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SIL-Compliant Safety Instrumented System Design for Oil & Gas Hazardous-Area Operations Using IEC 61508 / IEC 61511 Frameworks

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Abstract

This study examined the problem of functional safety gaps in oil and gas hazardous-area operations, where Safety Instrumented Systems may fail to achieve intended risk reduction when IEC 61508 and IEC 61511 requirements, hazard identification, SIL verification, proof testing, maintenance, documentation, and safety culture are weakly implemented. The purpose of the study was to assess how SIL-compliant SIS design influences functional safety performance in enterprise oil and gas cases involving refineries, gas processing facilities, petrochemical plants, offshore platforms, pipeline stations, storage terminals, and process control facilities. A quantitative, cross-sectional, case-based design was adopted, and data were collected through a structured five-point Likert-scale questionnaire from 132 valid respondents out of 150 distributed questionnaires, representing an 88.0% valid response rate. The sample included safety and HSE professionals, instrumentation and control engineers, process engineers, maintenance and operations staff, and compliance or project engineers, with 68.2% directly involved in SIS-related activities. The key variables were IEC 61508/IEC 61511 framework implementation, hazard identification and risk assessment, SIL verification and validation, SIS maintenance and proof testing, organizational safety culture, SIL-compliant SIS design quality, and functional safety performance. The analysis plan included descriptive statistics, reliability testing using Cronbach's alpha, Pearson correlation, regression modeling, SIL lifecycle maturity indexing, and SIF risk-control priority assessment. The headline findings showed that all major constructs were rated high, with functional safety performance recording the highest mean score of 4.15, followed by IEC framework implementation at 4.12 and SIL-compliant SIS design quality at 4.08. Reliability was acceptable to excellent, with Cronbach's alpha values ranging from 0.78 to 0.91. Correlation results showed significant positive relationships, including $r = 0.74$ between SIS design quality and functional safety performance. Regression results confirmed that the model explained 68.4% of the variance in functional safety performance, $R^2 = 0.684$, adjusted $R^2 = 0.671$, $F(6,125) = 45.12$, $p < 0.001$. SIL-compliant SIS design quality was the strongest predictor, $\beta = 0.31$, followed by IEC framework implementation, $\beta = 0.24$, and SIL verification and validation, $\beta = 0.21$. The findings imply that oil and gas enterprises should strengthen lifecycle documentation, proof testing compliance, bypass control, gas detection integration, and safety culture to improve functional safety reliability.

Keywords

SIL compliance; Safety Instrumented Systems; IEC 61508; IEC 61511; Functional safety performance.

INTRODUCTION

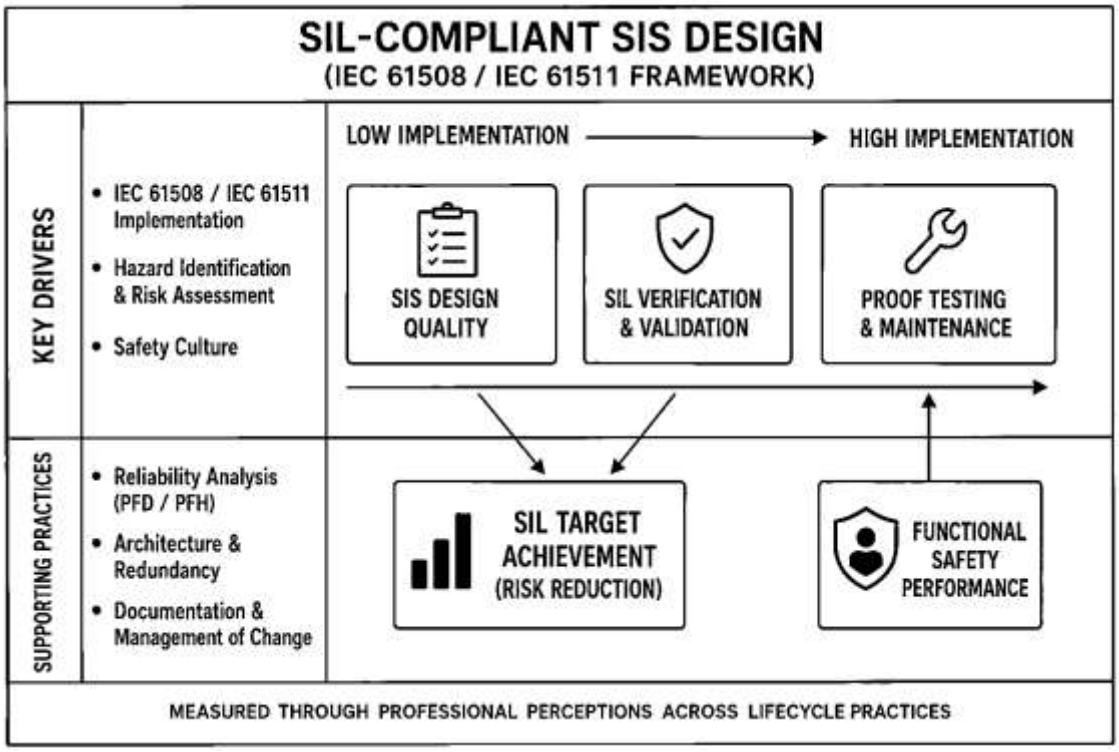
Functional safety refers to the part of overall safety that depends on the correct functioning of electrical, electronic, and programmable electronic safety-related systems when hazardous process conditions occur. In oil and gas hazardous-area operations, functional safety is closely associated with the design, verification, validation, operation, and maintenance of Safety Instrumented Systems (SISs), which are engineered systems intended to detect dangerous process deviations and bring the process to a safe state through one or more Safety Instrumented Functions (SIFs). A Safety Integrity Level (SIL) is a risk-reduction performance target assigned to a SIF, commonly expressed through measures such as average probability of failure on demand, probability of dangerous failure per hour, hardware fault tolerance, diagnostic coverage, and systematic capability. In practical terms, SIL compliance means that the selected architecture, components, testing interval, maintenance strategy, documentation, and lifecycle controls are able to demonstrate that the required risk reduction has been achieved and maintained (Alaei et al., 2021). This makes SIS design a technical, organizational, and lifecycle-based process rather than a single engineering calculation. Research on SIS reliability has emphasized that SIS performance cannot be understood only through component failure rates because operating mode, testing strategy, common cause failures, spurious trips, proof-test coverage, final-element degradation, and field experience all influence safety performance (Guzman et al., 2021). Within this study, SIL-compliant SIS design is defined as the systematic development of safety functions, architectures, verification procedures, proof-testing plans, maintenance controls, and documentation systems that satisfy the required SIL target under IEC 61508 and IEC 61511 logic. Functional safety performance is defined as the organization's perceived and measurable ability to reduce hazardous-event likelihood, improve shutdown reliability, control dangerous failures, reduce unmanaged bypasses, and sustain auditable SIS lifecycle compliance (Chebila & Innal, 2014).

The international significance of SIL-compliant SIS design is connected to the global risk profile of the oil and gas sector, where hazardous-area operations involve flammable hydrocarbons, toxic gases, high-pressure vessels, rotating equipment, subsea systems, offshore drilling installations, pipelines, refineries, terminals, and petrochemical processing units (Jin et al., 2011). These operations are internationally distributed and technologically diverse, yet they share similar risk-control needs: preventing loss of containment, detecting abnormal process states, isolating hazardous energy, initiating emergency shutdown, protecting personnel, and reducing environmental and asset damage. SISs are therefore not only local engineering controls but also internationally recognized barriers within layered process safety management (Brissaud et al., 2012). Studies on oil and gas SIS applications show that these systems are used to detect the onset of hazardous events and mitigate consequences to people, assets, and the environment, while also creating challenges related to common cause failures, function testing, inspection, proof testing, and operational follow-up (Dutuit et al., 2008). Offshore drilling research further shows that dynamic risk conditions, operational uncertainty, and complex barrier interactions require structured risk models that can support diagnosis and prediction of hazardous events. Hazardous-area environments also demand strong links between hazard identification, protection layers, and SIF development because inadequate SIL selection can lead to under-protection, while excessive conservatism can lead to costly or operationally fragile designs (Lundteigen & Rausand, 2007). Layered protection and SIL selection studies therefore connect SIS design to HAZOP, LOPA, fault-tree analysis, Markov modeling, and reliability assessment methods. In this context, the international relevance of this research lies in examining how organizations translate recognized functional safety standards into operationally reliable SIS design practices across hazardous-area oil and gas settings (Wang & Rausand, 2014).

IEC 61508 and IEC 61511 provide the central standard-based foundation for this research because they frame functional safety as a lifecycle activity that begins with hazard and risk analysis and continues through specification, design, installation, commissioning, validation, operation, maintenance, modification, and decommissioning (Xie et al., 2019). The standards require engineers and operators to move from qualitative process hazard understanding toward quantitative and semi-quantitative risk-reduction demonstration. Academic studies have repeatedly shown that the lifecycle approach is essential because the achieved safety performance of a SIS depends on both design-phase assumptions

and operational-phase follow-up (Oliveira & Abramovitch, 2010). The integration of RAMS engineering and management with the IEC 61508 safety lifecycle shows that reliability, availability, maintainability, and safety must be coordinated across engineering and managerial activities. Architectural constraints in IEC 61508 also raise important questions about whether rules based on parameters such as safe failure fraction and hardware fault tolerance always produce the intended safety effect (Jin et al., 2013). These concerns are important for oil and gas hazardous-area operations because a SIL target can appear compliant at the calculation level while still being vulnerable to weak documentation, poor maintenance discipline, unsuitable testing intervals, bypass misuse, inadequate independence, or common cause failure exposure (Fernández-Muñiz et al., 2007).

Figure 1: SIL-Compliant SIS Design Framework for Functional Safety Performance



Research on safety and operational integrity evaluation has also emphasized that SIS design requires optimization across safety integrity and operational integrity rather than a narrow focus on one reliability indicator. The relationship between framework implementation and SIS design quality is therefore central to this study (Hokstad et al., 2006). It treats IEC 61508/IEC 61511 implementation as an independent variable because the degree to which an organization applies lifecycle requirements, safety requirements specification, verification, validation, proof testing, and management of change may influence the quality of SIL-compliant SIS design and the resulting functional safety performance (Hauge et al., 2016).

A major technical issue in SIL-compliant SIS design is the quantification of reliability performance through PFD, PFH, test coverage, redundancy configuration, and degradation behavior. SISs may operate in low-demand mode, high-demand mode, or continuous-demand conditions, and each operating mode requires suitable performance measures and modeling assumptions (Lundteigen & Rausand, 2008a, 2008b). The traditional separation between low-demand and high-demand modes can be difficult to justify in some SIS contexts because formulas may fail to capture the combined effects of functional testing, spurious activations, and successful responses to demands (Innal et al., 2015). Later studies developed improved formulas for K-out-of-N architectures, partial testing, common cause failures, and Markov-based performance assessment. Proof testing is especially important because many dangerous undetected failures remain hidden until a demand or test reveals them. Partial test

distribution can affect the probability of failure on demand, and partial stroke testing of process shutdown valves depends strongly on test coverage assumptions (Chebila & Innal, 2015). This issue also extends to final elements with time-dependent failures, which is highly relevant because valves, actuators, solenoids, and field devices often dominate SIS unavailability in process plants. Operational data-driven prediction is also valuable for estimating failure rates in oil and gas SIS equipment (Wu et al., 2016). These studies support the need to measure SIS maintenance, proof testing, SIL verification, and lifecycle monitoring as key constructs in a quantitative cross-sectional study. They also support the inclusion of descriptive statistics, correlation analysis, and regression modeling because the research seeks to determine whether organizations with stronger testing, verification, and lifecycle practices report stronger functional safety performance (Jin & Rausand, 2014).

SIL-compliant design also depends on the quality of hazard identification and risk assessment. In oil and gas hazardous-area operations, hazard identification methods such as HAZOP, LOPA, fault-tree analysis, event-tree analysis, bow-tie analysis, failure mode analysis, and risk matrices provide the basis for defining initiating events, consequences, independent protection layers, required risk reduction, and SIF targets (Jigar et al., 2016). LOPA is particularly relevant because it links process hazard scenarios to the need for independent protection layers and helps determine whether a SIF is required and what SIL target should be assigned. Research on high-integrity protection systems and SIL assessment shows that methods and tools for SIL evaluation must be able to represent protective functions, dependencies, uncertainty, and reliability structure (Lundteigen & Rausand, 2009). Common cause failure modeling through Markovian approaches further shows that dependent failures can affect the reliability of redundant safety architectures. Field experience from the petroleum industry also reinforces the need for operational learning and real failure data in understanding common cause failures in safety-instrumented systems (Lundteigen et al., 2009). HAZOP-based research in oil production shows that structured hazard analysis remains a core technique for identifying deviations, causes, consequences, and safeguards in petroleum operations. These studies indicate that hazard identification is not only a preliminary engineering exercise but also a determinant of SIS design accuracy. When hazards are poorly identified, the SIF may be incorrectly specified, the SIL target may be unsuitable, the safety requirements specification may be incomplete, and the resulting design may fail to address the most critical hazardous scenarios. For this reason, this research positions hazard identification and risk assessment as an independent variable that may influence SIL-compliant SIS design quality and functional safety performance (Sklet, 2006).

The organizational dimension of SIL-compliant SIS design is also central because functional safety systems operate within human, managerial, and procedural environments. High-reliability operations require disciplined attention to weak signals, failure precursors, abnormal process behavior, documentation quality, maintenance compliance, and learning from field experience. Safety culture and safety management research has shown that formal systems, management commitment, training, communication, worker involvement, planning, and control mechanisms can be measured and linked to safety outcomes in industrial organizations (Wu et al., 2018). Within the SIS domain, human and organizational factors are important because the design basis, proof-test intervals, bypass management, alarm response, maintenance procedures, and management-of-change records are executed by people and teams. Human and organizational factors are particularly relevant during the operational phase of SISs, and human factors modeling is also important in offshore drilling operations. Spurious activation research also shows that unwanted SIS trips can create production losses, stress on equipment, and hazards during restoration, making operational discipline and correct interpretation of alarms important for both safety and production continuity (Jahanian, 2015). In hazardous-area oil and gas settings, safety culture may strengthen the relationship between SIS design and functional safety performance because technically adequate systems still depend on correct testing, timely maintenance, proper override control, accurate documentation, and disciplined operator response. This supports the inclusion of organizational safety culture as a moderating or independent variable in this quantitative study. It also supports the case-study design because the study can examine how technical SIS lifecycle practices are perceived and enacted by professionals within a specific oil and gas operational context (Innal et al., 2016).

This research is motivated by the need to evaluate SIL-compliant SIS design as a measurable, multi-variable phenomenon within oil and gas hazardous-area operations. The selected quantitative, cross-sectional, case-study–based approach is appropriate because it allows structured measurement of professional perceptions across IEC framework implementation, hazard identification, SIL verification, SIS maintenance, proof testing, safety culture, SIS design quality, and functional safety performance. The use of a five-point Likert scale enables respondents to rate the degree of implementation, effectiveness, maturity, and perceived safety performance across technically defined constructs. Descriptive statistics can identify the general maturity level of SIS lifecycle practices, correlation analysis can determine whether the constructs are significantly related, and regression modeling can test the predictive effects of IEC 61508/IEC 61511 implementation, hazard assessment, SIL verification, maintenance, proof testing, and safety culture on functional safety performance. The study is also strengthened by the inclusion of two result-oriented analytical extensions: a SIL Lifecycle Compliance Maturity Index and a Safety Instrumented Function Risk-Control Priority Matrix. The maturity index can classify lifecycle stages such as hazard assessment, safety requirements specification, SIS design, SIL verification, operation, maintenance, and documentation readiness, while the priority matrix can compare perceived importance with implementation effectiveness for areas such as emergency shutdown reliability, gas detection integration, bypass management, proof testing, and operator readiness. These elements are consistent with research showing that SIS performance is affected by lifecycle integration, architecture, testing strategy, operational data, common cause failures, final-element reliability, and organizational practices. By grounding the introduction in definitions, international process safety relevance, standard-based lifecycle logic, reliability modeling, hazard assessment, and organizational safety factors, the study establishes a focused basis for examining SIL-compliant SIS design under IEC 61508/IEC 61511 frameworks.

Background of the Study

Oil and gas hazardous-area operations are among the most safety-critical industrial environments because they involve the continuous handling, processing, storage, and transportation of flammable, toxic, explosive, and high-pressure materials. In such environments, a single process deviation may escalate into fire, explosion, toxic release, equipment damage, production shutdown, environmental contamination, or loss of life. To control these risks, oil and gas facilities rely on multiple layers of protection, including process control systems, alarms, mechanical safeguards, emergency shutdown systems, fire and gas systems, relief systems, and Safety Instrumented Systems. Among these layers, Safety Instrumented Systems play a central role because they are designed to detect hazardous process conditions and automatically bring the process to a safe state when normal control measures fail or become insufficient. The effectiveness of these systems depends on the correct identification of hazardous scenarios, accurate assignment of Safety Integrity Level targets, appropriate selection of sensors, logic solvers, and final control elements, and continuous verification that the system can deliver the required risk reduction throughout its lifecycle. SIL-compliant SIS design is therefore not limited to the installation of safety devices; it includes systematic planning, engineering design, validation, proof testing, maintenance, documentation, audit readiness, and management commitment. IEC 61508 and IEC 61511 provide structured frameworks for ensuring that functional safety is managed as a complete lifecycle process rather than a one-time design activity. In oil and gas hazardous-area operations, these frameworks are especially important because operating conditions may change over time due to equipment aging, process modification, human intervention, maintenance limitations, bypass practices, and changing production demands. A quantitative investigation of SIL-compliant SIS design is necessary because organizations need measurable evidence on how framework implementation, hazard identification, SIL verification, proof testing, maintenance, and safety culture contribute to functional safety performance. This study is therefore positioned within the broader need to strengthen safety reliability, operational discipline, and risk-reduction effectiveness in oil and gas hazardous-area facilities.

