Although the top event probability changed depending on the modified expert score, the dominant structure of the results remained stable. In all sensitivity scenarios, the abnormal jacket cooling water inlet condition branch remained the highest-contributing main shutdown branch, while the low lubricating oil pressure branch remained the second most important branch. Table 7 shows the corresponding sensitivity range.

Table 7. Sensitivity ranges of the main shutdown branch probabilities.

Branch	Description	Baseline Probability	Minimum Probability	Maximum Probability
A	Low lubricating oil pressure	1.169×10^{-1}	5.583×10^{-2}	1.367×10^{-1}
B	Engine overspeed	4.463×10^{-3}	3.204×10^{-3}	7.967×10^{-3}
C	High thrust bearing segment temperature	4.535×10^{-4}	2.370×10^{-4}	1.716×10^{-3}
D	Abnormal jacket cooling water inlet condition	1.763×10^{-1}	1.193×10^{-1}	2.296×10^{-1}
E	Oil mist in crankcase/cylinder	2.288×10^{-4}	1.166×10^{-5}	1.491×10^{-3}
T	Main engine shutdown	2.764×10^{-1}	2.263×10^{-1}	3.232×10^{-1}

The largest changes in the top event probability were produced by variations in the basic events that were already identified as the most important contributors in the baseline Fussell–Vesely analysis. Decreasing the expert score of X3, representing lubricating oil filter blockage, from 7 to 6 reduced the top event probability to (2.263×10^{-1}), corresponding to an 18.11% decrease. The same effect was observed when X27, representing clogging or fouling in the cooling water flow path, decreased from 7 to 6. Conversely, increasing X24, representing jacket cooling water leakage, or X26, representing an incorrectly positioned or closed cooling water valve, from 6 to 7 increased the top event probability to (3.232×10^{-1}), corresponding to a 16.94% increase. Table 8 presents the scenarios with the largest effects on the top event probability.

Table 8. Scenarios with the largest effects on the top event probability.

Basic Event	Variation	New P(T)	Change from Baseline
X3	7 $\rightarrow$ 6	2.263×10^{-1}	−18.11%
X27	7 $\rightarrow$ 6	2.263×10^{-1}	−18.11%
X24	6 $\rightarrow$ 7	3.232×10^{-1}	+16.94%
X26	6 $\rightarrow$ 7	3.232×10^{-1}	+16.94%
X24	6 $\rightarrow$ 5	2.598×10^{-1}	−6.00%
X26	6 $\rightarrow$ 5	2.598×10^{-1}	−6.00%
X4	5 $\rightarrow$ 6	2.926×10^{-1}	+5.86%
X28	5 $\rightarrow$ 6	2.926×10^{-1}	+5.86%

The sensitivity analysis also confirmed the robustness of the minimal cut set ranking. In the baseline analysis, X3 and X27 had the highest Fussell–Vesely importance values, followed by X24 and X26. Under the sensitivity scenarios, the most important events remained concentrated in the same failure groups, namely the lubricating oil pressure branch and the jacket cooling water inlet condition branch. X3 and X27 remained among the most influential events, while X24 and X26 consistently remained within the leading group of important contributors. The ranking of the dominant basic events is not an artefact of a single fixed expert score but is structurally supported by the fault-tree logic and the relative magnitudes of the fuzzy probability inputs.

4. Conclusions and Suggestions

This study applies Fuzzy Fault Tree Analysis (FFTA) to systematically investigate the causes of shutdown events that may occur in a MAN B&W S50MC6 two-stroke low-speed marine diesel main engine. In the study, the main engine shutdown event was defined as the peak event, and the critical protection functions that could lead to this event were modelled under five main branches: low lubrication oil pressure, overspeed, high thrust bearing segment temperature, abnormal jacket coolant inlet condition, and crankcase/cylinder oil mist formation. A total of 34 basic events were identified in the constructed fault

tree, and the probabilities of these events occurring were quantified using a fuzzy-logic approach with expert opinions. As a result of the FFTA analyses performed, the total probability value for the main engine shutdown event was calculated to be 2.764×10^{-1} . The findings reveal that the shutdown risk is not homogeneously distributed across all sub-components of the system but is concentrated on specific failure mechanisms. Specifically, the branch representing abnormal jacket coolant inlet conditions was determined to have the highest probability value, followed by the low lubrication oil pressure branch. In contrast, the branches associated with overspeed, high thrust bearing segment temperature, and oil mist formation in the crankcase/cylinder area had relatively low contributions to the shutdown probability.

