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Optimizing Operational Performance and Compliance in LPG Distribution Networks: A Risk-Based Framework for Developing Countries

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Research Article

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Abstract: Managing operational performance and compliance in downstream energy logistics represents a critical challenge for emerging economies. This study develops and evaluates an integrated, risk-based performance management framework deployed across 50 Liquefied Petroleum Gas (LPG) distribution facilities over a twelve-month period. A dual-layered methodology combining Failure Modes and Effects Analysis (FMEA) with Key Performance Indicators (KPIs) was established, structurally aligned with ISO 9001, ISO 45001, ISO 31000, ISO/IEC 31010, and NFPA 58 standards. The framework quantifies operational risk exposure through Risk Priority Numbers (RPNs) and monitors productivity and safety compliance via systematic KPI benchmarking. To ensure model reliability, a complementary operational sensitivity analysis was conducted to validate performance stability under conditions of uncertainty. Post-intervention empirical results demonstrated significant operational and quality gains: the composite KPI score increased from 72.1% to 90.1%, while the operational incident rate decreased by 33.6% (from 3.27 to 2.17 per 10,000 operations). The sensitivity assessment confirmed the stability and reproducibility of these performance metrics across heterogeneous operating environments. This research bridges a critical gap in the operations management literature by providing a scalable, quantitative performance framework for hazardous material logistics, offering a methodological foundation for continuous improvement and operational excellence in downstream supply chains.

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1. Introduction

The Liquefied Petroleum Gas (LPG) supply chain constitutes a critical component of energy infrastructure in many developing and emerging economies, where residential dependence on bottled LPG remains substantial **[1]**. In countries such as Ecuador, as well as across Latin America, Africa, India, and Southeast Asia, the safe storage, handling, and distribution of pressurized LPG cylinders are essential to ensuring operational continuity, supply chain reliability, and public safety **[2]**. These operations inherently involve a complex combination of mechanical, procedural, and regulatory risks, requiring robust performance and safety management frameworks supported by strict compliance with technical standards and risk management principles **[3]**.

Recent research has underscored the importance of systematic safety assessment within LPG supply chains. Gallab et al. (2017) employed a systemic modelling approach using the unified modelling language (UML) and Multi-Agents Systems (MAS) to model the complexity and analyze the risks of maintenance activities within a Liquefied Petroleum Gas (LPG) supply chain [1]. Equally, Arıcan & Ünal (2025) employed a Delphi-FTA hybrid method to assess safety risks in maritime LPG and LNG transport, identifying human error and equipment faults as primary failure points [4]. Sutanto et al. (2020) conducted a Fault Tree Analysis on LPG storage and distribution in Indonesia, isolating leakage, pump malfunction, and fire as dominant hazards [5]. Furthermore, Gabhane & Kanidarapu (2023) designed a neural-network-based consequence modeling approach at a major LPG terminal in India to quantify worst-case leak and explosion

scenarios, highlighting the growing relevance of data-driven predictive safety tools in industrial risk management [6].

Concurrently, literature in operations management has demonstrated that operational risks directly impair logistics productivity, process quality, and overall organizational performance, highlighting the need for frameworks that bridge risk mitigation with performance measurement.

While these studies demonstrate significant advances in hazard identification, the majority focus either on qualitative or failure-centric risk analysis, often in isolation from operational performance evaluation. As a result, there remains a notable gap in the literature regarding the integration of structured risk assessment techniques with quantitative performance metrics capable of capturing operational effectiveness, regulatory compliance, and productivity improvement outcomes, particularly within national LPG distribution networks operating under resource and regulatory constraints. [7].

Ecuador provides a representative case for addressing this gap. The national regulatory framework governing LPG distribution comprising standards such as NTE INEN 1534:2015, exhibits strong alignment with internationally recognized quality, safety, and risk management standards, including ISO 9001, ISO 45001, ISO 31000, ISO/IEC 31010, and NFPA 58 [8]. This regulatory congruence creates a suitable environment for implementing and validating internationally grounded safety methodologies, while also enabling the extrapolation of findings to other countries with comparable institutional and operational contexts [9].

This study undertakes a comprehensive evaluation of risk exposure and operational performance across multiple LPG distribution centers in Ecuador, employing an integrated dual-framework approach combining Failure Modes and Effects Analysis (FMEA) with Key Performance Indicators (KPIs) [10]. FMEA facilitates the systematic identification and prioritization of failure modes intrinsic to LPG distribution processes, while KPIs serve as quantitative measures of operational efficacy, quality control, and compliance with established protocols. By coupling these complementary tools, the proposed framework enables both risk prioritization and performance benchmarking within a unified management structure [11].

The main contributions of this research are threefold:
(i) the development of a reproducible, ISO-aligned risk-based performance framework for LPG cylinder distribution systems; (ii) the quantitative validation of the framework through a multi-depot, real-world case study in a developing economy; and (iii) the demonstration of its scalability and applicability to other national LPG supply chains facing similar operational and performance challenges.

By addressing the persistent disconnect between risk analysis and performance measurement, this study provides a robust foundation for enhancing operational performance and safety compliance in LPG distribution, while supporting future predictive and data-driven risk management systems within the energy logistics sector.

2. Methods

This section describes the methodological framework used to assess operational risk exposure and performance efficiency within the LPG cylinder distribution chain in Ecuador [12]. The approach integrates national regulatory requirements with internationally recognized risk management and safety assessment methodologies,

ensuring methodological rigor and reproducibility in contexts where LPG is distributed in pressurized cylinders [13].

2.1 Research Design

A descriptive-analytical research design was adopted to evaluate both qualitative and quantitative dimensions for safety and operational performance of the LPG distribution chain. This hybrid structure enables systematic identification of risk exposure using Failure Modes and Effects Analysis (FMEA), while assessing operational efficiency through Key Performance Indicators (KPIs) [14]. The combined use of these tools provides a comprehensive technical view of safety and logistical performance, suitable for adaptation in other regional or national contexts [15].

2.2 Scope and Units of Analysis

The analysis covered the main operational phases of LPG cylinder distribution, including cylinder reception, filling, transportation, depot storage, and retail delivery [16]. A total of 50 distribution depots were selected across Ecuador, selected to capture geographic diversity, infrastructure variability, and differences in operational scale [17]. This selection reflects the range of logistical and safety challenges encountered in real-world LPG distribution systems [18].

2.3 Regulatory and Normative Framework

The analysis of technical compliance and operational practices was based on the following Ecuadorian standards:

- NTE INEN 1534:2015 – Safety requirements for LPG cylinder storage [19].
- NTE INEN 1535:1998 – Guidelines for the safe transportation of LPG cylinders [20].
- NTE INEN 1536:1998 – Operational criteria for bottling plants [21].
- National Occupational Health and Safety Regulations – Worker protection and workplace safety [22].