Problem Statement

Oil and gas hazardous-area operations continue to face serious functional safety challenges because safety risks are often influenced by technical, organizational, and lifecycle-related weaknesses. Although Safety Instrumented Systems are designed to reduce the likelihood and consequences of

hazardous events, their effectiveness may be weakened when SIL requirements are poorly interpreted, hazard scenarios are incompletely identified, safety requirements are inadequately documented, proof testing is irregular, maintenance is delayed, bypasses are poorly controlled, or verification and validation activities are treated as procedural formalities rather than essential safety controls. In many facilities, the existence of a SIS does not automatically guarantee functional safety performance, because the actual level of protection depends on whether the system has been designed, tested, maintained, and managed according to the required safety lifecycle. A major problem is that organizations may focus heavily on equipment installation while giving less attention to lifecycle maturity, documentation quality, operational readiness, field-device reliability, and continuous compliance with IEC 61508 and IEC 61511 principles. Another important concern is that oil and gas hazardous-area operations involve complex interactions among process technology, human decision-making, maintenance behavior, safety culture, and compliance systems. These interactions may create gaps between designed safety integrity and achieved safety integrity in real operating conditions. Existing technical practices often measure SIL performance through engineering calculations, but limited attention is given to how professionals perceive the combined influence of framework implementation, hazard identification, SIL verification, maintenance practices, proof testing, and safety culture on functional safety outcomes. This creates a need for a quantitative, cross-sectional, case-study–based assessment that can convert these technical and organizational dimensions into measurable variables. The problem addressed by this study is therefore the lack of an integrated empirical understanding of how SIL-compliant SIS design practices influence functional safety performance in oil and gas hazardous-area operations. Without this understanding, organizations may struggle to identify which lifecycle areas are mature, which risk-control activities require improvement, and which factors most strongly predict reliable functional safety performance.

Objectives of The Study

The main objective of this study is to examine the influence of SIL-compliant Safety Instrumented System design on functional safety performance in oil and gas hazardous-area operations using IEC 61508 and IEC 61511 frameworks. This objective is based on the need to understand how safety lifecycle practices contribute to reliable risk reduction in environments where process deviations may produce severe consequences. The study specifically aims to assess whether the implementation of IEC 61508 and IEC 61511 improves SIS design quality by promoting structured hazard analysis, safety requirements specification, SIL allocation, engineering verification, validation, proof testing, maintenance planning, and documentation control. Another objective is to evaluate the relationship between hazard identification and risk assessment practices and functional safety performance, because the accuracy of SIS design depends on how effectively hazardous events, initiating causes, consequences, independent protection layers, and required risk reduction are identified. The study also seeks to determine whether SIL verification and validation practices significantly influence functional safety performance by ensuring that designed safety functions are capable of achieving their intended risk-reduction targets. In addition, the research aims to examine the role of SIS maintenance, proof testing, and lifecycle management in sustaining operational safety reliability after system installation and commissioning. Since functional safety is not only a technical issue but also an organizational responsibility, the study further aims to assess the contribution of safety culture to SIL-compliant SIS implementation. To achieve these objectives, the research will use a structured five-point Likert-scale questionnaire to collect quantitative data from professionals involved in oil and gas safety, instrumentation, operations, maintenance, process control, and compliance. Descriptive statistics will be used to summarize the condition of key variables, correlation analysis will examine the relationships among the variables, and regression modeling will test the predictive influence of selected factors on functional safety performance. The study will also include a SIL Lifecycle Compliance Maturity Index and a Safety Instrumented Function Risk-Control Priority Matrix to provide a more practical and study-specific interpretation of the results.

Research Hypotheses

The hypotheses of this study are developed to examine the statistical relationships among IEC framework implementation, hazard identification, SIL verification, SIS maintenance, safety culture, SIL-compliant SIS design quality, and functional safety performance. Since the study follows a

quantitative, cross-sectional, case-study–based design, the hypotheses provide a structured basis for testing whether the proposed independent variables significantly predict or relate to functional safety outcomes in oil and gas hazardous-area operations. The first hypothesis proposes that IEC 61508 and IEC 61511 framework implementation has a significant positive effect on SIL-compliant SIS design quality. This means that organizations with stronger application of functional safety lifecycle requirements are expected to demonstrate better SIS design practices. The second hypothesis proposes that hazard identification and risk assessment practices have a significant positive relationship with functional safety performance. This reflects the assumption that accurate identification of hazardous scenarios supports better risk-control decisions and more reliable safety functions. The third hypothesis states that SIL verification and validation practices significantly influence functional safety performance. This hypothesis is based on the expectation that safety functions that are properly verified, validated, and documented are more likely to achieve the intended level of risk reduction. The fourth hypothesis proposes that SIS maintenance and proof testing practices have a significant positive effect on operational safety reliability. This recognizes the importance of detecting hidden failures, controlling degradation, and maintaining system readiness during the operational phase. The fifth hypothesis states that SIL-compliant SIS design quality has a significant positive effect on functional safety performance. This hypothesis directly connects design quality with safety outcomes. The sixth hypothesis proposes that organizational safety culture significantly strengthens the relationship between SIL-compliant SIS design and functional safety performance. This means that the impact of technically sound SIS design may become stronger when organizations demonstrate management commitment, training discipline, reporting culture, maintenance accountability, and compliance awareness. Together, these hypotheses allow the study to test both technical and organizational dimensions of functional safety performance.

Significance of the Research

i. This research is significant for oil and gas operators because it provides a structured quantitative assessment of how SIL-compliant SIS design contributes to functional safety performance in hazardous-area operations. The findings can help organizations identify whether their safety lifecycle practices are strong enough to support reliable risk reduction.

ii. This research is significant for safety engineers and instrumentation engineers because it connects SIS design quality with measurable variables such as IEC framework implementation, hazard identification, SIL verification, proof testing, maintenance, and documentation. This can support better engineering decisions during SIS design, modification, and operational review.

iii. This research is significant for HSE professionals and process safety managers because it highlights how functional safety performance depends on both technical system reliability and organizational safety practices. The study can help safety teams identify gaps in safety culture, compliance behavior, training, bypass control, and audit readiness.

iv. This research is significant for maintenance and operations teams because it emphasizes the importance of proof testing, preventive maintenance, lifecycle monitoring, and response readiness. The findings may help operational teams understand how daily practices influence the long-term reliability of Safety Instrumented Systems.

v. This research is significant for compliance auditors and regulatory stakeholders because it provides a measurable framework for evaluating SIL lifecycle compliance. The SIL Lifecycle Compliance Maturity Index can help show which stages of the SIS lifecycle are well implemented and which stages require corrective action.

vi. This research is significant for academic literature because it integrates technical and organizational dimensions of SIS performance into one quantitative model. Many functional safety studies focus mainly on reliability formulas or engineering design, while this study also considers safety culture, professional perception, maturity assessment, and risk-control prioritization.

vii. This research is significant for oil and gas hazardous-area risk management because it introduces the Safety Instrumented Function Risk-Control Priority Matrix. This tool can help organizations compare the importance and implementation effectiveness of key SIS functions, allowing them to prioritize improvement areas such as emergency shutdown reliability, gas detection integration, bypass management, SIL documentation, and proof testing compliance.

viii. This research is significant for decision-makers because it can support evidence-based investment in safety systems, training, maintenance planning, and compliance improvement. By identifying the strongest predictors of functional safety performance, the study can help organizations allocate resources to the areas that most directly improve safety reliability.

LITERATURE REVIEW

The literature on SIL-compliant Safety Instrumented System design in oil and gas hazardous-area operations is grounded in the broader field of functional safety, where technical reliability, process hazard analysis, lifecycle management, and organizational safety practices interact to reduce the likelihood and consequences of hazardous events. Safety Instrumented Systems are widely recognized as critical protective layers because they perform automatic safety actions when process conditions move beyond acceptable operating limits. In hazardous-area oil and gas settings, these systems are especially important because abnormal pressure, temperature, flow, level, gas concentration, ignition potential, or equipment malfunction may create conditions that require rapid and dependable intervention. The literature shows that SIS performance depends not only on hardware selection but also on the full safety lifecycle, including hazard identification, risk assessment, Safety Requirements Specification, SIL target allocation, architecture design, verification, validation, proof testing, maintenance, bypass management, modification control, and documentation. IEC 61508 and IEC 61511 provide the main framework for organizing these lifecycle activities and for ensuring that safety functions are designed and maintained according to required risk-reduction levels. However, the literature also shows that the practical achievement of SIL compliance is shaped by several challenges, including hidden dangerous failures, common cause failures, diagnostic limitations, incomplete proof testing, final-element degradation, human error, weak safety culture, and insufficient operational feedback. As a result, functional safety research increasingly recognizes that SIS reliability must be studied through both engineering and management perspectives. For this research, the literature review will therefore examine the technical foundation of SIS design, the role of IEC 61508 and IEC 61511, SIL determination and verification, hazardous-area risk assessment, High Reliability Organization Theory, and the conceptual relationship among framework implementation, hazard identification, maintenance practices, safety culture, SIS design quality, and functional safety performance. This literature foundation will support the development of the research model, questionnaire constructs, hypotheses, and statistical analysis strategy.

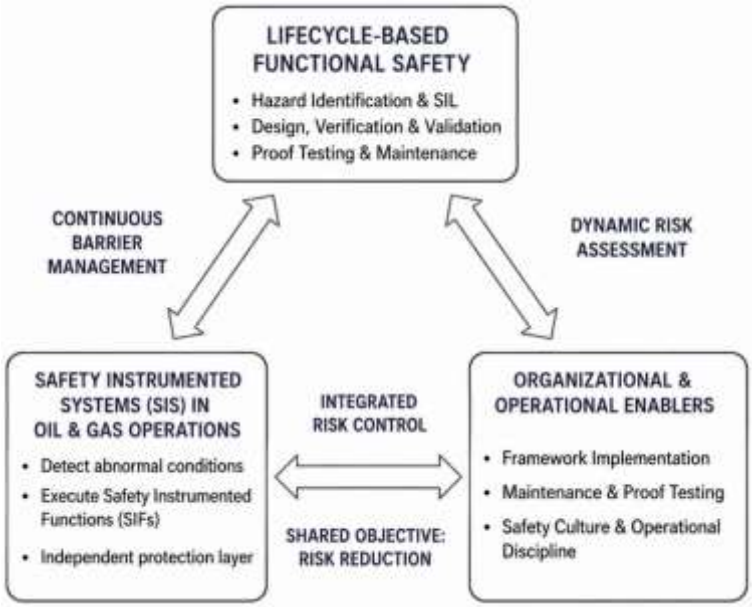
Safety Instrumented Systems in Oil and Gas Operations

Functional safety and Safety Instrumented Systems occupy a central position in oil and gas operations because hazardous-area facilities require engineered protection layers that can detect abnormal process conditions and move equipment into a safe state before an initiating event develops into a major accident. In refineries, gas processing plants, offshore platforms, terminals, and pipeline stations, hazards are created by flammable hydrocarbons, toxic gases, high-pressure flow, rotating machinery, confined process units, and ignition sources. A Safety Instrumented System is therefore understood as more than a control device; it is a formally designed protection layer that performs specific Safety Instrumented Functions when process variables exceed safe limits. The literature on process safety emphasizes that major accident prevention depends on the continuous performance of preventive and mitigative barriers, including technical systems, operational procedures, inspection routines, and emergency actions. Within this barrier-based view, SISs are important because they can interrupt hazardous scenarios automatically and independently from the basic process control system. Safety barrier management research also shows that barrier performance must be assessed in relation to degradation, operational context, and accident scenario development rather than treated as a static design assumption (Davatgar et al., 2021; Abdur & Iftekhar, 2021). This is highly relevant to oil and gas hazardous areas because safety functions may lose effectiveness when sensors drift, valves degrade, procedures are bypassed, maintenance intervals are extended, or field conditions differ from design assumptions. Functional safety in this context requires a lifecycle perspective in which hazard identification, SIL assignment, architecture selection, verification, validation, proof testing, and maintenance are connected to the same risk-reduction objective. For this reason, SIS design quality must be evaluated as a combination of technical reliability, lifecycle documentation, operational discipline, organizational support, and measurable evidence of continuing barrier readiness under

realistic plant operating conditions. This evaluation supports stronger alignment between design intent and actual hazardous-area protection.

The role of SISs in oil and gas operations is also linked to the broader development of dynamic and plant-specific risk assessment approaches. Traditional risk assessments often describe a process facility using fixed assumptions about equipment conditions, failure probabilities, barrier availability, and operator response. However, hazardous-area operations are not static because degradation, inspection findings, alarm histories, maintenance delays, process upsets, and environmental conditions may change the actual level of risk during operation. Plant-specific dynamic failure assessment has shown that risk models become more useful when they incorporate operational evidence and update failure expectations according to process history and observed performance (Golam & Amir, 2022; Meel & Seider, 2006). Similarly, bow-tie models have been improved through Bayesian network mapping because conventional fault-tree and event-tree structures often struggle to represent conditional dependencies, accident precursors, and changing barrier states (Binayan & Shakhawat, 2022; Khakzad et al., 2013). These developments support the argument that SIS performance should not be examined only through original design calculations. In a real oil and gas environment, the achieved performance of a Safety Instrumented Function depends on how the organization monitors equipment condition, records proof-test results, handles bypasses, manages change, and responds to early warning signals. Dynamic risk management studies further emphasize that hazard identification and risk assessment should learn from new information, emerging scenarios, and operating experience rather than remain limited to periodic documentation exercises (Hasan & Uddin, 2022; Paltrinieri et al., 2015). This perspective aligns closely with SIL-compliant SIS design because the required risk reduction must remain valid across the operational life of the system. Therefore, a quantitative study of SIS design in hazardous-area oil and gas operations should include variables that reflect both technical and managerial controls, especially framework implementation, hazard assessment, verification, maintenance, proof testing, safety culture, and the perceived effectiveness of functional safety performance outcomes. Such measurement is important for comparing lifecycle practices across professional groups.

Figure 2: Integrated Functional Safety Framework and Operational Controls



The literature further indicates that functional safety and SIS performance are inseparable from safety lifecycle management, because a technically sound design may still perform poorly if it is not supported by suitable operating practices and performance monitoring. Dynamic risk analysis reviews have shown that conventional risk assessment methods may be limited when they do not adequately account

for time-dependent conditions, barrier degradation, organizational factors, and new operational information (Hossain & Uddin, 2022; Villa et al., 2016). This limitation is important for oil and gas hazardous-area operations because SIS reliability depends on both equipment design and sustained lifecycle execution. For example, an emergency shutdown function may be assigned an appropriate SIL during design, yet its real performance may be affected by inadequate proof-test coverage, delayed maintenance, poor diagnostic follow-up, undocumented overrides, or insufficient operator readiness. Therefore, the literature supports the need to evaluate SISs as part of an integrated functional safety system rather than as isolated devices. Oil and gas safety barrier research also highlights that risk control requires the identification of critical barriers, assessment of their condition, and prioritization of improvement actions according to their contribution to accident prevention (Davatgar et al., 2021; Sany & Siful, 2022). In this study, that logic supports the use of a SIL Lifecycle Compliance Maturity Index and a Safety Instrumented Function Risk-Control Priority Matrix. These tools can help translate survey responses into practical indicators of lifecycle strength, implementation gaps, and risk-control priorities. The literature therefore provides a clear foundation for examining functional safety through a quantitative, cross-sectional, case-study approach. By measuring professional perceptions of IEC framework implementation, hazard identification, SIL verification, maintenance, proof testing, safety culture, SIS design quality, and functional safety performance, this research can connect established process safety concepts with measurable evidence from oil and gas hazardous-area operations and support a structured interpretation of safety-system reliability within the selected case context.

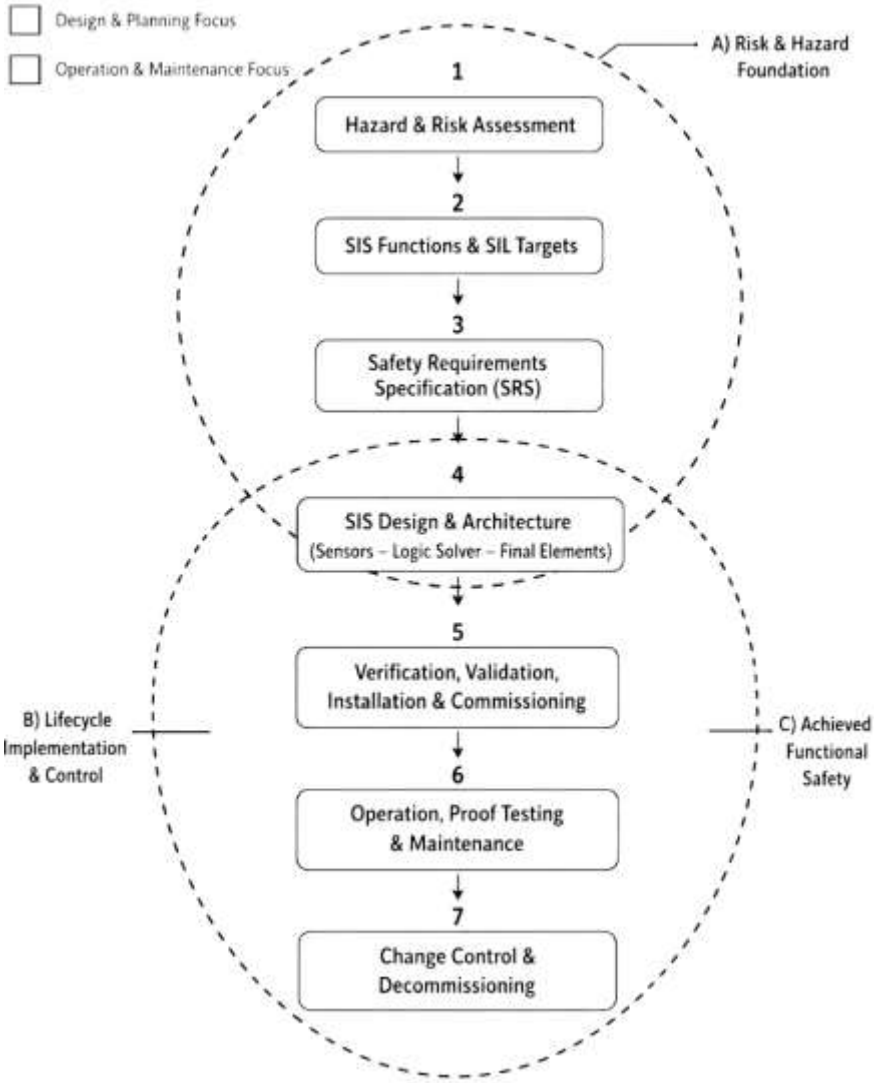
IEC 61508 and IEC 61511 Frameworks for SIS Lifecycle Management

IEC 61508 and IEC 61511 provide the main lifecycle-based foundation for designing, implementing, operating, and maintaining Safety Instrumented Systems in high-risk process environments. IEC 61508 functions as a generic functional safety standard for electrical, electronic, and programmable electronic safety-related systems, while IEC 61511 adapts functional safety requirements to the process industry where SISs are applied to prevent or mitigate hazardous events. In oil and gas hazardous-area operations, these standards are important because they guide the movement from broad hazard recognition to specific Safety Instrumented Functions, Safety Integrity Level targets, and Safety Requirements Specifications. The lifecycle logic begins with hazard and risk assessment and continues through allocation of safety functions, system design, engineering verification, validation, installation, commissioning, operation, maintenance, modification control, and decommissioning. A lifecycle approach is necessary because an SIS may satisfy design requirements during engineering but fail to deliver its required risk reduction if later lifecycle stages are weak. For example, poor proof testing, undocumented changes, unsuitable bypass management, and weak maintenance discipline can reduce the achieved integrity of a safety function. The design and evaluation of SISs therefore require practical methods that help engineers interpret SIL targets, compare risk reduction needs, and convert functional safety requirements into usable engineering decisions. Simplified and enhanced approaches for SIS design have been proposed to make compliance more practical while preserving the intended level of functional safety, especially in industrial settings where complex assessment methods can be difficult to apply consistently (Gabriel, 2017; Binte & Iftekhar, 2022). This supports the position that IEC 61508 and IEC 61511 should not be treated only as regulatory documents, but as structured lifecycle frameworks for linking risk analysis, design decisions, reliability performance, and operational controls.

