

Development of an Integrated RBD–FMEA–Based Reliability Optimization Model for Safety Shutdown Instrumentation Systems

Adi Aman

Institut Sains dan Teknologi
Nasional Departemen of
Electrical Engineering
Jl. Moh. Kahfi II, Bumi
Srengseng Indah, Jagakarsa
12640, Jakarta Selatan
adiaman05@gmail.com

Rivira Yuana

Institut Sains dan Teknologi
Nasional Departemen of
Electrical Engineering
Jl. Moh. Kahfi II, Bumi
Srengseng Indah, Jagakarsa
12640, Jakarta Selatan
rivira@istn.ac.id

Iwan Krisnadi

Institut Sains dan Teknologi
Nasional Departemen of
Electrical Engineering
Jl. Moh. Kahfi II, Bumi
Srengseng Indah, Jagakarsa
12640, Jakarta Selatan
iwan_krisnadi@istn.co.id

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Abstract – The reliability of Gas Engine Compressors is essential for ensuring production continuity and operational safety in the oil and gas industry, where the performance of the Safety Shutdown Instrumentation System (SSIS) plays a critical role in detecting abnormal conditions and preventing hazardous failures. This study proposes an integrated reliability optimization model for the SSIS by combining Reliability Block Diagram (RBD) and Failure Mode and Effects Analysis (FMEA) to improve system reliability, maintenance effectiveness, and operational safety. A quantitative case study was conducted using operational and maintenance data from a Gas Engine Compressor in an oil and gas production facility. Reliability parameters were evaluated using RBD, while component failure risks were assessed through FMEA based on Severity, Occurrence, and Detection ratings. The initial analysis showed an MTBF of 1,197 h, an MTTR of 730.67 h, a failure rate of $8.35 \times 10^{-4} \text{ h}^{-1}$, a system reliability of 43.37%, and an availability of 62.10%. Critical components identified were the Vibration Switch (RPN = 64), Temperature Switch (RPN = 54), and Power Supply (Magnet) (RPN = 40). The proposed optimization increased system reliability to 73.91% and availability to 99.64%, while decreasing failures and downtime during the evaluation period. The developed RBD–FMEA model provides a practical decision-support framework for reliability improvement and maintenance prioritization and can be adapted to Safety Instrumented Systems with similar architectures.

Keywords: Reliability Optimization; Safety Shutdown Instrumentation System; Gas Engine Compressor; Reliability Block Diagram; Failure Mode and Effects Analysis.



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I. INTRODUCTION

The oil and gas industry relies on the continuous and reliable operation of production facilities to ensure energy supply, operational efficiency, and process safety [1], [2]. One of the critical pieces of equipment in natural gas production systems is the Gas Engine Compressor, which increases gas pressure to maintain production rates and deliver gas to processing and distribution facilities. Failures of compressor systems may result in production shutdowns, economic losses, equipment damage, and increased operational risks [3]. Consequently, maintaining high system reliability has become an essential objective in compressor operation and maintenance.

The reliability of a Gas Engine Compressor is strongly influenced by the performance of its Safety Shutdown Instrumentation System, which functions as part of the Safety Instrumented System (SIS). A Safety Instrumented System consists of three primary elements: sensors, a logic solver, and final control elements [4]. These components continuously monitor critical operating parameters, such as pressure, temperature, vibration, lubricating oil pressure, rotational speed, and fluid level. When abnormal operating conditions are detected, the system automatically initiates a shutdown sequence to prevent equipment damage, process accidents, and environmental hazards. Therefore, the reliability of every component within the Safety Shutdown Instrumentation System directly affects the effectiveness of the overall protection function [5], [6], [7].

During long-term operation, instrumentation components are subjected to degradation caused by

aging, corrosion, contamination, vibration, and harsh environmental conditions [3], [7], [8]. Such degradation may lead to false trips, resulting in unnecessary production interruptions, or dangerous failure to trip, where the protection system fails to respond under hazardous operating conditions [9]. Both failure modes reduce operational reliability and may significantly compromise plant safety. Consequently, reliability assessment and maintenance optimization of Safety Shutdown Instrumentation Systems have become increasingly important in modern industrial facilities[10].

Reliability engineering provides quantitative approaches for evaluating system performance throughout its operational life [11], [12]. Among these approaches, the Reliability Block Diagram (RBD) is widely applied because it effectively models the logical relationship among system components and estimates the overall system reliability based on component failure characteristics [13], [14], [15]. However, although RBD provides a quantitative evaluation of system reliability, it has limitations in representing maintenance-related aspects and does not adequately support maintenance prioritization based on failure consequences [15].