To ensure international relevance, these standards were compared and contextualized with global references, including:

- NFPA 58: Widely adopted in North America and Latin America for LPG storage and handling [23].
- ISO 45001:2018: Occupational health and safety management systems [24].
- ISO 31000:2018 and ISO/IEC 31010:2019: Guidelines and tools for risk assessment methodologies [25], [26].
- ISO 9001:2015: Quality management systems-Requirements [27].

This alignment supports methodological consistency with international best practices in hazardous materials logistics for use in countries with similar industrial safety and energy distribution requirements [28].

2.4 Data Collection Techniques

A multi-method approach was used to capture both on-site data and procedural insights. Field data were gathered over a twelve-month period through:

- Structured technical inspections using validated checklists aligned with ISO, NTE INEN and NFPA 58 [29].
- Structured interviews with depot managers and safety officers to understand procedural gaps and risk perceptions [30].
- Document analysis of historical safety reports, regulatory audits, and operational manuals [31].

Data triangulation enhanced the reliability and completeness of the dataset.

2.5 Failure Modes and Effects Analysis (FMEA)

Failure Modes and Effects Analysis (FMEA) was applied to systematically identify, classify, and quantify operational risks across the 50 LPG distribution units [32]. The methodology was used to assess specific failure modes observed in each critical phase of the supply chain, namely transport, storage, handling, and cylinder delivery based on three standard risk dimensions:

- Severity (S): The magnitude of potential damage to personnel, assets, or operational continuity if the failure occurs.
- Occurrence (O): The estimated probability or frequency of the failure taking place under current conditions.
- Detection (D): The probability of detecting the failure before it leads to adverse consequences, considering current monitoring or control measures.

Each of the three parameters was rated on a 10-point scale (1 = best case, 10 = worst case), in accordance with the standard FMEA evaluation matrix. The Risk Priority Number (RPN) was then calculated for each failure mode using the following formula:

$$\mathrm{RPN} = \mathrm{S}\,x\,\mathrm{O}\,x\,D \qquad (1)$$

Where:

- S = Severity score
- O = Occurrence score
- D = Detection score

The resulting RPN values range from 1 (low priority) to 1000 (critical priority). For each operational unit, the highest individual RPN was selected as a representative indicator of risk exposure [33]. This value was used to classify units into performance-risk quadrants when correlated with KPI scores [34].

Failure modes with RPN values exceeding 150 were classified as high priority, consistent with commonly adopted thresholds in hazardous materials logistics, and were targeted for immediate corrective actions [35]. This scoring framework enabled technical prioritization of mitigation strategies and informed the proposed improvement roadmap [36].

2.6 Key Performance Indicators (KPIs)

A structured and replicable set of Key Performance Indicators (KPIs) was defined to quantitatively assess both regulatory compliance and operational efficiency across the 50 LPG distribution units [37]. These KPIs were aligned with national safety standards (NTE INEN 1534:2015, 1535:1998, 1536:1998) and international references such as NFPA 58 and ISO 45001. The selected indicators included:

- Compliance with safety protocols (%) – Percentage of required safety procedures implemented at the unit level based on a standardized checklist.
- Personnel training coverage (%) – Proportion of operational staff who received formal safety and handling training within the evaluation period.
- Cylinder inspection rate (%) – Percentage of LPG cylinders inspected for defects prior to customer dispatch.
- Availability of safety signage (%) – Presence of mandatory warning, zoning, and procedural signs as per technical requirements.
- Monthly incident rate – Number of operational incidents normalized per 10,000 transactions or dispatch operations.

To enable cross-comparison between units, a Composite KPI Score was calculated per depot as the arithmetic mean of the four compliance indicators (excluding the incident rate [38], which is inversely related to performance):

$$\text{Composite KPI Score (\%)} = \frac{C_{SP} + C_{TR} + C_{CI} + C_{SS}}{4} \quad (2)$$

Where:

- C_{SP} = Compliance with safety protocols
- C_{TR} = Training coverage
- C_{CI} = Cylinder inspection rate
- C_{SS}= Safety signage availability

Each component is expressed as a percentage score per unit. The composite score enables unit ranking and integration with FMEA-based RPN analysis for combined performance-risk classification [39].

2.7 Data Analysis Strategy

The data collected from each of the 50 LPG distribution units were analyzed in two structured phases:

- Descriptive risk assessment using FMEA, including identification and quantification of failure modes based on their Risk Priority Numbers (RPN) [40].
- Performance benchmarking using defined KPIs, which were normalized and standardized to enable comparative analysis across all units [41].

To synthesize both dimensions a cross-matrix classification model was constructed, placing each unit in a category based on its RPN (risk exposure) and KPI (performance) [42]. Categories included: High Risk/Low Performance, Medium

Risk/Moderate Performance, and Low Risk/High Performance. This allowed a clear prioritization of intervention needs across the distribution network [43].

2.8 Methodological Justification and Replicability

The combined use of FMEA and KPIs, validated against both local and international standards, allows for a dual-layered technical evaluation of safety and logistics. The use of internationally recognized norms ensures that the methodological framework is not only applicable in Ecuador, but also replicable across countries with LPG distribution systems that involve pressurized cylinders [44].

This model can be adapted by energy authorities, safety regulators, and private distributors operating under different national guidelines, if baseline technical equivalence with NFPA, ISO 45001, or equivalent standards exists [45]. The approach thus offers both diagnostic value and strategic applicability for continuous improvement in safety-critical energy logistics environments [46].

2.9 Operational Sensitivity Assessment

To validate the robustness of the results obtained in this study, an operational sensitivity assessment was performed on post-intervention KPI values [47]. In accordance with ISO 9001:2015 and ISO 31000:2018, perturbations of ±3 % and ±5 %, were applied to analyze variations arising from operational variability, human factors, or measurement uncertainty [48]. This assessment evaluated the extent to which such fluctuations could influence the overall improvement trends observed across the LPG distribution units [49].

3. Results

3.1 Overview of Technical Outcomes

This section presents the results obtained from a structured evaluation conducted over a twelve-month period across 50 operational units within Ecuador's LPG cylinder distribution chain. The findings derive from two integrated methodological axes: (i) risk assessment using Failure Modes and Effects Analysis (FMEA) and (ii) performance benchmarking using a defined set of Key Performance Indicators (KPIs). These results are subsequently integrated to generate a comprehensive risk-performance profile across the network, supported by cross-classification and pattern analysis.