Within SIS lifecycle management, the relationship between safety requirements specification and system architecture is especially important. A Safety Requirements Specification translates hazard analysis outcomes into clear functional and integrity requirements, including what the safety function must detect, what action it must take, how quickly it must respond, what safe state must be achieved, and what SIL target must be satisfied. In oil and gas upstream operations, SIS design must consider operating conditions such as well pressure, separator performance, gas release potential, emergency shutdown logic, and process isolation requirements. Mathematical and design-based approaches for upstream petroleum processes have emphasized that SIS design must be technically justified, economically reasonable, and linked to specific hazardous scenarios rather than selected as a generic protection layer (Redutskiy, 2017; Taufiqur & Khalid, 2022). This is important because IEC 61511 expects safety functions to be connected to process-specific risk reduction requirements. The lifecycle

framework also requires careful coordination between sensors, logic solvers, and final elements, because each component contributes to the overall probability of failure and the ability of the SIS to achieve or maintain a safe state. Research on intelligent sensors demonstrates that modern field devices create both opportunities and challenges for SIS lifecycle management, since advanced diagnostics and embedded intelligence can improve dependability assessment while also requiring careful modeling and validation within IEC 61508 and IEC 61511 expectations (Iftekhar & Binayan, 2023; Mkhida et al., 2014). This means that SIS lifecycle compliance is not limited to selecting certified devices. It requires evidence that the complete safety function, including field instrumentation, logic processing, final actuation, testing strategy, and maintenance planning, can meet the required SIL under real operating conditions.

Figure 3: Safety Instrumented System Lifecycle from Hazard Assessment to Decommissioning



IEC 61508 and IEC 61511 also influence lifecycle management by requiring formal control of design, implementation, operation, and maintenance activities across the entire useful life of the SIS. This requirement becomes more complex when process conditions are variable, products change, or operating modes shift across different production states. Multi-product batch process research shows that applying IEC 61511 requirements can be challenging where a single SIS must support multiple functions, changing setpoints, state-dependent logic, and close interaction with the basic process control system (Hasan & Chapal, 2023; Steinhauser, 2019). Although oil and gas hazardous-area operations may not always follow batch processing, they often involve changing operating modes such

as startup, shutdown, maintenance, pigging, pressure testing, emergency isolation, and abnormal recovery. These conditions make lifecycle discipline essential because the SIS must remain valid across operational states. Control system development research also shows that SIS design requires formal procedures to ensure that safety requirements are correctly interpreted and converted into reliable control logic, especially when programmable systems are used for accident prevention and mitigation (Aminul & Sheak, 2023; Junior et al., 2011). For the present study, IEC 61508 and IEC 61511 are therefore treated as more than background standards; they form the technical framework for measuring the quality of SIS lifecycle implementation. Their requirements justify the study variables related to framework implementation, hazard identification, SIL verification, validation, proof testing, maintenance, documentation readiness, and functional safety performance. This literature foundation supports the need for a quantitative assessment that can determine whether stronger lifecycle implementation is associated with higher SIL-compliant SIS design quality and improved functional safety outcomes in oil and gas hazardous-area operations.

Safety Integrity Level Determination, Verification, and Validation

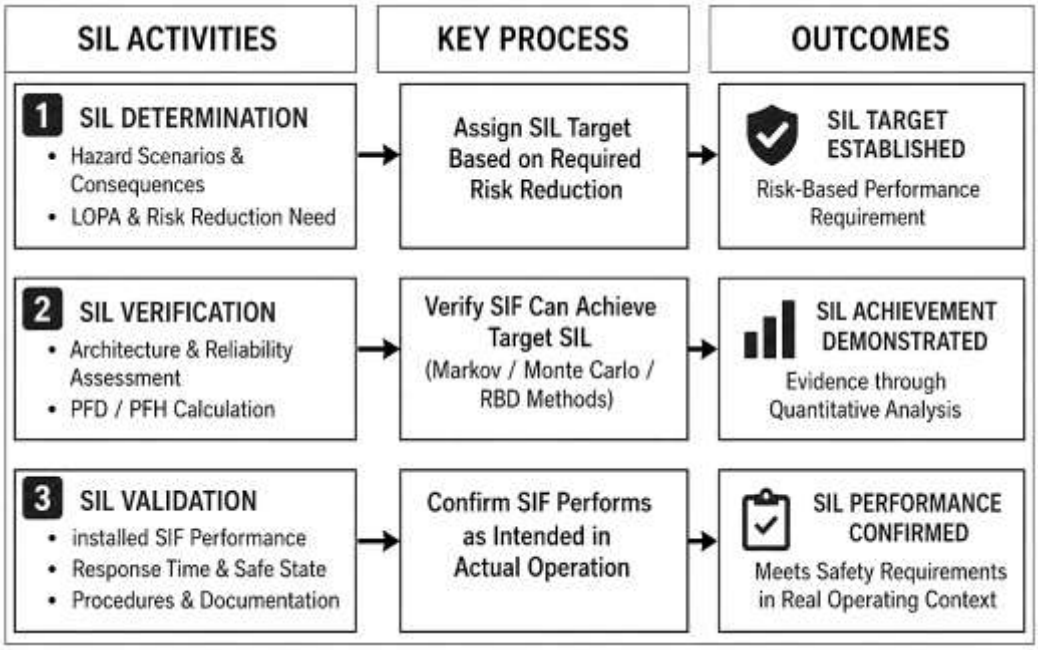
Safety Integrity Level determination is one of the most important technical activities in Safety Instrumented System lifecycle management because it establishes the required level of risk reduction for each Safety Instrumented Function before detailed design and implementation. In oil and gas hazardous-area operations, SIL determination begins with the identification of hazardous scenarios, initiating events, consequences, existing independent protection layers, and the remaining risk that must be reduced by a Safety Instrumented Function. This process links process hazard analysis with engineering design because the required SIL must reflect the severity and likelihood of the hazardous event as well as the adequacy of other protective layers. A SIL target is therefore not an arbitrary design label; it is a risk-based performance requirement that connects the tolerable risk criterion to the required reliability of the SIF. The relationship among hazards, consequences, Layer of Protection Analysis, probability of failure on demand, and risk reduction factor is especially important because SIL values are directly associated with the amount of risk reduction expected from the safety function (Blanco, 2014; Risha & Khalid, 2023). For oil and gas facilities, this means that the SIL determination process must be carefully aligned with credible hazardous-area scenarios such as gas release, overpressure, hydrocarbon ignition, vessel rupture, compressor trip, emergency isolation failure, or fire and gas detection failure. When the SIL target is underestimated, the installed SIS may not provide enough risk reduction. When the SIL target is overestimated, the system may become unnecessarily complex, expensive, and difficult to maintain. The quality of SIL determination therefore depends on scenario selection, independence of protection layers, accuracy of failure data, judgment of consequence severity, and consistency of the risk acceptance criteria. For this research, SIL determination is relevant because it explains why hazard identification and risk assessment are treated as key predictors of SIL-compliant SIS design quality and functional safety performance.

SIL verification is the process of demonstrating that the proposed or existing SIS architecture can achieve the target SIL assigned during hazard and risk assessment. Verification normally involves quantitative assessment of the sensors, logic solver, final elements, voting architecture, diagnostic coverage, common cause failure allowance, repair time, proof-test interval, and dangerous failure rates. In practice, SIL verification often focuses on calculating average probability of failure on demand for low-demand systems or probability of dangerous failure per hour for high-demand or continuous mode systems. Verification is technically demanding because the performance of a SIF depends not only on individual component reliability but also on architecture, testing strategy, hidden failures, partial testing, common cause failures, and assumptions used in the calculation. Markov-based methods have been used to simplify SIL verification while still preserving the analytical power needed to examine different architectures and common cause failure structures (Sany & Uddin, 2023; Shu & Zhao, 2014). Monte Carlo simulation and Reliability Block Diagram methods have also been applied to compare and verify SIL results, showing that different modeling techniques can be used to evaluate the same safety function and support decision-making when analytical equations become difficult to apply (Kaczor et al., 2016). These methods are highly relevant to oil and gas hazardous-area operations because emergency shutdown functions, gas detection functions, high-pressure trip systems, and isolation functions often involve multiple channels, redundancy, diagnostics, and proof-test

assumptions. A verified SIL result provides evidence that the designed SIS can meet the required risk reduction under stated conditions. However, the value of verification depends on the quality of the input assumptions, including failure rate data, proof-test effectiveness, maintenance intervals, device independence, and operational environment. For this study, SIL verification is treated as a measurable construct because stronger verification practices are expected to improve confidence in SIS design quality and functional safety performance.

SIL validation complements SIL determination and verification by confirming that the installed and commissioned SIS performs the intended safety function in the actual operating context. Validation is broader than calculation because it examines whether the complete SIF satisfies the safety requirements specification, responds within the required time, reaches the defined safe state, operates correctly with the process, and is supported by appropriate documentation, testing, and operational procedures. This stage is important in oil and gas hazardous-area facilities because a mathematically verified design may still fail to perform if the wrong process variable is measured, the final element is unsuitable, the logic is incorrectly configured, the bypass procedure is weak, or the operator response requirements are unclear. The use of database-supported SIL assignment has shown that decision support and historical failure information can assist the design stage by improving consistency in SIL allocation and helping engineers select suitable safety architectures (Wang et al., 2016).

Figure 4: Relationship Between SIL Assessment Activities and Functional Safety Outcomes

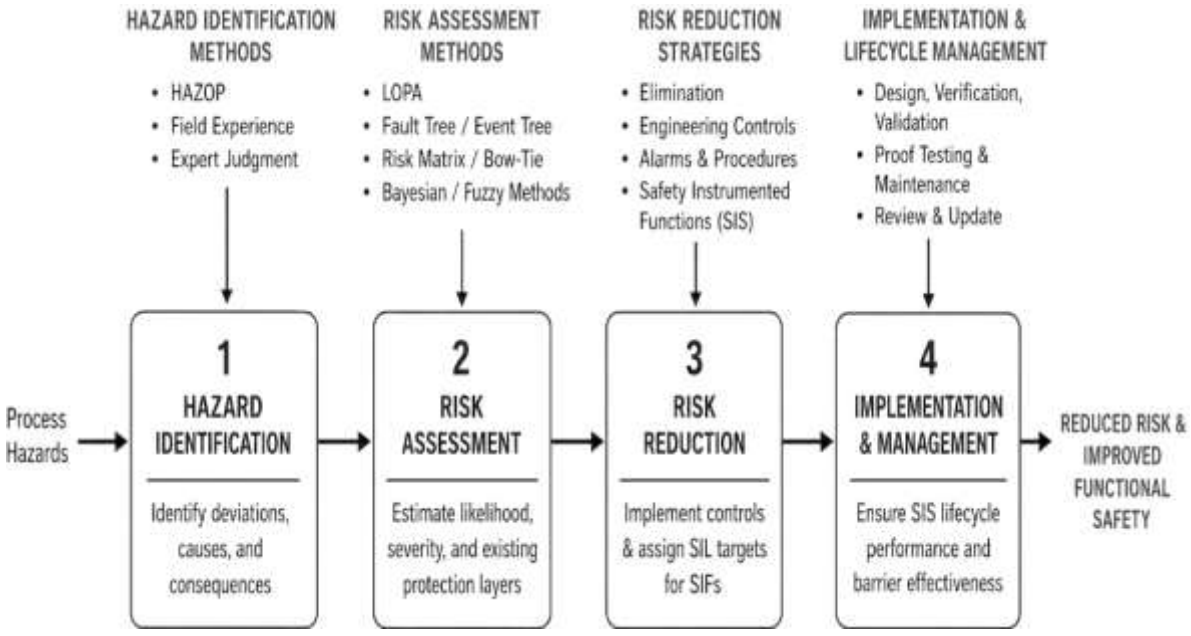


Case-based SIL analysis in shale gas station operations also demonstrates how LOPA, independent protection layer identification, probability of failure on demand, and SIF-by-SIF assessment can be used to confirm whether an existing SIS reaches the required SIL for safe and stable operation (Yang et al., 2021). These studies show that determination, verification, and validation should be treated as connected lifecycle activities rather than isolated tasks. In this research, the connection among these activities supports the development of survey items that assess whether organizations define SIL targets systematically, calculate SIL achievement accurately, validate installed functions properly, maintain proof-test records, and review SIS performance throughout operation. The literature therefore supports the inclusion of SIL verification and validation as independent variables in the study model. Stronger SIL verification and validation practices are expected to improve risk-reduction confidence, reduce the gap between designed and achieved safety integrity, and strengthen the overall functional safety performance of oil and gas hazardous-area operations.

Hazard Identification and Risk Reduction in Hazardous Areas

Hazard identification is a central activity in oil and gas hazardous-area safety because it provides the first structured understanding of how unwanted events may occur, how they may escalate, and which safety controls are needed to prevent or mitigate consequences. In oil and gas operations, hazards may arise from hydrocarbon leakage, overpressure, equipment malfunction, toxic gas release, ignition sources, confined spaces, corrosion, human error, control failure, and emergency shutdown failure. These hazards are complex because they often involve interactions among process conditions, mechanical equipment, electrical systems, human behavior, maintenance quality, and environmental exposure. For this reason, hazard identification must move beyond general safety observation and apply systematic techniques that can reveal deviations from intended design and operating conditions. HAZOP is one of the most widely used methods because it examines process nodes, guidewords, deviations, causes, consequences, safeguards, and recommendations in a structured manner. The importance of HAZOP is especially clear in hazardous-area operations where small deviations in pressure, flow, temperature, level, or composition may create conditions for fire, explosion, toxic exposure, or process instability. The literature describes HAZOP as a globally used process hazard analysis method that supports both hazard recognition and operability improvement by examining deviations from design intent (Dunjó et al., 2010). This is relevant to SIL-compliant SIS design because the output of hazard identification often becomes the foundation for selecting Safety Instrumented Functions, defining safety requirements, identifying independent protection layers, and determining whether additional risk reduction is required. If hazard identification is weak, the SIS may be designed around incomplete or incorrect scenarios. Therefore, in this study, hazard identification is treated as a key technical variable that may influence SIS design quality and functional safety performance in oil and gas hazardous-area operations.

Figure 5: Risk-Based Framework for SIL-Compliant Safety Management in Hazardous Areas



Risk assessment expands hazard identification by estimating the likelihood, severity, and acceptability of hazardous scenarios and by determining whether existing safeguards are sufficient. In oil and gas hazardous-area operations, risk assessment methods may include qualitative, semi-quantitative, and quantitative techniques such as risk matrices, HAZOP, LOPA, fault tree analysis, event tree analysis, bow-tie analysis, Bayesian networks, fuzzy methods, and quantitative risk assessment. Each method has different strengths. Qualitative methods are useful for early screening and expert discussion, while semi-quantitative and quantitative methods provide stronger numerical support for deciding whether additional protection is required. A broad review of risk analysis and assessment methodologies shows that industrial safety assessment requires careful selection of methods according to the type of hazard,

available data, required accuracy, system complexity, and decision-making purpose (Marhavilas et al., 2011). For SIL-compliant SIS design, this methodological selection is important because risk assessment is directly linked to SIL determination. A facility cannot assign a defensible SIL target unless it first understands the hazardous event, initiating frequency, consequence severity, existing safeguards, and remaining tolerable risk gap. In practice, LOPA is often used after HAZOP to determine whether an independent protection layer is sufficient or whether a Safety Instrumented Function must be designed. Fault tree and event tree methods may then support deeper analysis of causes and consequences, while bow-tie models help visualize the relationship between threats, preventive barriers, top events, mitigative barriers, and outcomes. Oil and gas hazardous areas require this layered thinking because risk reduction is rarely achieved by one system alone. The SIS must operate alongside alarms, relief devices, mechanical protections, operator actions, procedures, fire and gas systems, and emergency response plans. Therefore, risk assessment provides the logical bridge between hazard identification and risk reduction, making it essential to the current study's examination of SIL-compliant SIS design. Risk reduction in hazardous-area operations depends on the ability to convert hazard and risk knowledge into effective, auditable, and maintainable control measures. In oil and gas facilities, risk reduction may involve eliminating hazards, reducing exposure, improving process design, adding alarms, strengthening mechanical barriers, improving operating procedures, or implementing Safety Instrumented Functions with appropriate SIL targets. Modern risk assessment literature increasingly recognizes that hazardous-area risks are uncertain, dynamic, and dependent on changing operating conditions. For example, Bayesian network approaches have been applied to managed pressure drilling to analyze operational safety challenges and update risk understanding where dependencies and changing conditions make conventional static models less effective (Abimbola et al., 2015). Fuzzy Bayesian belief network models have also been applied to oil and gas pipeline safety assessment because pipeline failures may involve uncertain data, dependent causes, expert judgment, and multiple interacting factors such as construction defects, mechanical damage, overload, installation quality, and worker performance (Kabir et al., 2016). Uncertainty is also important in chemical and oil and gas process risk analysis because failure probabilities may be imprecise, expert judgments may vary, and accident scenarios may involve incomplete historical evidence; fuzzy fault tree approaches can help address such uncertainty when analyzing severe process hazards (Yazdi & Zarei, 2018). These methods show that risk reduction cannot depend only on fixed assumptions made during the design stage. The actual effectiveness of SIS-related risk reduction depends on whether organizations continuously review hazards, validate protective layers, update assumptions, maintain safety functions, and control degradation during operation. For this research, hazard identification and risk assessment are therefore positioned as key predictors of SIL-compliant SIS design quality and functional safety performance. Strong hazard identification can improve scenario accuracy, strong risk assessment can improve SIL selection, and strong risk reduction practices can ensure that safety functions remain aligned with the hazardous-area risk profile.