Failure Mode and Effects Analysis (FMEA) complements reliability analysis by systematically identifying potential failure modes, their causes, their effects on system performance, and their associated risks [16]. Using Severity, Occurrence, and Detection ratings, FMEA calculates the Risk Priority Number (RPN), enabling maintenance engineers to prioritize corrective actions for the most critical components [16]. Nevertheless, FMEA alone does not provide quantitative information regarding the overall reliability of interconnected system components.

Several previous studies have investigated the reliability of Safety Instrumented Systems using methods such as Safety Integrity Level (SIL), Probability of Failure on Demand (PFD), Reliability Block Diagram (RBD), Markov analysis, and FMEA [5], [7], [17], [18], [19], [20], [21]. Recent studies have also shown a growing trend toward integrating multiple analytical methods into unified frameworks for process safety assessment [22]. However, these integrated approaches primarily focus on safety assessment, hazard analysis, or Safety Integrity Level (SIL) evaluation [22]. Furthermore, most studies employed RBD and FMEA independently or emphasized either quantitative reliability analysis or qualitative risk assessment. In addition, many investigations relied primarily on standard reliability databases or simulation models rather than actual operational data obtained from industrial facilities. Therefore, a research gap remains in the development of an integrated approach that combines quantitative

reliability evaluation using RBD and qualitative risk prioritization using FMEA based on actual field failure data, particularly for Safety Shutdown Instrumentation Systems in Gas Engine Compressors. Addressing this gap, the present study develops an integrated RBD–FMEA-based reliability optimization model using actual operational and failure data from a Gas Engine Compressor.

To address these limitations, this study proposes an integrated reliability optimization model based on Reliability Block Diagram (RBD) and Failure Mode and Effects Analysis (FMEA). The proposed approach combines quantitative system reliability evaluation with qualitative failure risk assessment to identify critical components and establish maintenance priorities. Unlike previous studies, this research utilizes actual operational data, including operating time, downtime, running hours, and historical component failure records obtained from a Gas Engine Compressor operating in an oil and gas production facility. The integration of RBD and FMEA provides a practical decision-support framework for optimizing maintenance activities, including preventive maintenance, calibration, functional testing, proof testing, and replacement of critical components.

The primary contribution of this study lies in the development of a reliability optimization model for Safety Shutdown Instrumentation Systems through the integration of RBD and FMEA using actual field operational data. The proposed model not only evaluates the reliability performance of the system but also prioritizes maintenance actions based on component criticality and failure risk. Therefore, the model is expected to improve system reliability and availability, reduce downtime, extend equipment service life, and enhance operational safety. Furthermore, because the proposed model is developed based on the generic architecture of Safety Instrumented Systems consisting of sensors, logic solvers, and final elements, it has the potential to be adapted to other industrial process safety applications with appropriate adjustments to system configuration and operating characteristics.

II. METHOD

The research methodology adopted in this study is illustrated in Figure 1. The study consists of five main stages: introduction, data collection, data analysis, optimization model evaluation, and conclusion.

This study employed a mixed-method approach combining quantitative reliability analysis and qualitative failure analysis to develop a reliability optimization model for the Safety Shutdown Instrumentation System of a Gas Engine Compressor.

The quantitative approach was used to evaluate system reliability based on historical operational data, while the qualitative approach was applied to identify failure mechanisms and determine maintenance priorities through Failure Mode and Effects Analysis (FMEA).