3.2 Risk Prioritization via FMEA

To systematically assess and quantify operational risks within Ecuador's LPG cylinder distribution network, a Failure Modes and Effects Analysis (FMEA) was conducted across 50 operational units using field inspection checklist (Appendix C) and structured risk-identification interviews (Appendix D). This methodology enabled the identification of failure modes with the highest potential impact, based on their Risk Priority Number (RPN), detailed descriptions of the supplementary dataset description are available in Appendix A. Table 1 presents the analysis focused on high-risk events with significant implications for safety, operational continuity, and regulatory compliance.

Table 1. Risk Severity and Prevalence in LPG Cylinder Distribution Network

Failure Mode	Process Area	Max RPN	Units Affected (n)	Prevalence (%)	Implication
Unsecured cylinder during transport	Transport/loading	216	29	58.0	High risk of mechanical shock and valve rupture
Lack of safety signage	Depot operation zones	180	24	48.0	Increased probability of unsafe behaviors and misinterpretation of hazards
Absence or misuse of PPE	Handling and maintenance	200	36	72.0	Exposure to chemical hazards, burns, and mechanical injuries
Missed leak detection	Cylinder preparation/delivery	160	20	40.0	Potential undetected gas release at the end-user interface

As illustrated in Figure 1, the most prevalent failure mode corresponds to "Absence or misuse of PPE," representing 72% of observed cases and the highest RPN value of 200.

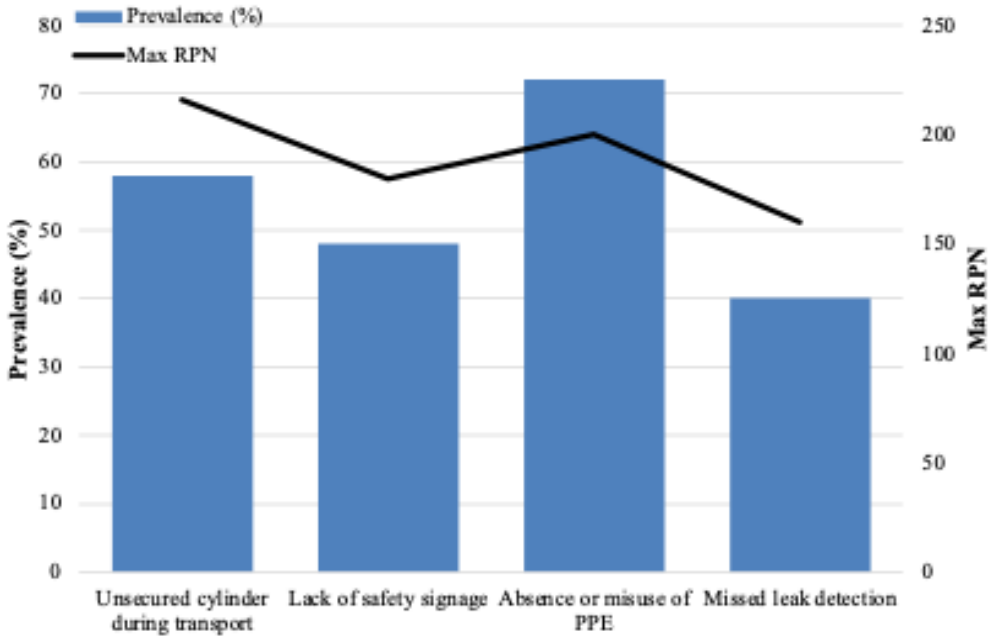


Figure 1. Risk Severity and Prevalence across Failure Modes in LPG Cylinder Distribution Network

The findings confirm that several critical risk factors are not only severe in technical consequence (as reflected in their high RPN values), but also widely distributed across operational sites, indicating systemic procedural deficiencies.

- Unsecured cylinder transport affected 58% of depots and poses severe mechanical and safety hazards. Its widespread occurrence suggests inadequate enforcement of transportation protocols, contrary to NFPA 58 and NTE INEN 1535:1998 requirements.
- Lack of safety signage, observed in 48% of units, directly compromises visual hazard communication. This deficiency contributes to human error, especially in

high-traffic areas, and reflects weak implementation of signaling standards specified under ISO 45001.

- Absence or misuse of PPE in 72% of depots highlights critical gaps in worker protection culture. Despite being a low-cost corrective action, PPE compliance remains inconsistent, underscoring the importance of both policy enforcement and behavioral reinforcement.
- Missed valve leak detection, prevalent in 40% of units representing a direct end-user hazard. This finding suggests that last-mile safety controls are either omitted or poorly standardized, calling for urgent SOP formalization and audit integration under ISO 9001.

These findings demonstrate that high-priority risks are embedded within routine operational activities across the network.

3.3 Performance Analysis via KPIs

To complement the risk analysis, the operational performance of each depot was evaluated through five core KPIs: safety protocol compliance, staff training coverage, cylinder inspection rate, signage availability, and incident frequency (Appendix B). These were aggregated into a composite KPI score, allowing cross-unit comparison. The indicators presented on Table 2 reflect both compliance status and operational maturity relative to national and international safety standards (NFPA 58, ISO 45001, ISO 9001, NTE INEN 1534/1536).

Table 2. Quantitative Performance Analysis of Safety and Compliance in LPG cylinder distribution

KPI Indicator	Average (%)	Operational Units (n)	Technical Interpretation
Safety Protocol Compliance	72.3	50	Partial adherence to technical SOPs across depots; gaps in execution consistency
Staff Training Coverage	75.6	50	Reasonable level of training; not yet fully institutionalized
Cylinder Inspection Rate	71.1	50	Quality control programs underdeveloped; procedural variability persists
Safety Signage Availability	69.4	50	Hazard communication remains suboptimal; visual safety zoning is inconsistently applied
Composite KPI Score	**72.1**	50	General procedural alignment; insufficient for classification as high performing
Incident Rate (per 10k operations)	3.27	50	Moderate frequency of operational incidents; reflects inconsistencies in prevention

The aggregated data highlight a sector-wide pattern of moderate performance, where procedural standards are partially met but lack uniform implementation across facilities. Figure 2 presents the average performance levels across key operational safety and compliance indicators.