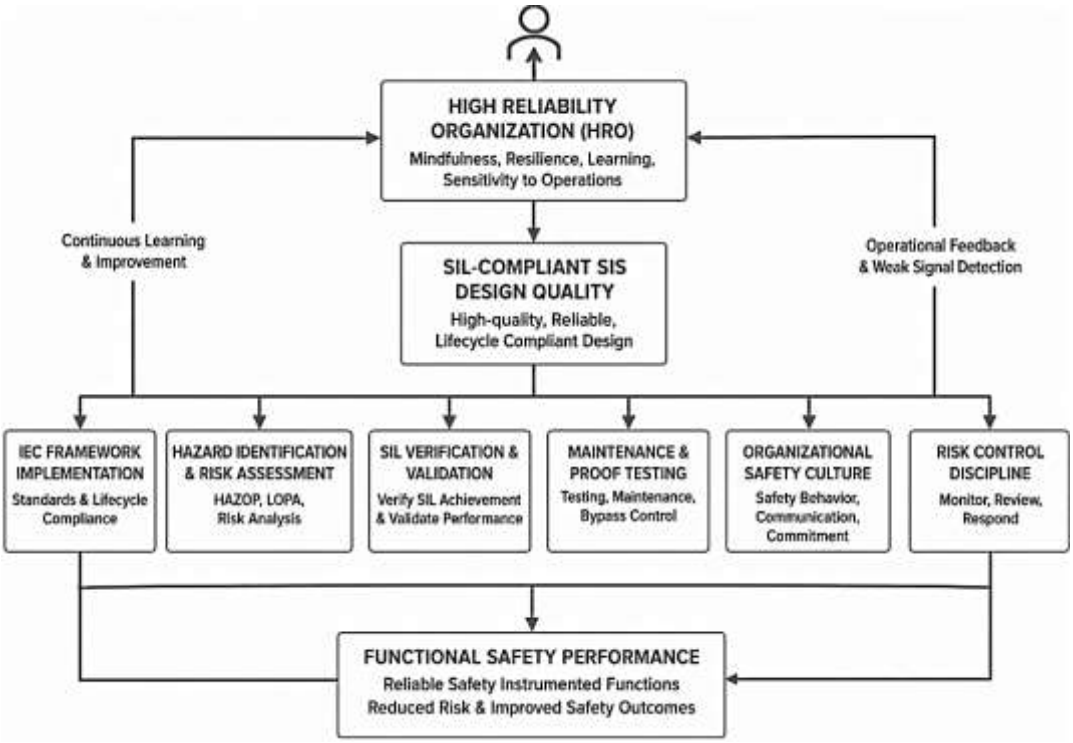
Theoretical Framework: High Reliability Organization Theory

This study is guided by High Reliability Organization Theory because oil and gas hazardous-area operations represent complex, high-risk environments where technical failure, human error, weak maintenance discipline, or incomplete safety documentation can create severe consequences for workers, assets, communities, and the environment. High Reliability Organization Theory explains how organizations operating in dangerous and technically complex settings maintain reliable performance through continuous risk awareness, disciplined safety behavior, learning from small failures, operational sensitivity, resilience, and respect for expertise. The theory is highly suitable for this research because SIL-compliant Safety Instrumented System design is not only an engineering activity; it is also an organizational reliability process that depends on how people, procedures, technologies, and management systems interact across the safety lifecycle. A Safety Instrumented Function may be technically well designed, but its real performance can be weakened if proof testing is delayed, bypasses are poorly controlled, operators ignore abnormal signals, maintenance records are incomplete, or management fails to support functional safety requirements. High Reliability Organization Theory therefore provides a strong explanation for why functional safety performance depends on both technical compliance and organizational behavior. In this study, the theory supports

the inclusion of organizational safety culture as a major explanatory variable, because high-reliability performance requires workers and managers to remain alert to weak signals, question unsafe assumptions, communicate errors, and respond quickly to abnormal operating conditions. Safety-organizing research shows that reliability in hazardous systems is strengthened when teams actively discuss mistakes, coordinate responses, identify process weaknesses, and treat small failures as warning signs rather than isolated incidents (Vogus & Sutcliffe, 2007). The theory also explains why organizational mindfulness should be treated as an active process rather than a general safety slogan, because reliability depends on repeated attention to operational details, unexpected events, and potential system degradation (Vogus & Sutcliffe, 2012).

High Reliability Organization Theory also supports the lifecycle focus of this study because SIS reliability must be maintained from hazard identification through SIL determination, Safety Requirements Specification, system design, verification, validation, operation, maintenance, proof testing, modification control, and audit readiness. In oil and gas hazardous-area operations, safety conditions may change because of equipment aging, production pressure, changing process states, deferred maintenance, environmental exposure, component degradation, and human decision-making. A high-reliability perspective suggests that organizations must continuously anticipate, monitor, respond, and learn in order to maintain safety performance under these changing conditions. Resilience engineering literature supports this view by showing that high-risk organizations require the ability to detect change, respond to disturbance, and learn from operational experience in order to sustain safe performance (Ranasinghe et al., 2020).

Figure 6: Socio-Technical Framework for Functional Safety Performance in Oil and Gas Hazardous-Area Operations



This is directly related to the proposed SIL Lifecycle Compliance Maturity Index because the maturity index will evaluate whether the organization demonstrates reliable practices across different SIS lifecycle stages rather than only during the design stage. High Reliability Organization Theory has also been applied in oil and gas contexts to examine how reliability tools, learning systems, and organizational routines can be used to manage chronic failures and improve operational safety in high-risk industrial environments (Rivera et al., 2021). In addition, safety culture research within high-reliability settings shows that technological, organizational, and human factors must operate together

when organizations attempt to sustain safety in complex socio-technical systems (Jabłoński & Jabłoński, 2021). Based on this theoretical foundation, the study assumes that functional safety performance is produced through the combined influence of technical compliance, risk-control discipline, and organizational reliability behavior. The general theoretical relationship can be shown as:

Functional Safety Performance = Technical Compliance + Risk Control + Organizational Reliability

A more study-specific theoretical form can be written as:

$$FSP = f(IFI, HIRA, SVV, SMPT, OSC, SISDQ)$$

Where:

FSP = Functional Safety Performance
IFI = IEC 61508/IEC 61511 Framework Implementation
$HIRA$ = Hazard Identification and Risk Assessment
SVV = SIL Verification and Validation
$SMPT$ = SIS Maintenance and Proof Testing
OSC = Organizational Safety Culture
$SISDQ$ = SIL-Compliant SIS Design Quality

For statistical testing in this quantitative study, the theoretical model can be translated into the following regression equation:

$$FSP = \beta_0 + \beta_1 IFI + \beta_2 HIRA + \beta_3 SVV + \beta_4 SMPT + \beta_5 OSC + \beta_6 SISDQ + \varepsilon$$

Where:

β_0 = Constant
β_1–β_6 = Regression Coefficients
ε = Error Term

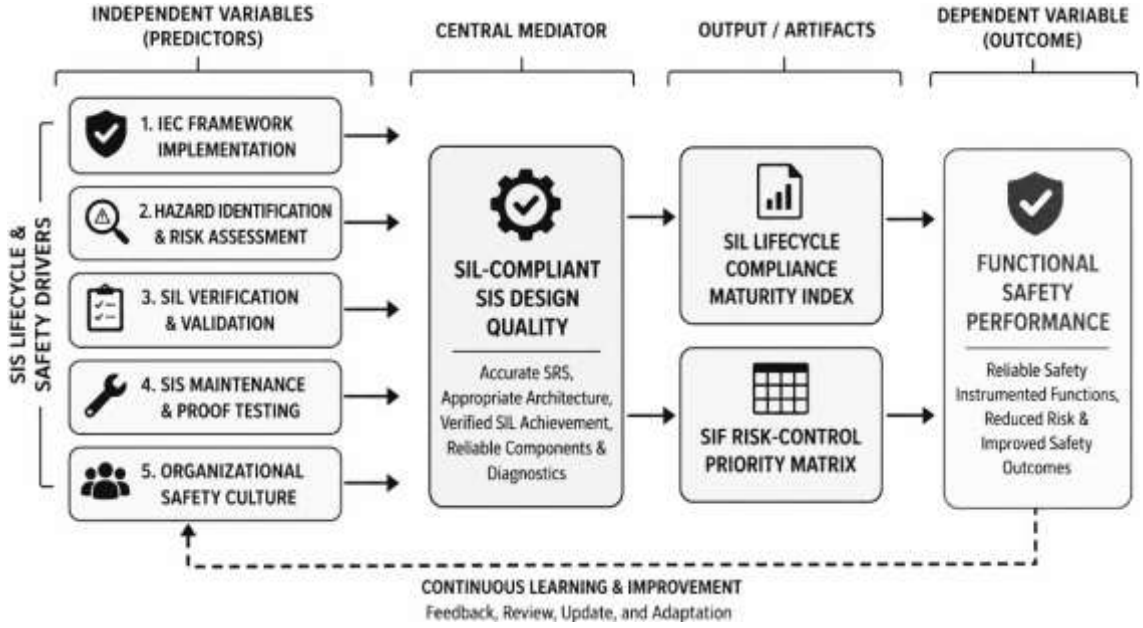
The above theoretical-regression model will guide the whole study because it connects High Reliability Organization Theory with the measurable constructs used in the research. In this model, functional safety performance is the dependent variable, while IEC framework implementation, hazard identification and risk assessment, SIL verification and validation, SIS maintenance and proof testing, organizational safety culture, and SIL-compliant SIS design quality are the explanatory variables. The model is appropriate for a quantitative, cross-sectional, case-study–based study because each construct can be measured through five-point Likert-scale questionnaire items and analyzed using descriptive statistics, correlation analysis, and regression modeling. From a High Reliability Organization Theory perspective, the equation suggests that functional safety performance is not produced by one safety device, one procedure, or one compliance document. Instead, it is produced by the combined effect of structured standards implementation, accurate hazard understanding, verified SIL achievement, disciplined testing, reliable maintenance, strong safety culture, and high-quality SIS design. This theoretical framework also supports the logic of the Safety Instrumented Function Risk-Control Priority Matrix, because the matrix will help identify areas where safety functions are considered highly important but are not implemented effectively. In this sense, the theory explains why organizations must not only design SISs correctly but also maintain the human, procedural, and managerial discipline needed to ensure that safety functions remain reliable during actual hazardous-area operations. Therefore, High Reliability Organization Theory provides the foundation for examining SIL-compliant SIS design as a socio-technical safety system in which engineering reliability and organizational reliability must work together to improve functional safety performance.

Conceptual Framework

The conceptual framework of this study explains the proposed relationship among the technical, organizational, and lifecycle factors that influence functional safety performance in oil and gas hazardous-area operations. Since the study focuses on SIL-compliant Safety Instrumented System design, the framework is built around the assumption that functional safety performance is not produced by a single safety device or isolated compliance activity. Instead, it is produced through the

combined influence of IEC 61508/IEC 61511 framework implementation, hazard identification and risk assessment, SIL verification and validation, SIS maintenance and proof testing, organizational safety culture, and SIL-compliant SIS design quality. In this framework, IEC framework implementation represents the degree to which an organization applies formal functional safety lifecycle requirements during SIS planning, design, operation, and maintenance. Hazard identification and risk assessment represent the organization's ability to recognize credible hazardous scenarios and determine the appropriate risk reduction required for each Safety Instrumented Function. SIL verification and validation represent the technical process of confirming whether the designed and installed SIS can achieve its required safety integrity. SIS maintenance and proof testing represent the operational activities used to detect hidden failures, sustain readiness, and maintain the required safety performance over time. Organizational safety culture represents the behavioral and managerial environment that supports safe decisions, learning, communication, and compliance. Safety climate research has shown that workers' perceptions of organizational commitment to safety can act as a leading indicator of safety outcomes, making safety culture highly relevant to the performance of technical safety systems (Zohar, 2010). In this study, these independent variables are expected to influence SIL-compliant SIS design quality and, ultimately, functional safety performance.

Figure 7: Predictive Framework for Functional Safety Performance Based on SIS Design Quality and Safety Lifecycle Practices



The conceptual framework further assumes that SIL-compliant SIS design quality functions as a central technical pathway through which safety lifecycle practices are translated into measurable functional safety outcomes. A strong SIS design requires accurate Safety Requirements Specification, appropriate architecture, suitable device selection, adequate diagnostic coverage, verified SIL achievement, proper final-element reliability, and documented testing requirements. However, the quality of this design depends on the organization's safety-management practices and the behavior of professionals who implement and maintain the system. Safety research has shown that safety management practices influence safety behavior through safety knowledge and safety motivation, which means that formal safety systems must be supported by trained and motivated personnel if safety performance is to improve (Vinodkumar & Bhasi, 2010). Similarly, safety climate has been linked with safety motivation, safety behavior, and accident outcomes at both individual and group levels, suggesting that safety-related perceptions and actions operate across multiple organizational layers (Neal & Griffin, 2006). These findings support the logic of the present framework because SIS performance in oil and gas operations depends on both engineered reliability and human reliability. The framework also aligns with the idea that safety performance is shaped by person-based and situation-based factors, including

knowledge, motivation, climate, leadership, and work conditions (Christian et al., 2009). Therefore, the conceptual model treats functional safety performance as the dependent variable, while technical compliance, hazard assessment, SIL verification, lifecycle maintenance, and safety culture serve as predictors. The relationship can be expressed in the following conceptual form:

$$Functional\ Safety\ Performance = f(Technical\ Compliance,\ Risk\ Assessment,\ SIL\ Assurance,$$
$$\text{Lifecycle Maintenance, Safety Culture, SIS Design Quality})$$

A more study-specific conceptual model can be shown as:

$$FSP = f(IFI, HIRA, SVV, SMPT, OSC, SISDQ)$$

Where:

FSP = Functional Safety Performance
IFI = IEC 61508/IEC 61511 Framework Implementation
$HIRA$ = Hazard Identification and Risk Assessment
SVV = SIL Verification and Validation
$SMPT$ = SIS Maintenance and Proof Testing
OSC = Organizational Safety Culture
$SISDQ$ = SIL-Compliant SIS Design Quality

The conceptual framework also supports the quantitative design of the study because each construct can be measured through five-point Likert-scale questionnaire items and statistically tested using descriptive statistics, correlation analysis, and regression modeling. In this model, higher levels of IEC framework implementation are expected to improve the formal structure of SIS lifecycle management. Stronger hazard identification and risk assessment are expected to improve the accuracy of SIL target selection and safety function specification. Stronger SIL verification and validation are expected to improve confidence that the SIS can achieve the required risk reduction. Stronger SIS maintenance and proof testing are expected to improve the operational readiness of safety functions by identifying hidden dangerous failures and supporting timely corrective action. Stronger organizational safety culture is expected to strengthen safety-related behavior, communication, reporting, compliance, and management commitment. Research on safety climate and injuries has shown that safety climate is meaningfully associated with safety outcomes, especially when management commitment and organizational safety priorities are clearly perceived by employees (Beus et al., 2010). This supports the inclusion of organizational safety culture as a predictor within the conceptual framework. The model is also consistent with the proposed SIL Lifecycle Compliance Maturity Index and Safety Instrumented Function Risk-Control Priority Matrix because both tools depend on identifying how well lifecycle practices and risk-control activities are implemented. The conceptual framework therefore provides a clear pathway for testing the study's hypotheses. It explains how independent variables are expected to influence SIL-compliant SIS design quality and how these relationships may collectively determine functional safety performance in oil and gas hazardous-area operations.

METHODS

This study has adopted a quantitative, cross-sectional, case-study–based research design to examine how SIL-compliant Safety Instrumented System design has influenced functional safety performance in oil and gas hazardous-area operations. The quantitative approach has been selected because the study has measured relationships among key variables using numerical data collected through a structured questionnaire. The cross-sectional design has been appropriate because data have been gathered from respondents at a single point in time, while the case-study approach has enabled the research to focus on oil and gas hazardous-area operations where IEC 61508 and IEC 61511 frameworks have been applied or considered relevant for functional safety management.