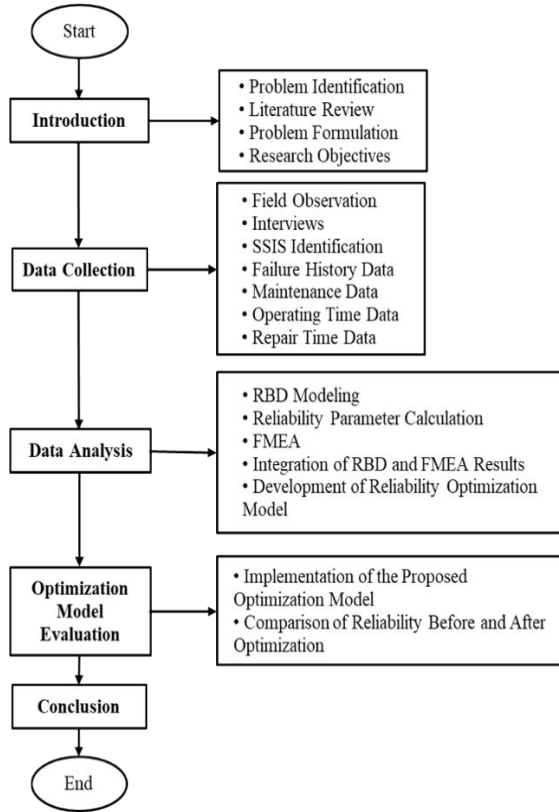


Figure 1. Research Methodology Flowchart

The research was conducted from September 2025 to August 2026 at the Gas Compressor Station of Pertamina Jakarta District, located at Tambun Field of Pertamina EP Zona 7. The object of the study was the Safety Shutdown Instrumentation System installed on Gas Engine Compressor Unit 463. The system consists of three principal subsystems representing the generic architecture of a Safety Instrumented System (SIS): sensors, logic solver, and final control element.

Data were collected through field observation, technical documentation, maintenance records, operating logs, and interviews with maintenance engineers, instrumentation technicians, and plant operators. The collected operational data included operating time, downtime, running hours, repair time, preventive maintenance history, and historical component failures. Technical documents, including equipment specifications, operation manuals, maintenance reports, and shutdown records, were also

used to verify the operational history and system configuration.

The reliability analysis was performed using the Reliability Block Diagram (RBD) method. Initially, all components constituting the Safety Shutdown Instrumentation System were identified and organized according to their functional relationships [13], [14]. The analyzed components included the power supply (magneto), logic controller (Murphy Mark IV), pressure switch, temperature switch, vibration switch, level switch, overspeed switch, and shut-off valve. Based on the system architecture, an RBD model representing the series configuration of the protection system was developed.

Historical failure data were subsequently processed to calculate the Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), and failure rate for each component. Component reliability was estimated using the exponential reliability model under the assumption of a constant failure rate, which is commonly associated with the useful life period of a component d [3], [11]. This assumption is applied to represent the average failure behavior of the components during the observation period. Given the limited number of observed failure events, a formal goodness-of-fit test for distribution identification is not considered statistically robust. Therefore, the exponential model is used as a simplifying assumption for the reliability analysis, and the results are interpreted within the scope and limitations of the available field data. System reliability was then calculated by combining the reliability values of all components according to the RBD configuration. In addition, system availability was determined using the calculated MTBF and MTTR values to evaluate the operational readiness of the Safety Shutdown Instrumentation System.

The reliability parameters considered in this study include Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), failure rate (λ), reliability $R(t)$, and availability A . The mathematical equations used for the reliability analysis are presented as follows.

$$MTBF = \frac{T_{operating}}{N_f}$$

where $T_{operating}$ is the total operating time (hours) and N_f is the number of failures.

$$MTTR = \frac{T_{repair}}{N_f}$$

where T_{repair} is the total repair time (hours) and N_f is the number of failures.

$$\lambda = \frac{1}{MTBF}$$

where λ is the failure rate (failures/hour).

$$R(t) = e^{-\lambda t}$$

where $R(t)$ is the reliability at time t , λ is the failure rate, and t is the operating time (hours).

$$A = \frac{MTBF}{MTBF + MTTR}$$

where A represents the operational availability of the system.

For the Reliability Block Diagram (RBD) analysis, the Safety Shutdown Instrumentation System is modeled using a series configuration. In a series configuration, the failure of any component can cause failure of the overall safety shutdown function. Therefore, the system reliability is calculated as:

$$R_{system}(t) = \prod_{i=1}^n R_i t$$

In this study, $n=8$, representing the eight components included in the series RBD configuration.

Failure Mode and Effects Analysis (FMEA) was conducted to identify potential failure modes, their causes, operational consequences, and maintenance priorities for each component [16]. Severity (S), Occurrence (O), and Detection (D) ratings were assigned using criteria adapted from previous reliability and FMEA studies and adjusted to the operational characteristics of the Safety Shutdown Instrumentation System [16]. The Risk Priority Number (RPN) for each failure mode was calculated as the product of Severity, Occurrence, and Detection scores. Components with higher RPN values were considered more critical and received higher maintenance priority.