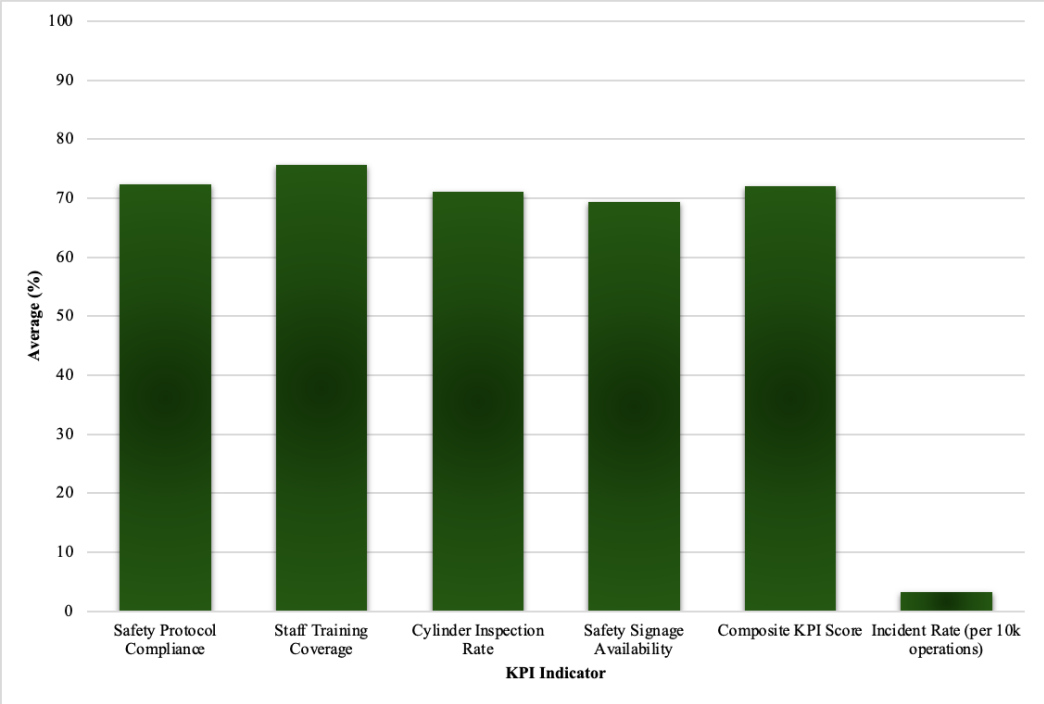


Figure 2. Quantitative Performance Analysis in LPG cylinder distribution

Key technical implications include:

- Safety protocol compliance (72.3%) reveals that written SOPs may exist, but operational enforcement is inconsistent. This affects procedural integrity during loading, storage, and customer delivery.
- Training coverage (75.6%) indicates progress in building workforce capacity; however, it remains dependent on external facilitators, rather than being part of a structured system.
- Cylinder inspection rate (71.1%) underlines the variability in quality control routines, a critical gap given the pressurized and flammable nature of LPG. Failures here directly impact end-user safety.
- Signage availability (69.4%) continues to limit risk visibility, especially in high-flow areas like docks and storerooms, undermining both operational efficiency and emergency preparedness.
- The composite KPI score (72.1%) reflects an incomplete convergence toward safety excellence, indicating the need for standardized implementation, internal audits, and KPI tracking systems.
- Finally, an incident rate of 3.27 per 10,000 operations suggests a persistent operational vulnerability, necessitating preventive action to avoid escalation in injury or material loss.

3.4 Cross-Classification: Risk Exposure vs. Performance

To integrate the diagnostic results, a cross-classification matrix was developed by correlating the maximum Risk Priority Number (RPN) per unit with its corresponding composite Key Performance Indicator (KPI) score (Appendix E). This matrix, presented in Table 3, enables a multidimensional assessment by aligning operational risk exposure with performance effectiveness, allowing the identification of systemic gaps across the

distribution network.

Table 3. Operational Risk-Performance Matrix

Classification Level	RPN Range	KPI Score Range	Number of Units
High risk / Low performance	>180	<65%	0
High risk / Moderate performance	>180	66–85%	10
High risk / High performance	>180	>85%	0
Medium risk / Low performance	130–180	<65%	0
Medium risk / Moderate perf.	130–180	66–85%	34
Low risk / Low performance	<130	<65%	0
Low risk / Moderate performance	<130	66–85%	6
Low risk / High performance	<130	>85%	0

The matrix depicts the interaction between operational risk exposure (RPN) and performance effectiveness (KPI). Figure 3 reveals that the majority of operational units cluster within the Medium Risk / Moderate Performance quadrant, suggesting that the distribution network operates within an improvable, safety margin.

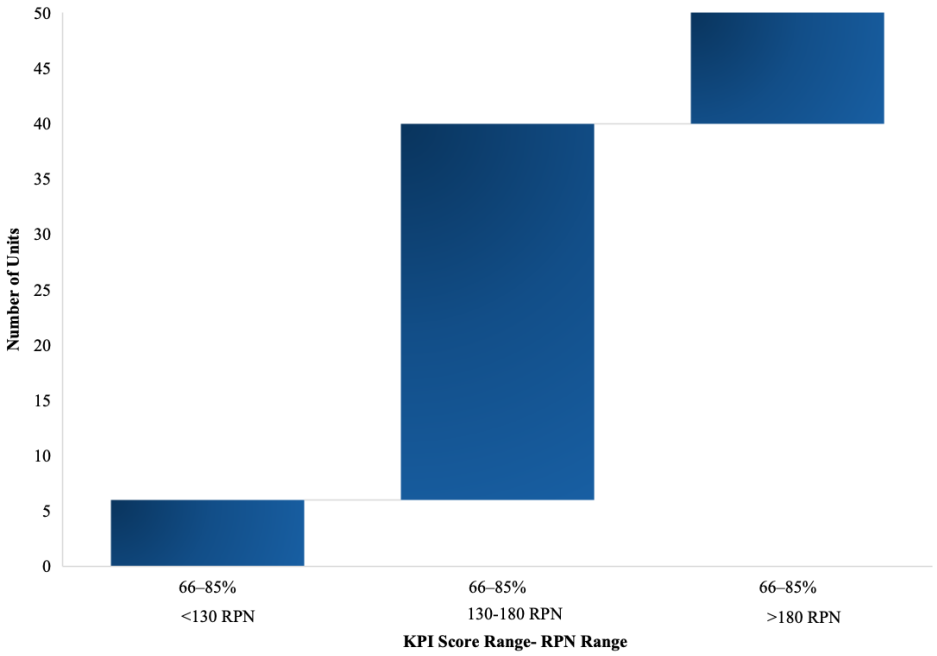


Figure 3. Operational Risk-Performance Matrix for LPG Cylinder Distribution Units.

The results show a pronounced concentration of LPG distribution units within the medium risk / moderate performance category (130 ≤ RPN ≤ 180; 66–85% KPI score), accounting for 34 out of 50 units (68%). This clustering suggests a prevalent operational baseline characterized by acceptable yet suboptimal procedural compliance and moderate risk exposure.

An additional 10 units (20%) were classified under high risk / moderate performance (>180 RPN; 66–85% KPI), indicating notable deficiencies in preventive controls despite fair performance outcomes.