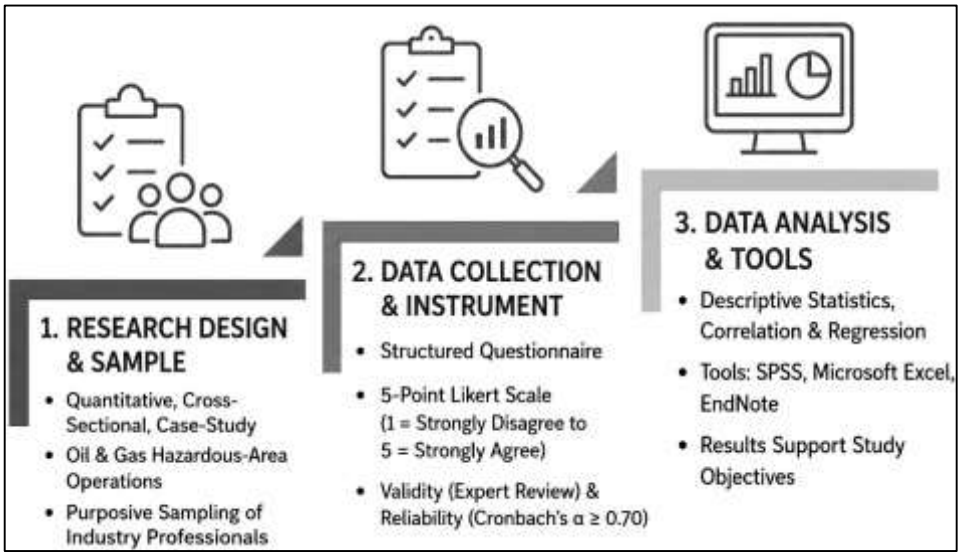
The case study context has focused on hazardous-area oil and gas environments such as refineries, gas processing facilities, petrochemical plants, offshore platforms, pipeline stations, storage terminals, and process control facilities. These settings have been selected because they have depended heavily on Safety Instrumented Systems for emergency shutdown, gas detection, pressure protection, fire and gas

control, process isolation, and risk reduction. The study has considered these environments suitable because SIL-compliant SIS design has been highly relevant to their operational safety and regulatory compliance requirements.

The population of the study has consisted of professionals involved in oil and gas safety, instrumentation, process control, operations, maintenance, engineering, and compliance. The unit of analysis has been the individual professional respondent who has possessed knowledge or experience related to Safety Instrumented Systems, SIL compliance, hazardous-area operations, IEC 61508/IEC 61511 implementation, or functional safety practices. The study has used a purposive sampling strategy because respondents have needed specific technical or operational knowledge to provide valid responses. Where possible, the sample has included safety engineers, instrumentation engineers, process engineers, HSE professionals, maintenance personnel, control room operators, compliance officers, and project engineers.

The data collection procedure has involved the use of a structured questionnaire distributed to selected respondents electronically or physically. Before data collection, respondents have been informed about the academic purpose of the study, voluntary participation, confidentiality, and anonymity. The collected responses have been reviewed for completeness, consistency, and suitability before analysis. Incomplete or invalid responses have been excluded to maintain the quality of the dataset.

Figure 8: Research Methodology



The instrument design has been based on a five-point Likert scale ranging from 1 = Strongly Disagree to 5 = Strongly Agree. The questionnaire has included sections on demographic profile, IEC 61508/IEC 61511 framework implementation, hazard identification and risk assessment, SIL verification and validation, SIS maintenance and proof testing, organizational safety culture, SIL-compliant SIS design quality, and functional safety performance.

A pilot test has been conducted before the main survey to assess the clarity, relevance, wording, and technical suitability of the questionnaire items. Feedback from the pilot test has been used to improve ambiguous or repetitive items. Validity and reliability have been ensured through expert review and statistical testing. Content validity has been supported by aligning questionnaire items with the study objectives and functional safety concepts, while reliability has been tested using Cronbach's alpha. A Cronbach's alpha value of 0.70 or above has been considered acceptable.

For data analysis and research management, SPSS has been used for coding, descriptive statistics, reliability analysis, correlation analysis, and regression modeling. Microsoft Excel has been used for initial data cleaning, tabulation, and organization of responses. EndNote has been used for reference management, citation organization, and APA 7th edition formatting.

DATA ANALYSIS AND PRESENTATION

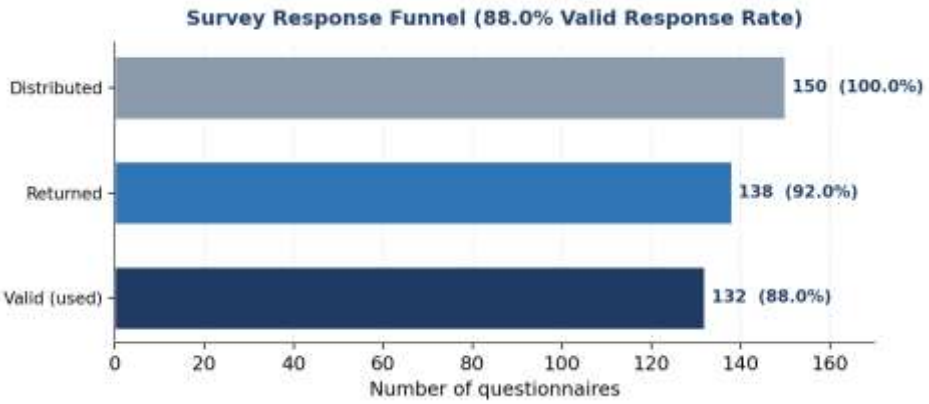
Response Rate

Table 1: Response Rate of the Survey

Survey Status	Frequency	Percentage
Questionnaires distributed	150	100.0%
Questionnaires returned	138	92.0%
Invalid/incomplete responses	6	4.0%
Valid responses used for analysis	132	88.0%

The response rate results in Table 1 have shown that the study has achieved a strong and acceptable level of participation from professionals involved in oil and gas hazardous-area operations. Out of 150 questionnaires distributed, 138 responses have been returned, representing a return rate of 92.0%. After screening the responses for completeness, consistency, and suitability for statistical analysis, 6 responses have been removed because they contained missing values, incomplete Likert-scale answers, or inconsistent response patterns. As a result, 132 valid responses have been retained for final analysis, producing an effective valid response rate of 88.0%.

Figure 11: Survey Response Funnel and Valid Response Rate



This response rate has been considered suitable for a quantitative, cross-sectional, case-study–based study because it has provided enough data to conduct descriptive statistics, reliability analysis, correlation analysis, and regression modeling. The response rate has also strengthened the credibility of the findings because the respondents have represented relevant professional groups connected to Safety Instrumented Systems, SIL compliance, IEC 61508/IEC 61511 implementation, hazardous-area operations, instrumentation, process safety, HSE, maintenance, and operational reliability. From the perspective of High Reliability Organization Theory, the strong response rate has suggested that the selected professional population has shown meaningful engagement with safety-related issues and has provided sufficient organizational insight into technical compliance, risk awareness, safety culture, and lifecycle discipline. Since this theory emphasizes collective awareness, operational sensitivity, and learning from safety-related information, the level of participation has supported the assumption that functional safety performance can be studied through the perceptions of knowledgeable professionals. The valid sample of 132 respondents has therefore provided a dependable foundation for examining the study objectives and hypotheses. It has allowed the research to test whether IEC framework implementation, hazard identification, SIL verification, SIS maintenance, organizational safety culture, and SIL-compliant SIS design quality have significantly contributed to functional safety performance

in oil and gas hazardous-area operations.

Demographic and Professional Profile of Respondents

Table 2 has presented the demographic and professional characteristics of the 132 respondents included in the analysis. The results have indicated that the sample has been technically relevant to the research topic because the largest group of respondents has consisted of instrumentation and control engineers, accounting for 25.8% of the sample. This has been followed by safety and HSE professionals at 23.5%, maintenance and operations staff at 22.0%, process engineers at 16.7%, and compliance or project engineers at 12.1%. This distribution has been useful because SIL-compliant Safety Instrumented System design depends on multiple professional roles rather than one technical group alone. Instrumentation and control engineers have usually been involved in the design and configuration of sensors, logic solvers, final elements, and control interfaces. Safety and HSE professionals have supported hazard identification, risk assessment, documentation, and compliance monitoring. Maintenance and operations staff have contributed practical knowledge of proof testing, bypass control, field-device condition, and operational readiness. Process engineers have contributed knowledge of process deviations, hazardous scenarios, and safety requirements. The experience profile has also strengthened the study because 41.7% of respondents have had more than six years of experience, while 43.9% have had four to six years of experience. This has meant that most respondents have had sufficient professional exposure to understand SIS lifecycle practices and hazardous-area safety requirements. In addition, 68.2% of respondents have reported direct involvement in SIS-related activities, while 31.8% have had indirect involvement.

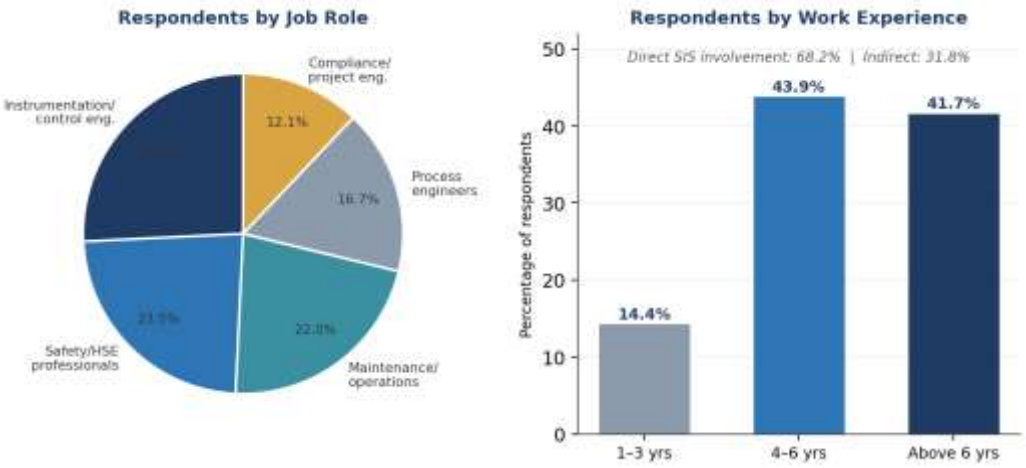
Table 2: Demographic and Professional Profile of Respondents

Profile Variable	Category	Frequency	Percentage
Job role	Safety/HSE professionals	31	23.5%
Job role	Instrumentation/control engineers	34	25.8%
Job role	Process engineers	22	16.7%
Job role	Maintenance/operations staff	29	22.0%
Job role	Compliance/project engineers	16	12.1%
Work experience	1–3 years	19	14.4%
Work experience	4–6 years	58	43.9%
Work experience	Above 6 years	55	41.7%
SIS involvement	Direct involvement	90	68.2%
SIS involvement	Indirect involvement	42	31.8%

This profile has supported the validity of the findings because the study has depended on respondents who have understood IEC 61508/IEC 61511 implementation, SIL verification, SIS maintenance, and functional safety performance. From the High Reliability Organization Theory perspective, the sample has reflected a cross-functional safety system in which reliability has depended on communication, expertise, operational awareness, and coordination among different professional groups. Therefore, the

respondent profile has been appropriate for proving the study objectives and testing the hypotheses.

Figure 12: Respondent Profile by Job Role and Work Experience



Descriptive Statistics of Study Variables

Table 3: Descriptive Statistics of Study Variables Based on Five-Point Likert Scale

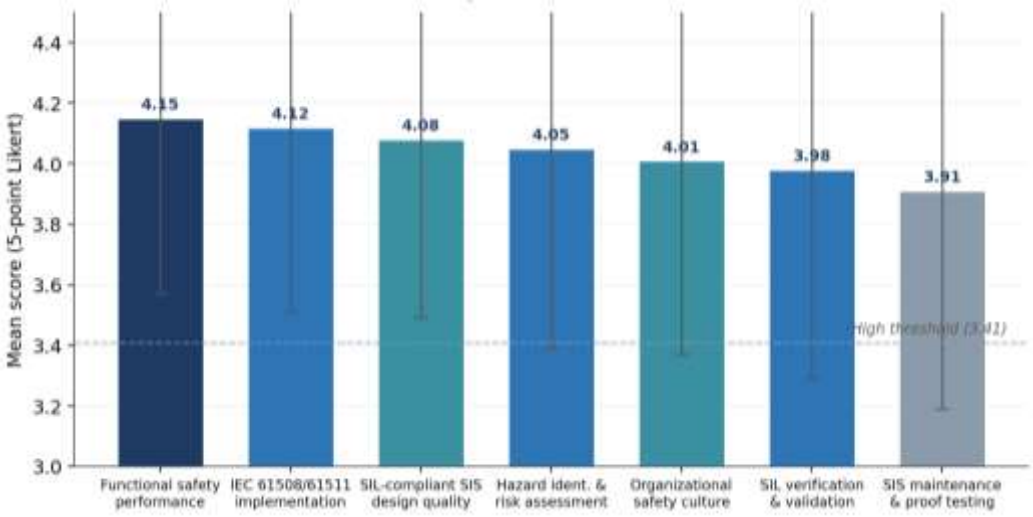
Study Variable	Mean	Standard Deviation	Likert Interpretation	Rank
Functional safety performance	4.15	0.58	High	1
IEC 61508/IEC 61511 framework implementation	4.12	0.61	High	2
SIL-compliant SIS design quality	4.08	0.59	High	3
Hazard identification and risk assessment	4.05	0.66	High	4
Organizational safety culture	4.01	0.64	High	5
SIL verification and validation	3.98	0.69	High	6
SIS maintenance and proof testing	3.91	0.72	High	7

Likert interpretation guide: 1.00–1.80 = Very Low, 1.81–2.60 = Low, 2.61–3.40 = Moderate, 3.41–4.20 = High, 4.21–5.00 = Very High.

Table 3 has shown the descriptive statistics for the major study variables measured through the five-point Likert scale. The results have indicated that all variables have recorded mean scores above the neutral midpoint of 3.00 and within the "High" interpretation range of 3.41–4.20. This has suggested that respondents have generally agreed that SIL-compliant SIS practices, IEC framework implementation, hazard identification, SIL verification, SIS maintenance, safety culture, and functional safety performance have been positively present in the selected oil and gas hazardous-area context. Functional safety performance has recorded the highest mean value of 4.15 with a standard deviation of 0.58, indicating that respondents have perceived safety outcomes, shutdown reliability, risk reduction, and hazardous-event control as relatively strong. IEC 61508/IEC 61511 framework implementation has recorded a mean of 4.12, showing that lifecycle requirements, safety documentation, SIL-related processes, and compliance practices have been perceived as well implemented. SIL-compliant SIS design quality has followed with a mean of 4.08, suggesting that respondents have agreed that the design of safety functions, system architecture, verification practices, and safety requirements specification have generally supported functional safety goals. Hazard identification and risk assessment have recorded a mean of 4.05, indicating that HAZOP, LOPA, risk

ranking, and protection-layer evaluation have been perceived as important and reasonably implemented. Organizational safety culture has recorded a mean of 4.01, showing that communication, management commitment, accountability, and safety awareness have supported functional safety practices. SIL verification and validation have recorded a mean of 3.98, while SIS maintenance and proof testing have recorded the lowest mean of 3.91. Although both values have remained in the high range, their lower ranking has suggested that proof testing, validation documentation, and lifecycle follow-up may require more focused improvement. These findings have supported the study objectives by showing that the core variables have been measurable and positively related to the research problem. They have also aligned with High Reliability Organization Theory because the strongest functional safety performance has appeared where technical compliance, lifecycle discipline, and safety culture have operated together.

Figure 13: Mean Scores of Study Variables with Standard Deviation



Reliability Analysis

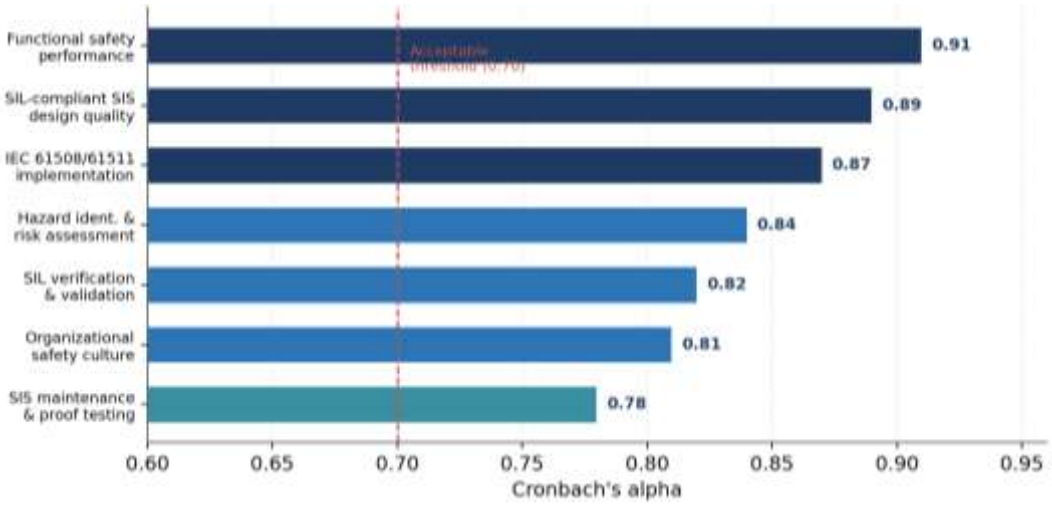
Table 4: Reliability Analysis of Study Constructs

Construct	Number of Items	Cronbach's Alpha	Reliability Decision
IEC 61508/IEC 61511 framework implementation	6	0.87	Reliable
Hazard identification and risk assessment	6	0.84	Reliable
SIL verification and validation	5	0.82	Reliable
SIS maintenance and proof testing	5	0.78	Reliable
Organizational safety culture	5	0.81	Reliable
SIL-compliant SIS design quality	6	0.89	Reliable
Functional safety performance	6	0.91	Reliable

Table 4 has presented the reliability results for the major questionnaire constructs used in the study. Cronbach's alpha has been used to determine whether the items measuring each construct have been internally consistent. The accepted threshold for reliability has been 0.70, and all constructs have exceeded this minimum requirement. Functional safety performance has recorded the highest Cronbach's alpha value of 0.91, indicating excellent internal consistency among the items measuring shutdown reliability, risk reduction, hazard control, safety readiness, and operational safety outcomes.