By evaluating minimal cross-sectional sets together with Fussell–Vesely significance analysis, it was determined that the main events most significantly affecting the shutdown risk were clogging in the lubrication oil filter (X_3) and contamination or clogging in the coolant circuit (X_{27}). Both events had the same significance coefficient and, individually, accounted for more than one-third of the total shutdown risk. In addition, jacket coolant leakage (X_{24}), incorrectly positioned or closed coolant valves (X_{26}), lubrication oil leaks (X_4), and other conditions restricting flow in the coolant line emerged as significant risk factors. The results show that the risk of main engine shutdown depends significantly on the effectiveness of maintenance activities, the continuity of system cleanliness, and the accuracy of operational controls. This highlights that preventive maintenance practices, particularly for lubrication and cooling systems, play a critical role in improving system reliability. One of the key findings of the study is that the risk contribution of individual basic events is much higher compared to combined events that must occur simultaneously. While event combinations represented by AND gates have a low probability of occurrence, individual failures under OR gates were found to have a more significant impact on system reliability. This indicates that periodic maintenance and condition monitoring activities, especially for critical equipment, play a significant role in reducing the risk of shutdowns.

Based on the findings, maintenance and operational efforts should primarily focus on maintaining lubrication oil filter integrity, controlling lubrication oil leaks, preventing fouling and blockages in the jacket cooling water system, verifying valve positions, and enhancing cooling system monitoring. This means regularly checking oil filters, stopping leaks in the lubrication system as soon as they show up, and removing contamination and blockages from the jacket coolant circuit. It also includes confirming the actual valve positions and performing more effective monitoring of the cooling system. Taking these steps together should reduce shutdown events and, at the same time, improve main engine reliability and ensure smoother operational continuity.

This study contributes to the literature on reliability analysis of main engine shutdown functions, which are critical for maritime safety. However, since the fuzzy evaluation process used in the analysis is based on the opinions of a single expert, the results are dependent on expert judgement. The main limitation of the study is that the quantitative FFTA calculations are based on the evaluations of a single expert. However, the shutdown mechanism of two-stroke marine diesel main engines requires advanced expertise regarding protection systems, lubrication systems, jacket water cooling systems, thrust bearing behaviour, speed control logic, and crankcase monitoring systems. Therefore, it is quite difficult to find enough experts with experience in this field. The evaluations of experts with insufficient technical knowledge may negatively affect the accuracy of probability estimates. Therefore, in this study, the opinions of a technically competent expert were preferred instead of a larger but less specialized group. In the future, applying expert weighting methods with the participation of more marine machinery experts with different experience levels will increase the robustness and generalizability of the results.

Furthermore, this study presents a case study specifically on the MAN B&W S50MC6 two-stroke low-speed marine diesel main engine. The proposed Fuzzy Fault Tree Analysis approach is not limited to this engine type and can be adapted to similar marine propulsion systems. However, the results obtained need to be evaluated within the context of the selected engine configuration and operating assumptions. Another limitation is that the fuzzy probability inputs were derived from expert judgement rather than long-term observational failure data from the same engine type. Although long-term monitoring data would provide a stronger empirical basis, obtaining detailed component-level shutdown and failure records from commercial ships is highly challenging due to operational continuity requirements, data confidentiality, legal restrictions, limited onboard connectivity, and the isolated nature of maritime operations. In future studies, it is suggested that the generalizability of the method be verified and the robustness of the model improved by applying it to different engine types and operating conditions.

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