Furthermore, only 6 units (12%) were identified within the low risk / moderate performance class (<130 RPN; 66–85% KPI), highlighting a limited segment operating under both reduced risk and controlled execution.

Overall, the cross-classification matrix reveals an unbalanced risk-performance profile with a dominant trend toward medium operational risk and moderate procedural adherence. These findings emphasize the need for targeted interventions aimed at reducing risk levels and elevating performance standards to transition a greater proportion of units into the high-performance, low-risk quadrant.

3.5 Prioritized Technical Interventions Based on Risk Analysis

To mitigate the most recurrent and severe failure modes identified through FMEA, a set of prioritized technical corrective actions was developed. The actions presented in Table 4, represent target operational weaknesses with high RPN values and are aligned with international standards to ensure systemic applicability across the LPG cylinder distribution network.

Table 4. Risk-Driven Technical Interventions Aligned with International Standards

Action	Justification	Standards Referenced
Mandatory PPE enforcement and audits	Reduces injury severity and legal liability	ISO 45001; NTE INEN 1536:1998
Installation of safety signage	Enhances risk awareness and depot zoning	NFPA 58; ISO 45001
Standardized valve leak detection SOPs	Prevents flammable gas exposure at customer interface	NFPA 58
Biannual staff training	Improves compliance consistency and procedural integrity	ISO 45001; ISO 9001
KPI monitoring dashboard implementation	Enables real-time performance visibility and data-driven audits	ISO 31000; ISO/IEC 31010
Internal depot self-inspection checklist	Promotes proactive hazard identification	Based on FMEA principles

The proposed actions address critical safety and compliance gaps and are aligned with recognized international standards. Emphasis is placed on procedural enforcement, risk signalling, operational training, and KPI-based performance monitoring. Collectively, these measures enhance system reliability, reduce incident probability, and enable continuous improvement through data-driven oversight.

3.6 Documented Improvements Following Risk-Based Interventions

Following the identification of critical operational weaknesses through integrated FMEA and KPI analysis (Appendix F), a set of targeted technical interventions was deployed in alignment with internationally recognized standards (NFPA 58, ISO 45001, ISO 9001, and ISO 31000). Table 5 presents the quantifiable improvements observed after the application of these interventions across selected LPG distribution units.

Table 5. Documented KPI Improvements Following Critical Point Interventions

KPI Indicator	Pre-Intervention Score (%)	Targeted Intervention(s)	Post-Intervention Score (%)	Improvement (%)
Safety Protocol Compliance	72.3	Internal self-inspection checklist; SOPs; KPI dashboard (FMEA-based, NFPA 58)	90.1	**17.8%**
Staff Training Coverage	75.6	Biannual staff training	91.5	**15.9%**
Cylinder Inspection Rate	71.1	Checklist control; staff training; leak SOPs (ISO 9001; NFPA 58)	88.6	**17.5%**
Safety Signage Availability	69.4	Standardized depot signage per risk zones (NFPA 58, ISO 45001)	90.2	**20.8%**
Composite KPI Score	72.1	Combined effect of all interventions	90.1	**18.0%**
Incident Rate (per 10k ops)	3.27	Not scored as %, but recorded reduction via improved PPE, signage & training	2.17	**33.6%**

Substantial improvements were recorded across the comparative performance of key safety and compliance indicators before and after the implementation of risk-based interventions. As shown in Figure 4, the implementation of targeted interventions produced measurable performance gains across all key indicators, demonstrating the tangible benefits of structured risk-based management in the LPG distribution system.

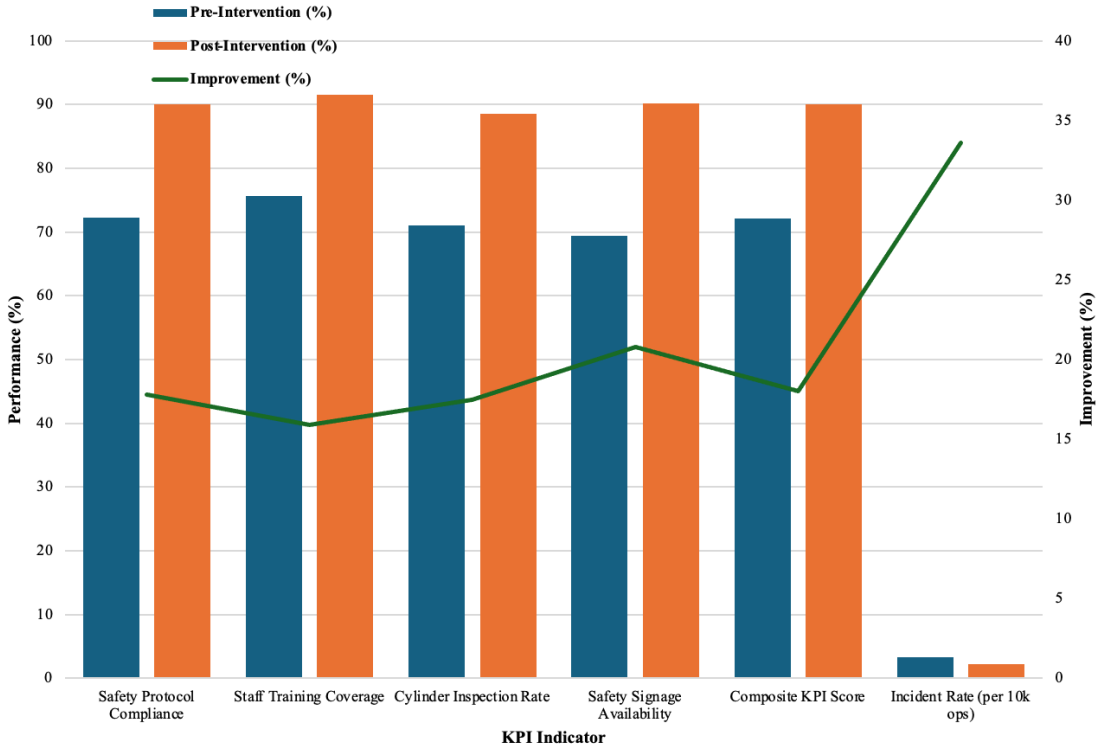


Figure 4. KPI Improvements Pre- vs. Post-Intervention across LPG distribution units.