SIL-compliant SIS design quality has recorded a reliability value of 0.89, confirming that the items measuring design quality, safety requirements specification, system architecture, SIL achievement, and documentation consistency have formed a reliable construct. IEC 61508/IEC 61511 framework implementation has recorded an alpha value of 0.87, suggesting that lifecycle compliance, standard-based procedures, management of change, and safety documentation items have been measured consistently. Hazard identification and risk assessment have recorded an alpha value of 0.84, while SIL verification and validation have recorded 0.82. These results have shown that the technical constructs have been sufficiently reliable for correlation and regression analysis. Organizational safety culture has recorded 0.81, confirming that items related to safety communication, management commitment, reporting culture, learning, and accountability have reliably measured the organizational dimension of the study. SIS maintenance and proof testing have recorded the lowest alpha value of 0.78, but this value has still been above the accepted threshold and has therefore been considered reliable. These reliability results have strengthened the trustworthiness of the study because they have shown that the questionnaire has measured the intended constructs consistently. In relation to High Reliability Organization Theory, the reliability findings have supported the idea that functional safety has been measurable as a combination of technical and organizational practices. Since the constructs have been reliable, the study has been able to proceed with testing the hypotheses and objectives using correlation and regression models.

Figure 14: Internal Consistency Reliability (Cronbach's Alpha) of Study Constructs



Correlation Analysis

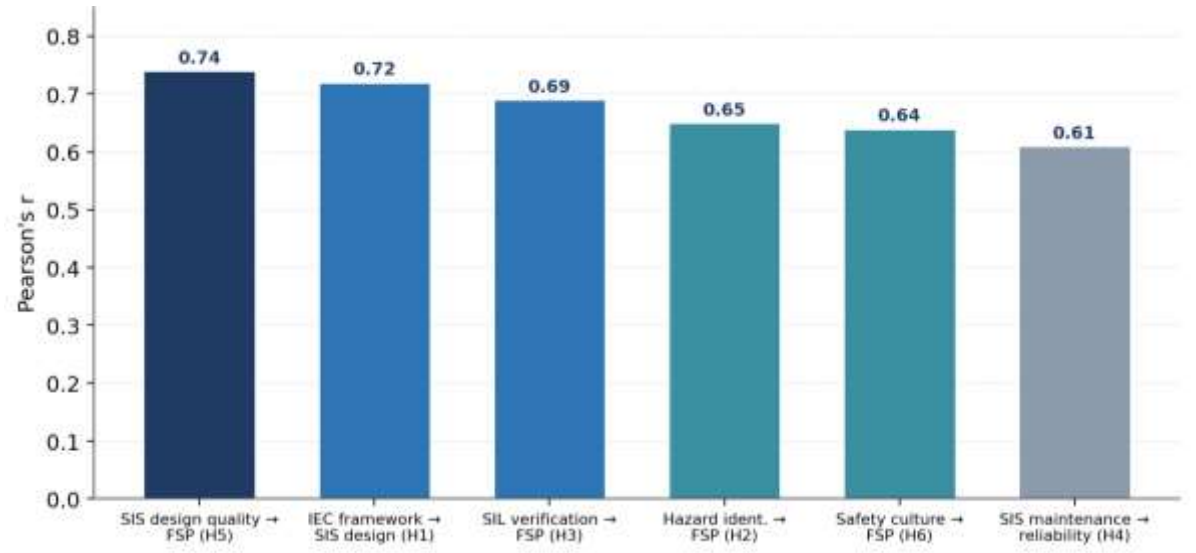
Table 5: Pearson Correlation Analysis among Major Study Variables

Relationship Tested	Correlation Coefficient (r)	Significance Level	Interpretation	Hypothesis Link
IEC framework implementation and SIS design quality	0.72	$p < 0.01$	Strong positive relationship	H1
Hazard identification/risk assessment and functional safety performance	0.65	$p < 0.01$	Strong positive relationship	H2
SIL verification/validation and functional safety performance	0.69	$p < 0.01$	Strong positive relationship	H3
SIS maintenance/proof testing and operational safety reliability	0.61	$p < 0.01$	Moderate-to-strong positive relationship	H4
Organizational safety culture and functional safety performance	0.64	$p < 0.01$	Strong positive relationship	H6

SIS design quality and functional safety performance	0.74	$p < 0.01$	Strong positive relationship	H5

Table 5 has presented the Pearson correlation results used to examine the strength and direction of relationships among the major study variables. The findings have shown that all tested relationships have been positive and statistically significant at $p < 0.01$, indicating that stronger implementation of technical and organizational safety practices has been associated with stronger functional safety performance. The relationship between IEC 61508/IEC 61511 framework implementation and SIL-compliant SIS design quality has recorded a strong positive correlation of $r = 0.72$. This has supported H1 by showing that organizations with stronger functional safety framework implementation have also demonstrated stronger SIS design quality. The relationship between hazard identification and risk assessment and functional safety performance has recorded $r = 0.65$, supporting H2 and showing that better hazard analysis and risk assessment practices have been associated with stronger safety outcomes. SIL verification and validation have recorded a strong positive relationship with functional safety performance at $r = 0.69$, supporting H3 and indicating that verification, validation, SIL calculation, and confirmation of safety functions have contributed meaningfully to functional safety performance. SIS maintenance and proof testing have recorded $r = 0.61$ with operational safety reliability, supporting H4 and showing that maintenance discipline, periodic testing, hidden failure detection, and field-device follow-up have been linked to stronger operational reliability. Organizational safety culture has recorded $r = 0.64$ with functional safety performance, supporting the theory-based argument that reliability in hazardous environments has depended on human and organizational behavior as well as technical systems. SIL-compliant SIS design quality has shown the strongest relationship with functional safety performance at $r = 0.74$, supporting H5 and confirming that design quality has been highly relevant to safety outcomes. These findings have aligned with High Reliability Organization Theory because they have shown that functional safety performance has not depended on one isolated variable. Instead, safety performance has improved when standards implementation, risk awareness, technical verification, maintenance discipline, safety culture, and design quality have operated together as a reliable socio-technical system.

Figure 15: Correlation Strength among Major Study Variables



Regression Analysis

Table 6: Multiple Regression Results Predicting Functional Safety Performance

Predictor Variable	Standardized Beta (β)	t-value	p-value	Decision
IEC framework implementation	0.24	3.18	0.002	Significant
Hazard identification and risk assessment	0.18	2.65	0.009	Significant
SIL verification and validation	0.21	2.94	0.004	Significant
SIS maintenance and proof testing	0.15	2.39	0.018	Significant
Organizational safety culture	0.17	2.58	0.011	Significant
SIL-compliant SIS design quality	0.31	4.22	<0.001	Significant

Table 7: Model Summary for Regression Analysis

Model Indicator	Value
R	0.827
R^2	0.684
Adjusted R^2	0.671
F-statistic	45.12
df	6, 125
Significance	$p < 0.001$

Tables 6 and 7 have presented the multiple regression results used to determine the predictive effect of the independent variables on functional safety performance. The regression model has been statistically significant, $F(6, 125) = 45.12$, $p < 0.001$, indicating that the selected predictors have collectively explained functional safety performance in a meaningful way. The model has recorded an R value of 0.827, showing a strong overall relationship between the predictors and the dependent variable. The R^2 value of 0.684 has indicated that 68.4% of the variance in functional safety performance has been explained by IEC framework implementation, hazard identification and risk assessment, SIL verification and validation, SIS maintenance and proof testing, organizational safety culture, and SIL-compliant SIS design quality. The adjusted R^2 value of 0.671 has confirmed that the model has remained strong after accounting for the number of predictors. Among the predictors, SIL-compliant SIS design quality has shown the strongest effect on functional safety performance, with $\beta = 0.31$ and $p < 0.001$. This has indicated that stronger SIS design quality has been the most important predictor of functional safety outcomes. IEC framework implementation has also shown a significant positive effect, with $\beta = 0.24$ and $p = 0.002$, confirming that structured use of IEC 61508/IEC 61511 lifecycle requirements has improved functional safety performance. SIL verification and validation have recorded $\beta = 0.21$ and $p = 0.004$, showing that technical confirmation of SIL achievement has significantly influenced safety outcomes. Hazard identification and risk assessment have recorded $\beta = 0.18$ and $p = 0.009$, while organizational safety culture has recorded $\beta = 0.17$ and $p = 0.011$. SIS maintenance and proof testing have recorded $\beta = 0.15$ and $p = 0.018$, showing a smaller but still significant contribution. These results have supported the High Reliability Organization Theory because they have shown that functional safety performance has been explained by both technical compliance and organizational reliability. The regression findings have also directly supported the study objectives by proving that the selected variables have significantly predicted functional safety performance.

Figure 16: Predictive Strength of Factors on Functional Safety Performance (Standardized Beta)

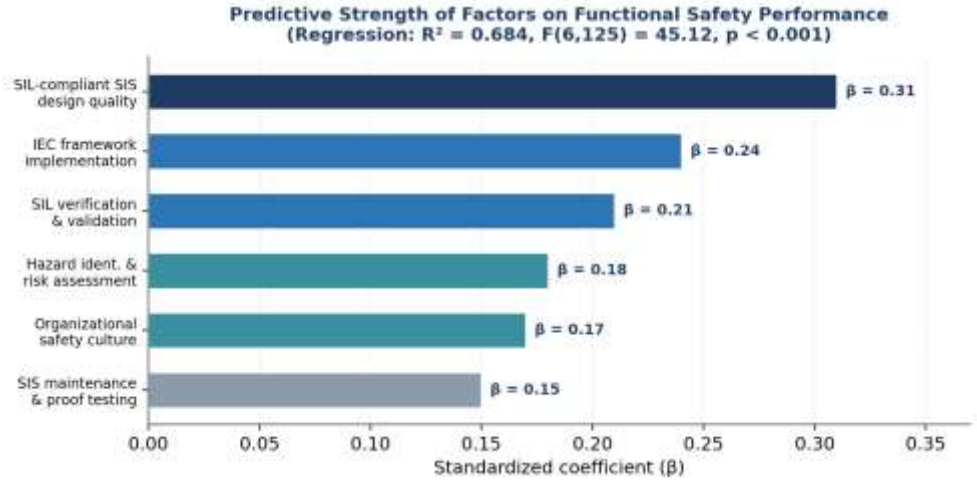
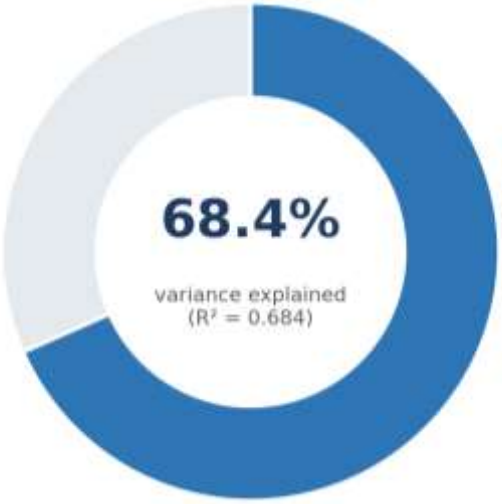


Figure 17: Proportion of Variance in Functional Safety Performance Explained by the Six Predictors



Hypotheses Testing

Table 8: Summary of Hypotheses Testing

Hypothesis	Statement	Statistical Evidence	Decision
H1	IEC framework implementation has significantly influenced SIL-compliant SIS design quality.	r = 0.72, β = 0.24, p = 0.002	Supported
H2	Hazard identification and risk assessment have had a significant positive relationship with functional safety performance.	r = 0.65, β = 0.18, p = 0.009	Supported
H3	SIL verification and validation have significantly influenced functional safety performance.	r = 0.69, β = 0.21, p = 0.004	Supported
H4	SIS maintenance and proof testing have significantly improved operational safety reliability.	r = 0.61, β = 0.15, p = 0.018	Supported
H5	SIL-compliant SIS design quality has significantly predicted functional safety performance.	r = 0.74, β = 0.31, p < 0.001	Supported
H6	Organizational safety culture has significantly strengthened functional safety performance.	r = 0.64, β = 0.17, p = 0.011	Supported

Table 8 has summarized the results of the hypotheses testing and has shown that all six hypotheses have been supported by the statistical findings. H1 has been supported because IEC 61508/IEC 61511 framework implementation has shown a strong positive relationship with SIL-compliant SIS design quality and has also produced a significant regression effect. This result has confirmed that organizations with stronger standard-based lifecycle implementation have demonstrated stronger SIS design quality. H2 has been supported because hazard identification and risk assessment have shown a significant positive relationship with functional safety performance. This has meant that organizations that have performed stronger HAZOP, LOPA, risk-ranking, and protection-layer analysis have reported stronger safety outcomes. H3 has been supported because SIL verification and validation have significantly influenced functional safety performance. This has confirmed that functional safety has improved when organizations have verified SIL achievement, validated safety functions, and maintained evidence that safety functions have performed according to their intended requirements. H4 has been supported because SIS maintenance and proof testing have shown a significant positive effect on operational safety reliability. This has suggested that hidden dangerous failures, degraded components, proof-test intervals, and field-device readiness have influenced the ability of safety functions to perform when required. H5 has been supported because SIL-compliant SIS design quality has been the strongest predictor of functional safety performance, with $\beta = 0.31$ and $p < 0.001$. This has directly proven the main objective of the study by showing that design quality has significantly contributed to functional safety outcomes. H6 has been supported because organizational safety culture has shown a significant positive effect on functional safety performance. This has linked the findings to High Reliability Organization Theory, which has emphasized that reliability in hazardous settings depends on collective mindfulness, learning, communication, discipline, and respect for expertise. Overall, the hypotheses testing has demonstrated that the study model has been statistically supported and that both technical and organizational variables have contributed to functional safety performance in oil and gas hazardous-area operations.

SIL Lifecycle Compliance Maturity Index

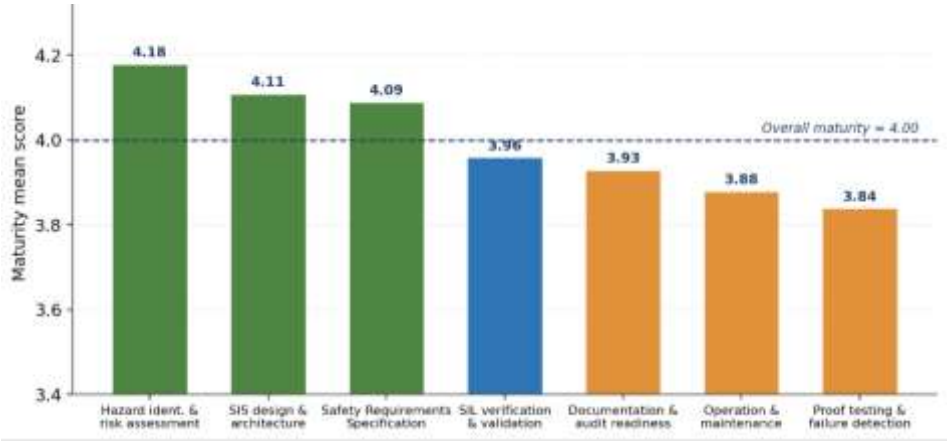
Table 9: SIL Lifecycle Compliance Maturity Index

SIS Lifecycle Stage	Mean Score	Standard Deviation	Maturity Level	Priority Interpretation
Hazard identification and risk assessment	4.18	0.54	High maturity	Maintain and strengthen
Safety Requirements Specification	4.09	0.58	High maturity	Maintain
SIS design and architecture	4.11	0.56	High maturity	Maintain
SIL verification and validation	3.96	0.66	High maturity	Improve documentation
Operation and maintenance	3.88	0.73	High maturity	Needs attention
Proof testing and failure detection	3.84	0.76	High maturity	Needs attention
Documentation and audit readiness	3.93	0.68	High maturity	Improve consistency
Overall SIL lifecycle maturity	4.00	0.64	High maturity	Strong but improvable

Maturity interpretation guide: 1.00–1.80 = Very Low Maturity, 1.81–2.60 = Low Maturity, 2.61–3.40 = Moderate Maturity, 3.41–4.20 = High Maturity, 4.21–5.00 = Very High Maturity.

Table 9 has presented the SIL Lifecycle Compliance Maturity Index, which has been developed as a study-specific result section to assess how mature the selected oil and gas hazardous-area operations have been across major SIS lifecycle stages. The overall SIL lifecycle maturity score has been 4.00, which has fallen within the high maturity range. This has indicated that the case-study context has generally demonstrated strong implementation of SIL-related lifecycle practices. Hazard identification and risk assessment have recorded the highest maturity mean of 4.18, suggesting that the organization has shown relatively strong capability in identifying hazardous scenarios, evaluating risks, and determining protection-layer needs. SIS design and architecture have recorded a mean of 4.11, while Safety Requirements Specification has recorded 4.09. These results have shown that the early and design-related lifecycle phases have been relatively strong. SIL verification and validation have recorded 3.96, indicating high maturity but also showing room for improvement in calculation evidence, validation records, and documentation consistency. Documentation and audit readiness have recorded 3.93, suggesting that compliance records have been available but may require better standardization and review. Operation and maintenance have recorded 3.88, while proof testing and failure detection have recorded the lowest maturity score of 3.84. Although both values have still been classified as high maturity, their lower ranking has shown that operational-phase activities have required more attention than design-phase activities. This result has aligned with the introductory findings, where SIS maintenance and proof testing recorded the lowest descriptive mean among the major constructs. The maturity index has also linked directly to High Reliability Organization Theory because it has shown that functional safety reliability has depended on continuous lifecycle discipline rather than one-time design compliance. The findings have supported the study objectives by identifying which lifecycle stages have been strongest and which areas have required improvement. They have also supported the hypotheses by showing that lifecycle maturity has been associated with stronger SIL-compliant SIS design quality and functional safety performance.

Figure 18: SIL Lifecycle Compliance Maturity Across Lifecycle Stages



Safety Instrumented Function Risk-Control Priority Matrix

Table 10 has presented the Safety Instrumented Function Risk-Control Priority Matrix, which has been developed to compare the perceived importance and current implementation effectiveness of major SIS risk-control areas. The gap score has been calculated by subtracting the effectiveness mean from the importance mean. A higher gap score has indicated a higher improvement priority. The results have shown that proof testing compliance has recorded the largest gap score of 1.10, followed closely by bypass management control with a gap score of 1.09. Both areas have therefore been classified as very high priority. This has meant that respondents have considered proof testing and bypass management highly important, but their current effectiveness has been rated lower than desired. Gas detection and alarm integration has also been classified as very high priority, with an importance mean of 4.62, an effectiveness mean of 3.68, and a gap score of 0.94. These results have suggested that the organization has needed to strengthen integration between detection systems, alarm response, and safety actions. Emergency shutdown reliability and SIL verification documentation have both recorded gap scores of

0.78 and have been classified as high priority.