The integration of RBD and FMEA constituted the core methodology of this research [23]. RBD provided quantitative information regarding component and system reliability, whereas FMEA identified the criticality and risk associated with individual component failures. By combining these complementary approaches, critical components exhibiting both low reliability and high RPN values were identified as the primary targets for reliability improvement.

Based on the integrated analysis, a reliability optimization model was developed to improve the performance of the Safety Shutdown Instrumentation System. The proposed optimization strategies included preventive maintenance enhancement, calibration interval adjustment, functional testing, proof testing, and replacement of degraded

components. The optimization recommendations were prioritized according to their expected impact on system reliability and operational safety.

Finally, the effectiveness of the proposed optimization model was evaluated by comparing system performance before and after implementation. The evaluation considered changes in reliability, availability, MTBF, MTTR, failure rate, downtime, and maintenance priority. Improvements in these indicators were used to validate the proposed model and demonstrate its applicability as a decision-support framework for reliability improvement of Safety Shutdown Instrumentation Systems in Gas Engine Compressors.

III. RESULTS AND DISCUSSION

A. Safety Shutdown Instrumentation System Configuration

The Safety Shutdown Instrumentation System (SSIS) of the Gas Engine Compressor consists of three main subsystems: sensors, a logic solver, and a final control element [4]. The sensors, including pressure, temperature, vibration, level, and overspeed switches, continuously monitor critical operating parameters. The Murphy Mark IV logic solver processes sensor signals to determine shutdown conditions, while the shut-off valve isolates the fuel supply and stops engine operation when a trip signal is generated. Based on this functional architecture, a series Reliability Block Diagram (RBD) was developed to represent the system reliability structure [13].

Historical operational data were processed to determine the reliability characteristics of each component. Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), and failure rates were calculated from recorded operating hours and maintenance history. Component reliability values were subsequently estimated using the exponential reliability model [11]. Reliability Block Diagram (RBD) provides an effective approach for evaluating the reliability of Safety Instrumented Systems by quantifying the probability of successful system operation and supporting the reliability assessment of protection systems [5].

Table 1. Summary of Operation Data Before and After Optimization

Parameter	Before	After
Operating hours (h)	3591	3307
Standby Time (h)	769	2513
Downtime (h)	2192	12
Number of Failures	3	1

Parameter	Before	After
Preventive Maintenance	Routine	Enhanced
Calibration	Corrective	Periodic
Functional Test	Limited	Periodic
Proof Test	Not Implemented	Implemented

Table 1 summarizes the actual operational data of the Gas Engine Compressor before and after the implementation of the proposed reliability optimization strategy. These data served as the basis for the reliability analysis using the RBD approach. Although standby time was not directly used in the reliability calculations, it was included to provide a complete description of the system's operational conditions throughout the observation periods. The operating hours and failure history were subsequently used to calculate MTBF, MTTR, failure rate, system reliability, and availability.

The calculated system reliability for 1000 hours was **43.37%**, indicating that the probability of the Safety Shutdown Instrumentation System performing its intended protection function throughout the operating period remained relatively low. This result demonstrates that reliability improvement is required to enhance system performance and operational safety.

Table 2. Reliability Analysis Results

Component	MTBF (h)	Failure Rate (λ)	Reliability
Power Supply (Magneto)	3591	1	0.7569
Logic Controller (Murphy Mark IV)	∞^*	0	1
Pressure Switch	∞^*	0	1
Temperature Switch	3591	1	0.7569
Vibration Switch	3591	1	0.7569
Level Switch	∞^*	0	1
Overspeed Switch	∞^*	0	1
Shut-off Valve	∞^*	0	1
System Reliability	—	—	43.37%

*No failure was observed for the component during the observation period

B. Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (FMEA) was performed to identify potential failure modes, evaluate their operational consequences, and determine maintenance priorities [16]. Each component was assessed using Severity (S), Occurrence (O), and Detection (D) ratings to calculate the Risk Priority Number (RPN).

The FMEA results indicated that the vibration switch obtained the highest RPN, followed by the temperature switch and the power supply (magneto). These components exhibited the greatest maintenance priority because their failures could significantly reduce the effectiveness of the Safety Shutdown Instrumentation System.