The observed outcomes can be analytically interpreted to reveal the operational mechanisms driving measurable improvement across all KPI dimensions, as follows:

- Safety Protocol Compliance (72.3 → 90.1%)
  The post-intervention increases of 17.8% indicates the effectiveness of enforcing standardized SOPs and internal checklists derived from NFPA 58. This result represents that procedural adherence improved once accountability mechanisms and KPI tracking were introduced into daily operations.
- Staff Training Coverage (75.6 → 91.5%)
  A 15.9% increase reflects the institutionalization of biannual safety and technical training. The measurable gain demonstrates that workforce competence can be substantially improved when training is integrated into the management system, rather than treated as an isolated activity.
- Cylinder Inspection Rate (71.1 → 88.6%)
  The improvement of 17.5% shows that inspection routines became more consistent after implementing ISO 9001 compliant quality procedures. This outcome directly enhances safety margins by minimizing the probability of leaks or mechanical failures in LPG cylinders.
- Safety Signage Availability (69.4 → 90.2%)
  The 20.8% gain confirms the operational relevance of risk-zoned under NFPA 58 and ISO 45001. Enhanced signage improved hazard awareness and emergency responsiveness, particularly in high traffic storage and loading areas.
- Composite KPI Score (72.1 → 90.1%)
  The improvement of 18% validates the impact of the combined interventions, indicating that integrated procedural standardization, training, and inspection systems create measurable operational conditions.
- Incident Rate (3.27 → 2.17 per 10,000 operations)
  The 33.6% reduction in recorded incidents highlights a safety outcome, attributed to improved PPE usage, standardized signage, and the reinforcement of preventive reporting protocols.

The amount of these results confirm that risk-based interventions significantly enhance operational discipline, procedural integrity, and overall safety performance within LPG distribution environments.

3.7 Operational Sensitivity Assessment of KPI Improvements

An operational sensitivity assessment was conducted on the post-intervention KPI values to validate the robustness and reliability of the results obtained in **Table 5.** This analysis was designed to evaluate the degree to which variations in performance data -arising from operational variability, human factors, or measurement uncertainty- could affect the overall improvement trends observed across the LPG distribution units included in the study (Appendix G).

Figure 5. illustrates the application of controlled perturbations of ±3% and ±5% to KPI improvement scores to analice fluctuations in data acquisition and process execution. These ranges were selected to reflect typical uncertainty margins encountered in field measurements and compliance audits, in alignment with ISO 9001:2015 and ISO 31000:2018 guidance on operational risk variability.

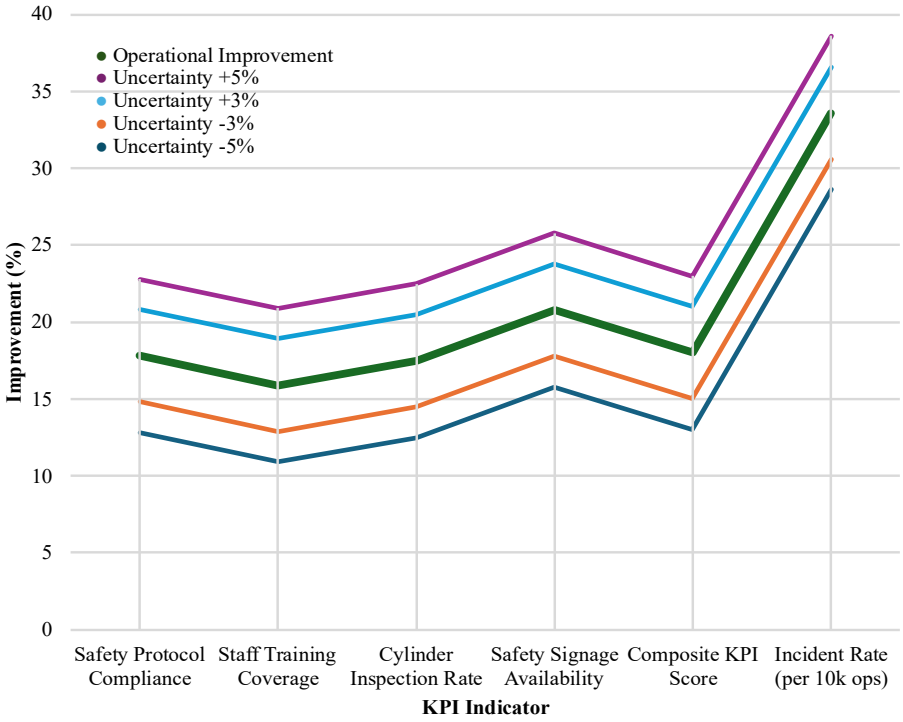


Figure 5. Sensitivity Analysis: KPI Improvement Pre- vs. Post-Intervention across LPG distribution units.

The sensitivity results demonstrate that, even under the most adverse variation scenario (−5%), all KPI improvements remained positive and operationally significant. The Composite KPI Score retained a net gain of +13% over baseline values, confirming the effect of the intervention outcomes to moderate uncertainty. Likewise, Safety Protocol Compliance, Staff Training Coverage, Cylinder Inspection Rate, and Safety Signage Availability maintained post-intervention gains exceeding +10%, while the Incident Rate remained above 28 % underscoring the structural consistency of the implemented safety and quality measures.

Overall, the sensitivity assessment confirms the stability, reproducibility, and robustness of KPI improvements across operational uncertainty margins. All indicators exhibited a consistent linear relationship between the applied perturbations and adjusted improvement rates, with no degradation or inversion of performance rankings below pre-intervention levels. These results reinforce the model's applicability and reliability for replication across diverse operational environments.

4. Discussion

The technical evaluation conducted through the integration of FMEA and KPI-based diagnostics provides a comprehensive risk-performance landscape of Ecuador's LPG cylinder distribution sector. The observed results yield significant insights not only for national policy implementation and depot-level corrective strategies, but also for the design of scalable safety management systems applicable in comparable international contexts.

4.1 Interpretation of Operational Risk (FMEA)

The FMEA results expose critical operational deficiencies in the LPG cylinder distribution chain. The most severe failure modes: unsecured cylinders during transport (RPN 216; 58.0%), improper use or absence of PPE (RPN 200; 72.0%), and insufficient safety signage (RPN 180; 48.0%), reflect elevated technical risk associated with systemic compliance gaps. These conditions contravene key regulatory frameworks such as NTE INEN 1535:1998, NFPA 58, and ISO 45001, which mandate physical containment, hazard identification, and occupational safety controls.

The recurring nature of these failures, particularly those with high prevalence, suggests structural deficiencies in safety culture, supervision, and procedural standardization. FMEA proved instrumental in disaggregating risk by process area and unit, allowing prioritization based on severity, occurrence, and detectability. This enables informed corrective actions and provides a replicable methodology for private operators and government regulatory entities of LPG distribution worldwide.