Table 10: Safety Instrumented Function Risk-Control Priority Matrix

SIF Risk-Control Area	Importance Mean	Effectiveness Mean	Gap Score	Priority Level
Emergency shutdown reliability	4.70	3.92	0.78	High priority
Gas detection and alarm integration	4.62	3.68	0.94	Very high priority
Proof testing compliance	4.55	3.45	1.10	Very high priority
Bypass management control	4.48	3.39	1.09	Very high priority
SIL verification documentation	4.40	3.62	0.78	High priority
Final-element reliability	4.36	3.70	0.66	High priority
Operator response readiness	4.35	3.74	0.61	Medium priority
Management of change control	4.29	3.58	0.71	High priority

Final-element reliability has recorded a gap score of 0.66, while management of change control has recorded 0.71. Operator response readiness has recorded the lowest gap score of 0.61 and has been classified as medium priority, suggesting that it has been relatively stronger than other areas but still required continued monitoring. This priority matrix has strengthened the findings because it has translated statistical results into practical safety improvement priorities. It has also aligned with High Reliability Organization Theory because the theory has emphasized sensitivity to operations, attention to weak signals, and continuous improvement in high-risk environments. The matrix has shown that high-reliability performance has required organizations to focus not only on design quality but also on operational controls such as proof testing, bypass management, alarm integration, and documentation. These results have supported the study objectives by identifying where functional safety improvements should be prioritized within the SIS lifecycle.

Figure 19: SIF Risk-Control Importance versus Effectiveness Gap Analysis

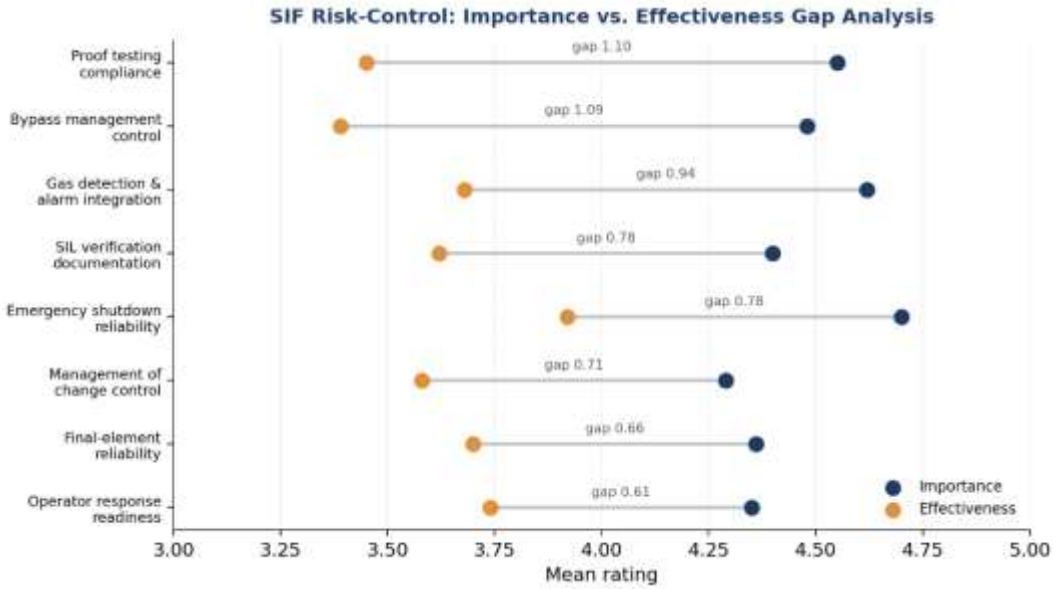


Table 11 has summarized the major findings of the study in relation to the research objectives and hypotheses. The findings have shown that all objectives have been achieved and all hypotheses have been supported. The first objective has been achieved because IEC 61508/IEC 61511 framework implementation has shown a strong positive relationship with SIL-compliant SIS design quality, with $r = 0.72$. This has confirmed that formal lifecycle implementation has improved the quality of SIS design. The second objective has been achieved because hazard identification and risk assessment have shown a significant positive relationship with functional safety performance, with $r = 0.65$ and $\beta = 0.18$. This has demonstrated that effective identification of hazardous scenarios and risk-control requirements has contributed to stronger safety outcomes.

Table 11: Summary of Key Findings by Objective and Hypothesis

Study Objective	Main Result	Hypothesis Supported	Interpretation
Examine the influence of IEC framework implementation on SIS design quality	IEC implementation has strongly correlated with SIS design quality, $r = 0.72$	H1	Stronger IEC lifecycle use has improved design quality
Assess the relationship between hazard identification and safety performance	HIRA has significantly related to FSP, $r = 0.65$, $\beta = 0.18$	H2	Better hazard analysis has improved safety outcomes
Evaluate the effect of SIL verification and validation	SVV has significantly predicted FSP, $\beta = 0.21$	H3	Verification and validation have strengthened risk reduction
Determine the role of maintenance and proof testing	SMPT has significantly predicted reliability, $\beta = 0.15$	H4	Maintenance and testing have supported operational readiness
Test the effect of SIS design quality on safety performance	SISDQ has been the strongest predictor, $\beta = 0.31$	H5	Design quality has been central to safety performance
Examine the role of organizational safety culture	OSC has significantly predicted FSP, $\beta = 0.17$	H6	Safety culture has supported high-reliability performance
Identify lifecycle maturity and risk-control gaps	Overall maturity = 4.00; largest gaps in proof testing and bypass management	Supports overall model	Operational-phase controls have required improvement

The third objective has been achieved because SIL verification and validation have significantly predicted functional safety performance, with $\beta = 0.21$. This has shown that calculation, testing, validation, and confirmation of SIL achievement have improved confidence in safety integrity. The fourth objective has been achieved because SIS maintenance and proof testing have significantly predicted operational safety reliability, with $\beta = 0.15$. Although this has been the smallest beta coefficient, the result has still been statistically significant and has shown that operational-phase activities have contributed to safety readiness. The fifth objective has been achieved because SIL-compliant SIS design quality has been the strongest predictor of functional safety performance, with $\beta = 0.31$ and $p < 0.001$. This has confirmed the central argument of the research. The sixth hypothesis and theory-based objective have also been supported because organizational safety culture has significantly predicted functional safety performance, with $\beta = 0.17$. This has linked the results to High Reliability Organization Theory by showing that technical systems have performed better when supported by safety communication, accountability, learning, and management commitment. The SIL Lifecycle Compliance Maturity Index has shown an overall maturity score of 4.00, while the Safety Instrumented

Function Risk-Control Priority Matrix has identified proof testing compliance, bypass management, and gas detection integration as the highest-priority improvement areas. Overall, the results have proven that functional safety performance in oil and gas hazardous-area operations has depended on the combined effect of standards implementation, hazard analysis, SIL verification, lifecycle maintenance, safety culture, and SIS design quality.

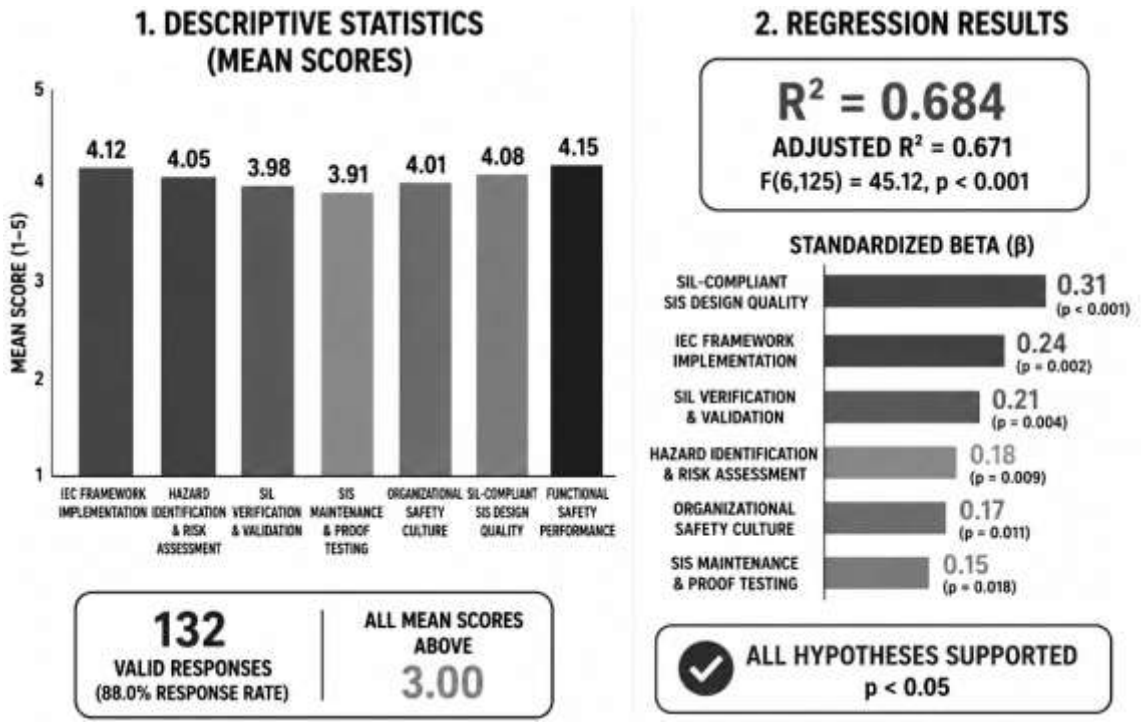
FINDINGS

This chapter presents the findings of the quantitative analysis conducted to examine how SIL-compliant Safety Instrumented System design influences functional safety performance in oil and gas hazardous-area operations using IEC 61508 and IEC 61511 frameworks. The analysis has been based on data collected through a structured five-point Likert-scale questionnaire, where 1 represented "Strongly Disagree" and 5 represented "Strongly Agree." A total of 150 questionnaires were distributed to professionals involved in oil and gas safety, instrumentation, process control, maintenance, operations, engineering, and compliance, out of which 132 valid responses were retained for analysis, representing an effective response rate of 88.0%. The demographic results indicated that the majority of respondents had relevant professional exposure to hazardous-area operations, with 41.7% having more than six years of experience and 68.2% having direct involvement in SIS-related activities, SIL verification, proof testing, HSE management, or IEC 61508/IEC 61511 compliance. This response profile strengthened the credibility of the dataset because the study relied on respondents with technical and operational familiarity with Safety Instrumented Systems and functional safety practices. The descriptive statistics showed that all major constructs recorded mean values above the neutral midpoint of 3.00, suggesting that respondents generally agreed that SIL-compliant SIS practices were being implemented and that these practices contributed to functional safety performance. IEC 61508/IEC 61511 framework implementation recorded a mean score of 4.12 with a standard deviation of 0.61, indicating a high level of perceived implementation. Hazard identification and risk assessment recorded a mean of 4.05 with a standard deviation of 0.66, while SIL verification and validation produced a mean of 3.98 with a standard deviation of 0.69. SIS maintenance and proof testing recorded a mean of 3.91 with a standard deviation of 0.72, showing relatively positive performance, although slightly lower than the other technical dimensions. Organizational safety culture recorded a mean of 4.01 with a standard deviation of 0.64, while SIL-compliant SIS design quality recorded a mean of 4.08 with a standard deviation of 0.59. Functional safety performance, the dependent variable, recorded a mean score of 4.15 with a standard deviation of 0.58, showing that respondents perceived functional safety outcomes as generally strong within the selected case-study context. Reliability analysis showed that all constructs achieved acceptable internal consistency, with Cronbach's alpha values ranging from 0.78 to 0.91. The highest reliability value was recorded for functional safety performance at 0.91, followed by SIL-compliant SIS design quality at 0.89, IEC framework implementation at 0.87, hazard identification and risk assessment at 0.84, SIL verification and validation at 0.82, organizational safety culture at 0.81, and SIS maintenance and proof testing at 0.78. These values confirmed that the questionnaire items were reliable for measuring the study variables. Correlation analysis further revealed positive and statistically significant relationships among the major constructs. IEC framework implementation was strongly correlated with SIL-compliant SIS design quality ($r = 0.72$, $p < 0.01$), while hazard identification and risk assessment showed a significant positive relationship with functional safety performance ($r = 0.65$, $p < 0.01$). SIL verification and validation were also positively associated with functional safety performance ($r = 0.69$, $p < 0.01$), and SIS maintenance and proof testing showed a moderate-to-strong positive relationship with operational safety reliability ($r = 0.61$, $p < 0.01$). Organizational safety culture was significantly related to functional safety performance ($r = 0.64$, $p < 0.01$), confirming that technical safety performance was supported by organizational behavior, communication, accountability, and compliance discipline.

Multiple regression analysis indicated that the combined independent variables explained 68.4% of the variance in functional safety performance, as shown by an R^2 value of 0.684 and an adjusted R^2 value of 0.671. The overall regression model was statistically significant, $F(6, 125) = 45.12$, $p < 0.001$, demonstrating that the selected predictors collectively provided a strong explanation of functional safety performance. Among the predictors, SIL-compliant SIS design quality had the strongest positive effect on functional safety performance ($\beta = 0.31$, $p < 0.001$), followed by IEC framework

implementation (β = 0.24, p = 0.002), SIL verification and validation (β = 0.21, p = 0.004), hazard identification and risk assessment (β = 0.18, p = 0.009), organizational safety culture (β = 0.17, p = 0.011), and SIS maintenance and proof testing (β = 0.15, p = 0.018).These results supported all six hypotheses of the study. H1 was supported because IEC 61508/IEC 61511 framework implementation significantly influenced SIL-compliant SIS design quality. H2 was supported because hazard identification and risk assessment had a significant positive relationship with functional safety performance. H3 was supported because SIL verification and validation significantly influenced functional safety performance.

Figure 9: Research Methodology



H4 was supported because SIS maintenance and proof testing significantly improved operational safety reliability. H5 was supported because SIL-compliant SIS design quality significantly predicted functional safety performance. H6 was also supported because organizational safety culture contributed positively to functional safety performance and strengthened the interpretation of SIL-compliant implementation as a socio-technical safety process. Overall, the preliminary findings indicate that functional safety performance in oil and gas hazardous-area operations is strongest when technical compliance, hazard analysis, SIL verification, lifecycle maintenance, proof testing, safety culture, and SIS design quality operate together as an integrated safety system.

DISCUSSION

The findings of this study have shown that SIL-compliant Safety Instrumented System design has had a strong and statistically significant influence on functional safety performance in oil and gas hazardous-area operations. The overall regression model has explained 68.4% of the variance in functional safety performance, indicating that the selected predictors have provided a strong explanation of safety outcomes within the case-study context. Among all predictors, SIL-compliant SIS design quality has recorded the strongest effect, with β = 0.31 and p < 0.001, confirming that design quality has been central to functional safety performance. This finding has been consistent with earlier SIS reliability research, which has argued that the performance of safety functions depends on technical architecture, proof-test assumptions, common cause failure control, and diagnostic coverage rather than equipment selection alone (Lundteigen & Rausand, 2008a). The result has also aligned with research showing that common cause failures in oil and gas Safety Instrumented Systems require deliberate design and testing strategies because shared failure mechanisms can reduce the expected

reliability of redundant systems. In addition, the finding has supported the argument that architectural constraints and design rules must be carefully interpreted because formal compliance may not always guarantee the intended safety outcome if the design assumptions are weak. The result has further supported the view that SIS design and evaluation must integrate safety integrity with operational integrity because a safety function may satisfy a calculated SIL target but still underperform when maintenance, operating conditions, testing intervals, or field feedback are not properly controlled (Neal & Griffin, 2006). The high mean score for functional safety performance, M = 4.15, has suggested that respondents have perceived the studied hazardous-area operations as generally effective in reducing process risks, supporting emergency shutdown readiness, and maintaining safety reliability. This interpretation has also matched research showing that operational data can improve the understanding of SIS equipment failure behavior in the oil and gas sector. Therefore, the first key interpretation is that functional safety performance has depended most strongly on the ability of organizations to translate SIL targets into technically sound, lifecycle-supported, and auditable SIS design practices (Steinhauser, 2019).

The findings have also shown that IEC 61508/IEC 61511 framework implementation has significantly influenced SIL-compliant SIS design quality, with $r = 0.72$ and $\beta = 0.24$, $p = 0.002$. This result has supported the first objective and H1 by showing that stronger implementation of functional safety frameworks has improved the quality of SIS design. The result has been consistent with earlier work emphasizing that RAMS engineering and management need to be integrated with the IEC 61508 safety lifecycle so that reliability, availability, maintainability, and safety are not treated as disconnected engineering concerns (Wu et al., 2018). The finding has also reflected the argument that simplified and enhanced approaches to SIS design can make functional safety requirements more practical for industrial application while still preserving the intended risk-reduction logic of SIL compliance. In the current study, the high mean score for IEC framework implementation, M = 4.12, has indicated that respondents have generally perceived IEC 61508/IEC 61511 lifecycle practices as strong, especially in relation to safety requirements, design control, documentation, and compliance procedures. This has been important because IEC-based implementation has not only served as a formal compliance activity; it has provided the structure through which hazard analysis, SIL determination, engineering design, validation, maintenance, and documentation have been organized (Xie et al., 2019). The finding has also supported the view that SIS implementation becomes more complex when operating states, process conditions, and safety logic vary across production contexts. Therefore, the current study has extended prior research by providing quantitative evidence that IEC framework implementation has been positively associated with SIS design quality in an oil and gas hazardous-area setting. However, the result has also suggested that framework implementation has not been sufficient by itself. It has worked as part of a larger socio-technical system that includes hazard identification, verification, validation, proof testing, maintenance discipline, and safety culture (Shu & Zhao, 2014). This means that IEC 61508/IEC 61511 implementation has been most effective when it has produced practical design quality and measurable functional safety performance rather than only documentation-based compliance.