Table 3. FMEA Results

Component	Severity	Occurrence	Detection	RPN	Priority
Vibration Switch	8	2	4	64	High
Temperature Switch	9	2	3	54	High
Power Supply (Magneto)	10	2	2	40	Medium
Overspeed Switch	9	1	3	27	Medium
Logic Controller	10	1	2	20	Medium
Shut-off Valve	10	1	2	20	Medium
Pressure Switch	9	1	2	18	Low
Level Switch	8	1	2	16	Low

C. Integration of RBD and FMEA

The quantitative reliability results obtained from the Reliability Block Diagram (RBD) analysis were integrated with the qualitative risk assessment generated by Failure Mode and Effects Analysis (FMEA) [23]. Components were evaluated using two complementary criteria: their contribution to overall system reliability and their failure criticality represented by the Risk Priority Number (RPN).

Based on this integrated assessment, the components were classified into four optimization priority levels. The vibration switch and temperature switch were identified as Priority I components, followed by the magneto as Priority II. Logic control, overspeed switch, and shut-off valve were classified as Priority III, whereas the pressure switch and level switch were assigned to Priority IV. This integrated prioritization provides a systematic basis for selecting maintenance optimization strategies by simultaneously considering reliability performance and operational risk, rather than relying solely on failure frequency or qualitative judgment.

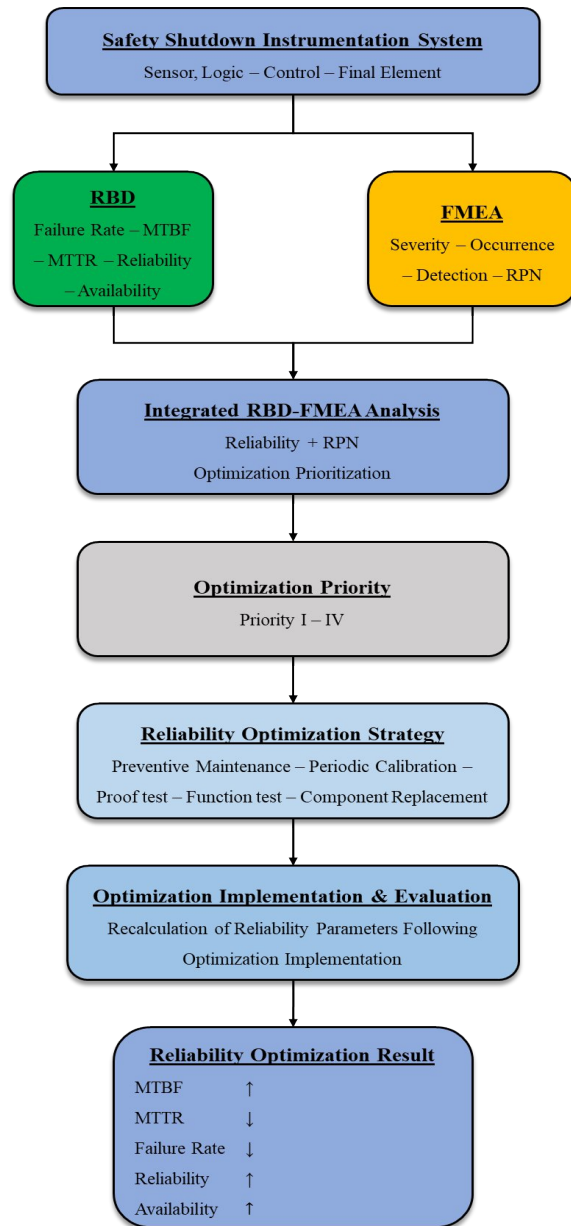


Figure 2. Proposed Reliability Optimization Model for the Safety Shutdown Instrumentation System

D. Reliability Optimization Results

Based on the integrated RBD–FMEA analysis, several optimization measures were implemented, including preventive maintenance enhancement, instrument calibration, functional testing, proof testing, and replacement of degraded components.

Following implementation, operational performance improved considerably. Reliability increased from **43.37%** before optimization to **73.91%** after optimization. Furthermore, improvements were observed in Mean Time Between

Failures (MTBF), Mean Time to Repair (MTTR), system availability, and operational downtime.