4.2 Analysis of Performance Metrics (KPIs)

The KPI assessment offers critical insight by quantifying adherence to safety protocols in areas such as training, inspections, compliance, and incident management. The composite average of 72.1% indicates moderate alignment with procedural standards but remains below thresholds expected in high-reliability operations. Notable deficiencies in safety signage (69.4%) and cylinder inspection coverage (71.1%) point to persistent infrastructural and procedural limitations.

While training coverage (75.6%) is relatively strong, the absence of formal certification undermines skill standardization and traceability. The incident frequency rate (3.27 per 10,000 operations) exposes residual risks, including gas leaks, pressurization failures, and valve damage. These variabilities reflect inconsistent application of preventive controls across depots.

The results indicate that regulatory frameworks alone may be insufficient to ensure consistent operational safety, as guided by ISO/IEC 31010 and ISO 9001, embedding continuous improvement mechanisms into daily operations.

4.3 Cross-Correlation and Strategic Implications

The intersection between risk exposure (RPN) and performance levels (KPIs), reveals critical insights for strategic resource deployment. The dominance of units in the medium-risk/moderate-performance quadrant indicates a system-wide need for both procedural enhancement and investment in technical training. This scenario supports the prioritization of integrated safety–performance management interventions, driven by quantifiable KPIs and dynamic risk dashboards with FMEA.

Furthermore, the cross-classification model used here can be adapted across diverse regulatory systems and geographies by substituting local compliance references with equivalent international standards. The methodological foundation thus enables its adaptation without compromising technical rigor.

4.4 Performance Gains Following Risk-Aligned Interventions: Quantitative Outcomes

The quantitative improvements observed across all evaluated KPIs following the targeted

interventions, driven by FMEA-derived risk identification and KPI-based prioritization, confirm a measurable enhancement in operational safety and compliance performance. Safety protocol adherence increased from 72.3% to 90.1%, staff training coverage from 75.6% to 91.5%, and cylinder inspection rate from 71.1% to 88.6%, while signage availability rose from 69.4% to 90.2% under NFPA 58-compliant implementation. The composite KPI score advanced from 72.1% to 90.1%, evidencing the cumulative efficacy of the integrated measures. Additionally, the incident rate decreased from 3.27 to 2.17 per 10,000 operations, representing a 33.6% reduction.

An operational sensitivity assessment, applying ±3% and ±5% data perturbations under ISO 9001:2015 and ISO 31000:2018, confirmed the persistence of these improvements under uncertainty. Even in the most adverse scenario, all indicators maintained positive margins, with the composite KPI preserving a +13% gain over baseline. These improvements suggest that risk-aligned prioritization enables more efficient allocation of corrective resources compared to non-targeted compliance approaches.

4.5 Structural Scope, Transferability, and Strategic Research Pathways

The proposed model exhibits strong transferability to global LPG logistics systems due to its modular integration of FMEA and KPI analytics under ISO 31000, ISO 9001, and NFPA 58. Its adaptable architecture supports localization without compromising methodological rigor. It establishes a robust foundation for potential integration with advanced digital technologies [50]. Such integration could support the development of a scalable and intelligent system for predictive risk monitoring, real-time operational diagnostics, and risk-informed decision-making in complex LPG distribution networks [51]. This positions the model as a strategic tool for international deployment and a catalyst for future research in safety-critical energy distribution systems.

4.6 Critical Analysis and Comparative Discussion

The findings of this study reveal a systematic underperformance across multiple LPG distribution units in Ecuador, particularly in safety compliance, procedural rigour, and adherence to established norms such as NFPA 58, ISO 9001:2015 and ISO/IEC 31010:2019, these results validate and extend patterns previously observed in African contexts. For instance, Naybuto et al. (2020) reported that over 71% of LPG retail sites in Kenya failed on employ Occupational Safety and Health practices in their operations [52]. In contrast, the initial assessment conducted in this study revealed a 72.1% compliance rate with OSH-related indicators in the Ecuadorian context, indicating a relatively more structured, though still incomplete, regulatory adherence.

Moreover, the omission of leak testing prior to dispatch identified as one of the Risk Priority Numbers (RPN) in this study has not been significantly addressed in earlier regional analyses, such as those by Li & Zhou (2014), which focused more the safety management of urban gas transmission and distribution system [53], or Venegas et al. (2024) who gives a perspective from international regulations on LPG systems [54]. This discrepancy suggests a divergence in the operational priorities of different international contexts and highlights a different branch of study that has been overlooked in prior literature.

From a global perspective, recent studies in Asia, Yongkui et al. (2018) [55] and Africa, Kitimbo et al. (2025) [56]; have demonstrated that incorporating structured risk assessment tools like FMEA and KPI dashboards results in a measurable reduction in

incident frequency particularly in our case when combined with ISO 45001 aligned training programmes.

Furthermore, the cross-classification of performance and risk introduced in this study as a diagnostic matrix, aligns with multi-dimensional maturity models proposed in industrial process safety literature Gallab et al. (2017) [1]. However, no previous studies have employed this framework in LPG distribution systems, making this contribution a novel and potentially replicable approach for the sector.

Finally, the proposed corrective actions, fully aligned with international standards, were validated through the operational sensitivity assessment, confirming their effectiveness, methodological consistency, reproducibility and their potential applicability in other operational contexts. Comparable studies in Indonesia Sutanto et al. (2020) [5] and India Gabhane & Kanidarapu (2023) [6]. though lacking a formal sensitivity analysis, likewise, demonstrate that mandatory safety training and autonomous checklists sustain KPI improvements. These findings reinforce the technical validity and global relevance of the risk-aligned management framework proposed in this study.

4.7 Transferability, Technical Validation, and Strategic Implications

The results confirm that the proposed framework, integrating Failure Modes and Effects Analysis (FMEA) with KPI-based performance assessment, provides a technically robust and transferable approach for managing operational risk in LPG cylinder distribution systems. Grounded in internationally recognized standards (ISO 31000, ISO/IEC 31010, ISO 9001, ISO 45001, and NFPA 58), the framework balances methodological rigor with contextual adaptability, enabling its application across heterogeneous regulatory and infrastructural settings.

The empirical validation conducted across 50 LPG distribution depots in Ecuador demonstrates the feasibility of combining structured risk analytics with performance-based monitoring to support systematic safety improvement. The modular configuration of the model, comprising FMEA matrices, KPI dashboards, SOPs, and internal audit mechanisms, was implemented within a Plan–Do–Check–Act (PDCA) cycle, facilitating risk prioritization, corrective action planning, and continuous performance control. The inclusion of an operational sensitivity assessment further strengthens the technical validation, confirming the stability of post-intervention improvements under realistic uncertainty conditions.