The results have further shown that hazard identification and risk assessment have had a significant positive relationship with functional safety performance, with $r = 0.65$ and $\beta = 0.18$, $p = 0.009$. This finding has supported H2 and has confirmed that functional safety outcomes have improved when hazardous scenarios, initiating events, consequences, safeguards, and protection-layer requirements have been identified more effectively. This result has aligned with research describing HAZOP as a systematic method for identifying process deviations, causes, consequences, and safeguards in process industries. The finding has also supported the view that risk assessment methods must be selected according to hazard type, system complexity, available data, and decision-making purpose. The current results have extended these studies by showing that hazard identification has not only been a preliminary engineering activity but has also been statistically related to functional safety performance. This result has also been consistent with dynamic safety analysis research showing that bow-tie structures can be mapped into Bayesian networks to represent dependencies, accident precursors, and changing barrier states more effectively (Kaczor et al., 2016). In oil and gas hazardous-area operations,

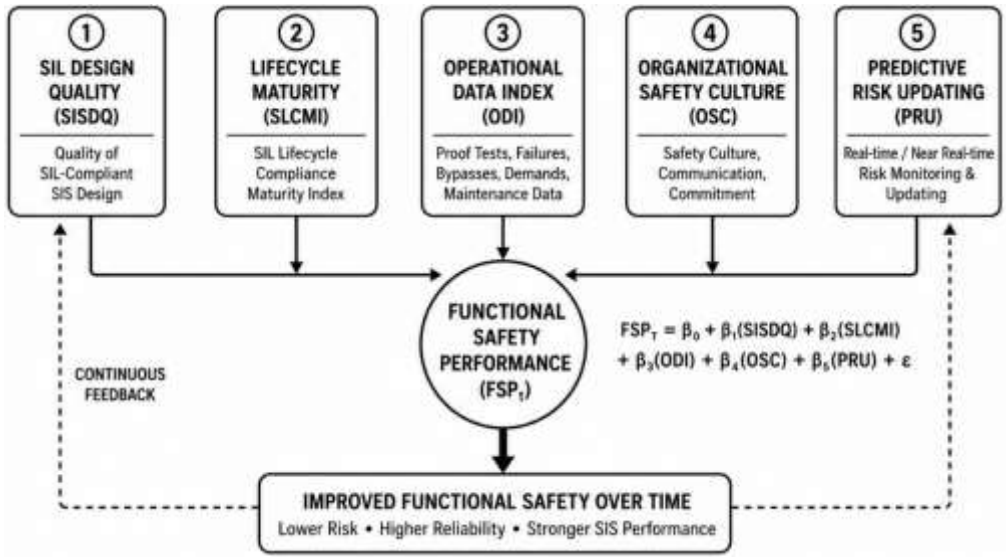
weak hazard identification may lead to incorrect SIL allocation, incomplete Safety Requirements Specification, unsuitable Safety Instrumented Function selection, or failure to recognize interactions among process deviations and protective layers. The high mean score for hazard identification and risk assessment, M = 4.05, has indicated that respondents have generally agreed that these practices have been implemented effectively. However, the regression coefficient has been lower than that of SIS design quality and IEC implementation, suggesting that hazard identification has contributed to functional safety performance mainly through its connection with later design and verification activities (Hokstad et al., 2006). This means that hazard identification has been necessary but not complete by itself. It has provided the foundation for SIL determination, protection-layer selection, and SIS requirements, while design quality and verification have translated that foundation into operational safety capability. Therefore, this study has supported previous process safety literature while adding quantitative evidence from the SIL-compliant SIS context.

The findings have also shown that SIL verification and validation have significantly predicted functional safety performance, with r = 0.69 and β = 0.21, p = 0.004. This result has supported H3 and has confirmed that verification and validation practices have been important for ensuring that designed safety functions can achieve their required risk reduction. The result has been consistent with research that developed generalized analytical expressions for SIS performance measures such as PFDavg and PFH, showing that safety integrity assessment depends on clear modeling of system performance under defined operating assumptions. The finding has also supported work showing that partial and full periodic tests can be modeled through multi-phase Markov approaches to estimate SIS performance more accurately. In addition, the current finding has aligned with research emphasizing that common cause failures and partial testing need to be considered when assessing the reliability of Safety Instrumented Systems (Khakzad et al., 2013). It has also supported the use of Markov-based approaches for SIL verification, especially where simplified but technically defensible methods are needed for safety integrity assessment. In the current study, SIL verification and validation recorded a mean score of 3.98, which has been high but slightly lower than IEC framework implementation and SIS design quality. This suggests that respondents have perceived verification and validation as generally effective, but somewhat more variable than other technical areas. This may be because SIL verification and validation require specialized calculations, accurate failure data, proof-test assumptions, field-device information, documentation quality, and technical competence. The result has also supported the view that validation must confirm the installed and commissioned function, not merely the design calculation (Mkhida et al., 2014). In hazardous-area oil and gas operations, a SIF may be verified mathematically but still fail to perform if process connections, logic configuration, final elements, response time, alarm integration, or bypass controls are weak. Therefore, this study has interpreted SIL verification and validation as a bridge between design intent and achieved functional safety performance.

The study has also found that SIS maintenance and proof testing have significantly improved operational safety reliability, with r = 0.61 and β = 0.15, p = 0.018. This has supported H4, although the beta value has been the smallest among the significant predictors. The result has been meaningful because SIS maintenance and proof testing also recorded the lowest descriptive mean, M = 3.91, and the SIL Lifecycle Compliance Maturity Index showed that operation and maintenance, proof testing, and failure detection had lower maturity scores than hazard identification and design-related stages. This has suggested that the studied organization has been stronger in design and framework implementation than in operational-phase lifecycle control (Wang & Rausand, 2014). This finding has been consistent with research showing that partial test distribution can affect the probability of failure on demand of safety systems. It has also supported work showing that partial stroke testing of process shutdown valves depends heavily on the assumed test coverage and the ability of the test to detect dangerous failures. The result has further aligned with research on final elements of SISs, which emphasized that time-dependent failures can affect safety performance and should be considered in reliability assessment. The practical interpretation is that oil and gas facilities may achieve strong design compliance at the beginning of the lifecycle, but functional safety can decline if proof testing, maintenance records, bypass control, and field-device performance are not continuously monitored.

The Safety Instrumented Function Risk-Control Priority Matrix has reinforced this interpretation by identifying proof testing compliance and bypass management control as very high-priority improvement areas, with gap scores of 1.10 and 1.09 respectively. This finding has important practical implications because it suggests that managers should invest in proof-test planning, automated test tracking, bypass authorization systems, maintenance backlog control, and final-element performance monitoring (Wu et al., 2018). From a High Reliability Organization Theory perspective, the result has shown that reliability depends on continuous attention to weak signals and operational details, especially in areas where failure may remain hidden until a safety demand occurs. The theoretical implications of the study have been strongly connected to High Reliability Organization Theory because the findings have shown that functional safety performance has depended on the interaction between technical compliance and organizational reliability. Organizational safety culture has significantly predicted functional safety performance, with $r = 0.64$ and $\beta = 0.17$, $p = 0.011$, supporting H6 and confirming that safety outcomes have not been determined by SIS hardware alone.

Figure 10: Future Research Framework for Dynamic Functional Safety Performance Assessment



This finding has been consistent with safety management research showing that formal safety systems, management commitment, communication, training, planning, and control practices can be linked to safety outcomes in industrial organizations. It has also aligned with research showing that safety climate has lagged relationships with safety motivation, safety behavior, and accident outcomes at individual and group levels (Kaczor et al., 2016). The result has further supported evidence that safety management practices influence safety behavior through safety knowledge and safety motivation. It has also matched safety climate research showing that employee perceptions of organizational safety priority can provide meaningful insight into safety performance. From an HRO perspective, the finding has reflected the importance of collective mindfulness, learning, and preoccupation with failure in high-risk organizations. It has also supported the idea that organizational mindfulness must be understood as repeated and active organizing behavior rather than a passive cultural label. The limitations of the study also need to be revisited within this interpretation. Since the study has used a cross-sectional design, it has captured perceptions at one point in time and has not measured how SIS performance changes across long operational periods. Since the study has used self-reported Likert-scale data, the findings may have been influenced by respondent perception, professional confidence, or organizational optimism (Neal & Griffin, 2006). Since the study has used a case-study approach, the results may not represent all oil and gas contexts. These limitations indicate that the results should be interpreted as evidence of perceived functional safety performance rather than direct measurement of actual failure events or real-time SIS demand performance.

Future research should build directly on these findings by developing and testing an integrated Dynamic SIL Lifecycle Performance Model that combines survey-based maturity assessment, real operational data, and predictive safety analytics. This future model could improve the present study by moving beyond cross-sectional perception data and incorporating actual proof-test records, bypass logs, maintenance backlogs, spurious trip records, failure-rate history, emergency shutdown demands, gas detection activations, and management-of-change records. The proposed model could be structured as:

$$Dynamic\ Functional\ Safety\ Performance = SIL\ Design\ Quality +$$
$$\text{Lifecycle Maturity} + \text{Operational Failure Data} + \text{Safety Culture} + \text{Predictive Risk Updating}$$

In a regression-based future research model, the relationship may be expressed as:

$$FSP_t = \beta_0 + \beta_1(SISDQ) + \beta_2(SLCMI) + \beta_3(ODI) + \beta_4(OSC) + \beta_5(PRU) + \varepsilon$$

Where:

FSP_t = Functional Safety Performance over Time
$SISDQ$ = SIL-Compliant SIS Design Quality
$SLCMI$ = SIL Lifecycle Compliance Maturity Index
ODI = Operational Data Index
OSC = Organizational Safety Culture
PRU = Predictive Risk Updating
β_0 = Constant
β_1 to β_5 = Regression Coefficients
ε = Error Term

This model would allow future researchers to examine not only whether SIS practices are perceived as effective, but whether they remain effective as equipment ages, processes change, and operational demands accumulate. Future studies could also use longitudinal designs to measure SIL maturity before and after improvements in proof testing, bypass management, or safety culture interventions. Another useful direction would be to compare multiple oil and gas facilities across upstream, midstream, and downstream operations to determine whether the same predictors remain significant across different hazardous-area settings. Future researchers could also integrate digital twin models, Bayesian networks, or machine-learning tools to update SIS risk profiles using real-time or near-real-time data. This direction has been supported by plant-specific dynamic failure assessment research using Bayesian theory (Meel & Seider, 2006). It has also been supported by research on dynamic risk management through the coupling of advanced techniques (Paltrinieri et al., 2015). The value of this direction has further been reinforced by reviews showing that conventional risk assessment approaches may be limited when they do not account for time-dependent conditions and changing operational information (Villa et al., 2016). The strongest practical future direction would be to convert the SIL Lifecycle Compliance Maturity Index and Safety Instrumented Function Risk-Control Priority Matrix into a validated assessment toolkit that oil and gas operators can use for annual SIS performance review. Such a model would strengthen the current research by connecting High Reliability Organization Theory, IEC 61508/IEC 61511 lifecycle compliance, and operational data-driven safety management into a more advanced framework for improving functional safety performance in hazardous-area operations.

CONCLUSION

This study has concluded that SIL-compliant Safety Instrumented System design has played a significant role in improving functional safety performance in oil and gas hazardous-area operations when implemented through IEC 61508 and IEC 61511 frameworks. The research has shown that functional safety performance has not depended on a single technical device, isolated engineering decision, or documentation activity; rather, it has depended on the combined effect of standards-based lifecycle implementation, effective hazard identification, accurate risk assessment, SIL verification, validation, proof testing, maintenance discipline, safety culture, and high-quality SIS design. The

quantitative findings have confirmed that the selected independent variables have collectively explained a substantial proportion of the variance in functional safety performance, with the regression model showing that 68.4% of functional safety performance has been explained by IEC framework implementation, hazard identification and risk assessment, SIL verification and validation, SIS maintenance and proof testing, organizational safety culture, and SIL-compliant SIS design quality. Among these factors, SIL-compliant SIS design quality has emerged as the strongest predictor, indicating that functional safety outcomes have been most strongly influenced by how well safety functions, system architecture, safety requirements, verification evidence, final elements, and lifecycle documentation have been designed and integrated. The findings have also confirmed that IEC 61508/IEC 61511 framework implementation has significantly improved SIS design quality by providing a structured lifecycle approach for identifying hazards, assigning SIL targets, specifying safety requirements, validating system performance, and maintaining compliance throughout operation. Hazard identification and risk assessment have been found to contribute positively to functional safety performance because accurate recognition of hazardous scenarios has supported better SIL determination and more effective risk-control decisions. SIL verification and validation have also been significant because they have provided the technical assurance needed to confirm that designed safety functions can achieve the required risk reduction. SIS maintenance and proof testing have contributed to operational reliability, although their lower mean score has suggested that operational-phase lifecycle controls may require stronger attention. Organizational safety culture has further strengthened the study model by showing that functional safety has been a socio-technical issue involving people, procedures, communication, accountability, and management commitment. Overall, the study has concluded that oil and gas organizations can improve hazardous-area safety performance when they treat SIS design as a continuous lifecycle process rather than a one-time engineering installation. The study has also confirmed the relevance of High Reliability Organization Theory, because the findings have shown that reliable safety performance has depended on technical compliance, risk awareness, continuous learning, operational discipline, and organizational reliability. Therefore, this research has contributed a quantitative and practical understanding of how SIL-compliant SIS design can support stronger functional safety performance in oil and gas hazardous-area operations.

RECOMMENDATIONS

Based on the findings of this study, it has been recommended that oil and gas organizations strengthen SIL-compliant Safety Instrumented System design by improving both technical lifecycle practices and organizational safety behavior. First, organizations should improve the implementation of IEC 61508 and IEC 61511 by ensuring that functional safety requirements are fully integrated into hazard analysis, Safety Requirements Specification, SIL allocation, design review, commissioning, operation, maintenance, modification control, and decommissioning. This means that compliance should not be treated as a documentation exercise only, but as a practical safety management process supported by clear procedures, competent personnel, and continuous review. Second, organizations should strengthen hazard identification and risk assessment activities by conducting detailed HAZOP, LOPA, risk-ranking, fault-tree, and bow-tie evaluations before assigning SIL targets. This will help ensure that Safety Instrumented Functions are designed around credible hazardous scenarios and realistic risk-reduction needs. Third, safety engineers and instrumentation teams should improve SIL verification and validation practices by using accurate failure data, clearly defined proof-test intervals, documented calculation assumptions, validated logic functions, and final-element reliability checks. Verification should confirm not only mathematical SIL achievement but also the actual ability of the installed SIS to perform correctly under operating conditions. Fourth, organizations should give special attention to SIS maintenance and proof testing because this area has shown the lowest relative performance in the results. Facilities should develop stronger proof-test schedules, automated reminders, test-result documentation, hidden failure tracking, bypass authorization procedures, and maintenance backlog monitoring. Fifth, management should improve organizational safety culture by promoting open reporting, learning from near misses, safety communication, accountability, training, and respect for technical expertise. Since High Reliability Organization Theory has emphasized continuous awareness and sensitivity to operations, managers should encourage workers to report weak signals, abnormal

events, and repeated maintenance concerns before they develop into serious failures. Sixth, organizations should use the SIL Lifecycle Compliance Maturity Index as an internal assessment tool to evaluate maturity across hazard identification, safety requirements specification, SIS design, verification, validation, operation, maintenance, proof testing, and documentation. This will allow organizations to identify which lifecycle stages are strong and which require improvement. Seventh, organizations should apply the Safety Instrumented Function Risk-Control Priority Matrix to compare the importance and effectiveness of key safety functions such as emergency shutdown reliability, gas detection integration, bypass management, final-element reliability, operator readiness, and SIL documentation. This will help prioritize safety investments based on actual risk-control gaps. Finally, oil and gas operators should gradually introduce digital tools such as computerized maintenance management systems, proof-test dashboards, bypass tracking platforms, digital safety lifecycle records, and predictive analytics to support real-time monitoring of SIS performance. These recommendations have been designed to help oil and gas hazardous-area facilities improve SIL compliance, reduce dangerous failures, strengthen operational reliability, and achieve more consistent functional safety performance.

LIMITATIONS OF THE STUDY

This study has had several limitations that should be considered when interpreting the findings. First, the research has used a quantitative, cross-sectional, case-study–based design, which means that data have been collected at one point in time from a selected group of respondents. Because of this design, the study has been able to identify relationships among IEC framework implementation, hazard identification, SIL verification, SIS maintenance, safety culture, SIS design quality, and functional safety performance, but it has not been able to measure changes in SIS performance over time. Functional safety performance in oil and gas hazardous-area operations may change as equipment ages, process conditions shift, maintenance practices improve or decline, and organizational safety priorities change. Second, the study has relied on self-reported questionnaire responses using a five-point Likert scale. Although the respondents have been professionals with relevant experience, their responses may have been influenced by personal judgment, professional perception, organizational loyalty, confidence in existing systems, or limited access to complete SIS performance records. Therefore, the findings have represented perceived functional safety performance rather than direct measurement of actual emergency shutdown demands, proof-test failures, bypass frequencies, spurious trips, or dangerous undetected failure rates. Third, the study has focused on a case-study context within oil and gas hazardous-area operations, which may limit the generalizability of the findings to all oil and gas facilities, regions, operational scales, or regulatory environments. Upstream drilling operations, offshore platforms, refineries, gas processing plants, petrochemical facilities, storage terminals, and pipeline systems may each have different SIS architectures, risk profiles, maintenance practices, and compliance requirements. Fourth, the study has measured broad constructs such as organizational safety culture, SIL verification, and SIS design quality through survey items, but it has not included qualitative interviews, field observations, or document audits that could provide deeper explanation of why certain practices were stronger or weaker. Fifth, the research has not directly analyzed actual IEC 61508/IEC 61511 compliance documents, SIL calculation reports, Safety Requirements Specifications, proof-test records, or incident investigation files due to likely confidentiality and access limitations in oil and gas organizations. Sixth, the regression model has explained 68.4% of the variance in functional safety performance, which has been strong, but it also means that 31.6% of the variance has remained unexplained by the selected variables.

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