Table 4. System Performance Before and after Optimization

Performance Indicator	Before	After
System Reliability 1000h	43.37%	73.91%
MTBF	1197	3307
MTTR	730	12
Availability	62.10%	99.64%
Failure Rate	8.35×10^{-4}	3.02×10^{-4}

Table 4 shows that the proposed reliability optimization strategy increased the system reliability from 43.37% to 73.91%, while also improving MTBF and system availability and reducing the failure rate. The comparison of reliability curves before and after optimization is presented in Figure 3

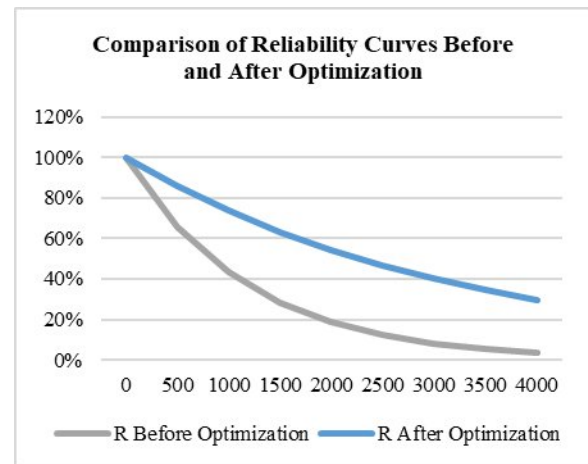


Figure 3. Comparison of Reliability Curve Before and After Optimization

The comparison demonstrates that implementation of the proposed optimization model resulted in measurable improvements in the reliability and operational performance of the Safety Shutdown Instrumentation System.

The reliability analysis demonstrated that the Safety Shutdown Instrumentation System of the Gas Engine Compressor exhibited a relatively low system reliability prior to optimization. Because the system operates in a series configuration, the failure of a single critical component directly reduces the probability of the entire protection system performing its intended safety function. This finding is consistent with reliability theory, which states that the reliability of a series system is determined by the combined reliability of all constituent components [11]. Therefore, improving the reliability of the most

critical components is essential to increase overall system performance.

The RBD analysis successfully quantified the reliability performance of individual components as well as the overall system [5], [13]. However, quantitative reliability alone was insufficient for determining maintenance priorities because components with similar reliability values may have different operational consequences when failures occur. This limitation highlights the importance of combining reliability assessment with risk-based evaluation [23]. By integrating RBD with FMEA, this study was able to identify not only components with low reliability but also those whose failures could have the greatest impact on process safety and operational continuity.

The FMEA results identified the vibration switch and temperature switch as the components with the highest Risk Priority Numbers [16]. These findings indicate that failures of these sensors are more likely to compromise the effectiveness of the Safety Shutdown Instrumentation System than failures of other components. Vibration and temperature are critical parameters in gas engine operation because abnormal conditions may rapidly develop into severe mechanical damage if not detected promptly. Consequently, improving the reliability of these components provides a greater contribution to overall system reliability than uniformly allocating maintenance resources across all components.

The integration of RBD and FMEA produced a structured maintenance prioritization framework. RBD quantified the probability of successful system operation, whereas FMEA evaluated the consequences and likelihood of individual component failures. The combined approach enabled maintenance decisions to be based on both quantitative reliability performance and qualitative risk assessment. This integration reduces subjectivity in maintenance planning and provides a more comprehensive basis for selecting optimization strategies than the application of either method independently.

Implementation of the proposed optimization strategies, including preventive maintenance enhancement, calibration, functional testing, proof testing, and replacement of degraded components, resulted in a substantial improvement in system performance [24]. Proof testing was included as part of the proposed maintenance strategy to ensure the functionality of the Safety Shutdown Instrumentation System [9], [18], [25], [26]. This finding is consistent with recent studies showing that proof test planning plays a critical role in maintaining the reliability and availability of Safety Instrumented Systems, particularly under component degradation conditions [25], [26], [27]. The increase in reliability following

optimization indicates that systematic maintenance activities can effectively reduce component degradation and restore the operational capability of the Safety Shutdown Instrumentation System [25], [26]. In addition, improvements in MTBF, MTTR, availability, and downtime demonstrate that reliability enhancement also contributes to improved operational efficiency and production continuity. As a result, the proposed reliability optimization strategy increased the overall system reliability from 43.37% to 73.82%, demonstrating the effectiveness of integrating RBD and FMEA in improving the performance of the Safety Shutdown Instrumentation System.

The proposed optimization model offers practical implications for maintenance management in the oil and gas industry [7]. Rather than scheduling maintenance solely on fixed intervals or reacting after failures occur, maintenance resources can be prioritized according to the combined results of reliability analysis and failure risk assessment. Such a strategy enables more efficient allocation of inspection, calibration, proof testing, and component replacement activities while maintaining the integrity of the Safety Shutdown Instrumentation System.