Beyond the national context, the framework exhibits strong transferability to countries with decentralized LPG distribution networks, uneven regulatory enforcement, or limited institutional capacity. Customization of severity scales, KPI thresholds, and audit criteria can be achieved without compromising analytical consistency, in accordance with ISO 31000 principles for risk-informed decision-making in complex socio-technical systems. This flexibility positions the model as a practical governance tool rather than a context-specific compliance exercise.

To support this international applicability, Table 6 presents a strategic projection of the framework's replicability across selected regions with high LPG dependency, including Latin America, South Asia, and Sub-Saharan Africa. The assessment considers logistical structure, regulatory maturity, and implementation readiness, indicating high replication potential in settings such as Peru, India, and China, while identifying targeted adaptation requirements in environments characterized by informal markets or fragmented oversight.

Table 6 Strategic Projection for International Replicability of the LPG Cylinder Safety and Quality Management Model

Country/Region	Operational Context	Replicability Potential	Key Adaptation Requirements
Peru	Decentralized LPG supply chain; high domestic consumption; partial regulatory enforcement	**High**	Normative alignment; translation of technical documentation
Bolivia	Informal distribution channels; limited data traceability; low institutional capacity	**High**	Comprehensive technical training; introduction of audit mechanisms
India	Rural LPG dependency; geographically dispersed logistics; existing quality frameworks	**High**	Integration with national quality management infrastructure
Nigeria	Urban-focused distribution; deficient logistics governance; regulatory gaps	**Medium–High**	Digitalization of operational data; establishment of oversight bodies
Bangladesh	Absence of unified technical standards; high safety risks in informal markets	**Medium**	Regulatory reinforcement; capacity building and risk-based audit protocols
Kenya	Expanding LPG market; regulatory fragmentation; growing urban-rural demand	**Medium–High**	Institutionalization of SOPs; KPI integration; workforce training programs
China	Diverse LPG supply models; strong national regulation in industrial zones; rural gaps remain	**High**	Model adaptation to regional governance structures; harmonization with existing digital systems

From a governance perspective, the integration of FMEA-based risk prioritization with KPI-driven monitoring enhances operational traceability, enables risk-based benchmarking, and supports evidence-informed decision-making for both regulators and operators. The Ecuadorian case provides empirical evidence of measurable improvements in depot maturity, operational safety, and process control, demonstrating that the framework operates not only as a diagnostic tool but also as a structured and performance-oriented safety management system.

Overall, the proposed model constitutes a technically validated and exportable risk–performance management framework for LPG logistics. By systematically integrating standardized risk assessment with measurable operational performance within an internationally aligned governance structure, it delivers a scalable and policy-relevant approach to strengthening safety management in hazardous materials distribution. Its alignment with key Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 9 (Industry, Innovation and Infrastructure), reinforces its relevance for emerging and developing economies. The model thus stands as an evidence-based and transferable management system capable of enhancing the structural integrity, safety performance, and regulatory coherence of LPG distribution operations under diverse and challenging conditions.

4.8 Contributions to Petroleum Industry and Operational Implications

This study advances the current understanding of operational risk management in LPG cylinder distribution by demonstrating the technical feasibility of integrating FMEA-based diagnostics with KPI-driven performance monitoring within an ISO-aligned governance framework. Unlike previous works focused primarily on qualitative hazard identification or compliance auditing, this research establishes a quantitative, standards-oriented validation model that directly connects risk mitigation actions to measurable

operational performance outcomes. Furthermore, the incorporation of an operational sensitivity analysis provides a structured mechanism to verify the robustness and consistency of post-intervention improvements under different uncertainty conditions, an element rarely addressed in existing risk frameworks. Collectively, these contributions reinforce the technical foundation for risk-aligned management systems in hazardous materials logistics, strengthening their replicability, scalability, and standardization across regulatory frameworks, industrial operations, and LPG supply-chain structure in emerging economies.

5. Conclusions

1. The integration of FMEA-based diagnostics with KPI-driven monitoring under an ISO-aligned operational framework demonstrated measurable improvements in process safety, efficiency, and regulatory compliance within the LPG downstream supply chain, establishing a robust baseline for empirical validation in hazardous materials logistics.
2. Quantitative evidence confirmed substantial performance gains, highlighted by a 33.6% reduction in the operational incident rate (from 3.27 to 2.17 per 10,000 operations) and post-intervention KPI increases exceeding 15% across all core metrics (including protocol compliance, training coverage, and cylinder inspection rates), validating the operational efficacy of the implemented management measures.
3. The operational sensitivity assessment, applying ±3% and ±5% uncertainty margins, verified the robustness, stability, and reproducibility of all KPI improvements, ensuring high confidence in the model's reliability and performance consistency under real-world operational variability and data disruptions.
4. The proposed framework establishes a scalable and replicable operational model for hazardous material distribution, offering a practical foundation for process standardization and the future integration of digital, data-driven performance management tools in resource-constrained environments. Future research should focus on integrating real-time telemetry (IoT) and machine learning algorithms into the KPI architecture to mitigate this subjectivity and transition the system into an automated, predictive performance management tool.
5. The dual-layered evaluation model combining RPN prioritization and KPI benchmarking proved to be an adaptable and technically sound framework with high potential for scalability in other emerging markets facing similar logistical, infrastructural, and regulatory constraints.

Abbreviations

LPG	Liquefied Petroleum Gas
FMEA	Failure Modes and Effects Analysis
RPN	Risk Priority Number
KPI	Key Performance Indicators
NTE INEN	Ecuadorian Technical Standards published by the Ecuadorian Standardization Service
NFPA	National Fire Protection Association
ISO	International Organization for Standardization
IEC	International Electrotechnical Commission
PPE	Personal Protective Equipment

SOP	Standard Operating Procedure
PDCA	Plan–Do–Check–Act
SDG 7	Affordable and Clean Energy
SDG 8	Decent Work and Economic Growth
SDG 9	Industry, Innovation and Infrastructure
OSH	Occupational Safety and Health

Declarations

Availability of data and materials
All data supporting the findings of this study are presented within the article and its appendices. Additional datasets or detailed information are available from the corresponding author upon reasonable request.

Declaration of competing interests
The author declares that he has not competing interests.

Consent to Publish declaration
Not applicable.

Consent to Participate declaration
Not applicable.

Ethics declaration
Not applicable

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Authors' contributions
Israel Alejandro Murillo-Calderon, is responsible for the conception, design, and execution of the study, including the development of the methodological framework, field data collection, analysis of risk and performance indicators, and interpretation of the results. The author also drafted and critically revised all sections of the manuscript, ensured compliance with international technical standards, and prepared the final version for submission. All research activities, including the elaboration of appendices and tables, were independently carried out by the author. The author has read and approved the final manuscript**.**

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