These findings are consistent with previous studies demonstrating the effectiveness of reliability engineering techniques in improving the performance of Safety Instrumented Systems (SIS). Earlier studies have investigated reliability assessment using Safety Integrity Level (SIL), Probability of Failure on Demand (PFD), and Probability of Dangerous Failure per Hour (PFH), as well as optimization of maintenance intervals and diagnostic strategies for SIS. However, compared with previous studies that generally applied Reliability Block Diagram (RBD) or Failure Mode and Effects Analysis (FMEA) separately, this research demonstrates the advantages of integrating both methods into a single decision-support framework [22]. The use of actual operational data from an industrial Gas Engine Compressor further enhances the practical relevance of the proposed model. Consequently, the developed model provides a more realistic representation of system performance than approaches relying solely on generic reliability databases or simulation assumptions.

This study contributes to the existing body of knowledge by developing an integrated reliability optimization framework for the Safety Shutdown Instrumentation System (SSIS) of a Gas Engine Compressor [22]. The proposed framework combines Reliability Block Diagram (RBD) for quantitative reliability evaluation with Failure Mode and Effects Analysis (FMEA) for systematic identification and prioritization of critical failure modes. Unlike previous studies that generally limited their analyses to reliability assessment or failure risk evaluation, this

framework translates analytical results into actionable maintenance strategies. Furthermore, the use of actual operational and failure-history data enhances the practical applicability of the proposed model under real industrial operating conditions. Consequently, the framework provides decision support for reliability-centered maintenance through prioritized preventive maintenance, proof testing, calibration, functional testing, and replacement of critical components, thereby improving both system reliability and operational availability.

Although this study focused on the Safety Shutdown Instrumentation System of a Gas Engine Compressor, the proposed reliability optimization model was developed based on the generic architecture of Safety Instrumented Systems consisting of sensors, a logic solver, and final control elements. Therefore, the proposed framework has the potential to be adapted to other industrial process safety applications that employ the same generic SIS architecture, provided that system configuration, operational characteristics, and maintenance data are appropriately adjusted. This potential is consistent with recent studies highlighting that modular and generic modeling frameworks provide greater flexibility for reliability assessment across different Safety Instrumented System configurations [27]. Consequently, the proposed framework can support reliability evaluation and maintenance decision-making across a broader range of industrial process systems while preserving the fundamental principles of Safety Instrumented System operation.

Future research may extend the proposed model by incorporating probabilistic safety assessment techniques, dynamic reliability analysis, machine learning-based failure prediction, or real-time condition monitoring to further improve maintenance decision-making and system reliability [22], [27].

IV. CONCLUSION

This study developed a reliability optimization model for the Safety Shutdown Instrumentation System of a Gas Engine Compressor by integrating Reliability Block Diagram (RBD) and Failure Mode and Effects Analysis (FMEA). The RBD method quantitatively evaluated the reliability performance of individual components and the overall system, while FMEA identified critical failure modes and established maintenance priorities based on risk assessment. The integration of these methods provided a comprehensive framework for evaluating both reliability performance and component criticality. The analysis identified the vibration switch, temperature switch, and power supply (magnet) as the highest-priority components for reliability improvement.

Based on the integrated RBD–FMEA results, optimization strategies consisting of preventive maintenance, calibration, functional testing, proof testing, and component replacement were proposed and implemented. The implementation of these strategies improved system reliability, increased operational availability, reduced downtime, and enhanced the effectiveness of the Safety Shutdown Instrumentation System. The principal contribution of this research is the development of a practical reliability optimization model that integrates quantitative reliability analysis with qualitative failure risk assessment using actual industrial operational data. The proposed model provides a systematic decision-support framework for maintenance planning by prioritizing maintenance actions according to both reliability and failure risk rather than relying solely on periodic maintenance schedules. Although the model was developed using a Gas Engine Compressor as the case study, it is based on the generic architecture of Safety Instrumented Systems consisting of sensors, a logic solver, and final control elements. Therefore, with appropriate adjustments to system configuration, operational characteristics, and maintenance data, the proposed model has the potential to be applied to other industrial process safety systems requiring reliability improvement and risk-based maintenance optimization.

Future research may validate the proposed model across different types of Safety Instrumented Systems and industrial facilities, as well as integrate more advanced reliability analysis techniques to further improve maintenance decision-making and system reliability.

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