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Research Paper

A Delphi-FMEA Framework for Proactive Risk Assessment in Smart Electrical Distribution Networks

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Abstract: The adoption of smart grid technologies has improved the efficiency and reliability of electrical distribution systems; however, it has also introduced new operational, environmental, and safety risks that require proactive management. This study aims to develop and implement a Delphi-FMEA framework for risk assessment in the smart electrical distribution network of PT PLN Tello Sector. Data were collected through three Delphi rounds involving eight experts with 16-22 years of professional experience in electrical distribution, maintenance, operations, reliability engineering, and SCADA systems. The Delphi method was used to achieve expert consensus on potential risks, while FMEA was applied to evaluate risk severity, occurrence, and detection, yielding Risk Priority Number (RPN) values for prioritization. The analysis identified 30 potential risks across four main components: network (23%), facilities (23%), inventory (27%), and planning (27%). The most critical risks were inadequate protection against extreme weather conditions (RPN = 270), falls from height due to insufficient safety measures (RPN = 200), and electrical shock during maintenance activities (RPN = 180). Pareto analysis showed that the five highest-priority risks accounted for approximately 44% of the total risk exposure. Root cause analysis revealed that human-related factors accounted for 30% of critical risk causes, followed by equipment (25%), methods (20%), environment (15%), and technology and communication factors (10%). The findings indicate that the Delphi-FMEA framework provides an effective and systematic approach for proactive risk identification and prioritization, supporting improved decision-making, system reliability, operational resilience, and sustainable risk management in smart electrical distribution networks.

Keywords: Delphi Method, Failure Mode and Effects Analysis, Smart Electrical Distribution Network, Risk Assessment, Risk Priority Number.

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1. Introduction

The rapid development of smart grid technologies and the increasing demand for electricity have significantly transformed modern electrical distribution systems, creating new challenges related to reliability, safety, and operational resilience [1], [2], [3]. In Indonesia, electricity consumption continues to increase by approximately 4-6 % annually due to population growth, urbanization, and industrial expansion, requiring electrical utilities to strengthen the reliability of distribution infrastructure and service continuity [4], [5]. As the national electricity provider, PT PLN is responsible for maintaining a resilient electrical distribution network while simultaneously adapting to technological advancements and digital transformation initiatives [6]. The implementation of Supervisory Control and Data Acquisition (SCADA), intelligent sensors, automated monitoring systems, and real-time communication technologies has substantially improved operational visibility and decision-making efficiency within modern smart distribution networks [7]. However, the increasing complexity and interconnectivity of these systems have also introduced new technical, operational, environmental,

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and cybersecurity risks that may significantly affect distribution reliability and system performance [2], [8].

Electrical distribution networks are exposed to various risk factors that can disrupt operational performance and service quality, including equipment failures, communication interruptions, environmental disturbances, cyberattacks, and human-related errors [9], [10], [11]. Previous studies reported that equipment-related failures contribute approximately 30-40 % of distribution interruptions, while environmental factors account for nearly 20-30% of outage events [12]. In addition, human errors and operational inefficiencies contribute approximately 10-15 % of system disruptions, directly affecting reliability indicators such as the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) [13]. Consequently, proactive risk identification and management have become strategic priorities for utility operators aiming to improve system reliability, operational continuity, and safety performance within smart electrical distribution environments [14].

The transition toward smart electrical distribution networks has created a highly interconnected and data-driven operational environment that integrates digital communication technologies, intelligent devices, and automated control systems [15]. Globally, more than 60 % of utility companies have adopted smart grid technologies to improve operational efficiency, reliability, and energy management capabilities [16]. Despite these advantages, increased digitalization also introduces new vulnerabilities, including communication failures, data integrity issues, false data injection attacks, software malfunctions, and cybersecurity threats that are often difficult to detect using conventional risk management approaches [17]. These emerging risks involve complex interactions between cyber and physical infrastructures, requiring more advanced and systematic risk assessment methodologies capable of evaluating multidimensional risk scenarios [18].

Traditional risk assessment approaches in electrical distribution systems primarily rely on historical failure records and corrective maintenance strategies, making them largely reactive rather than preventive [19], [20]. Although such approaches remain useful for evaluating known failure events, they often fail to identify emerging risks associated with increasingly complex cyber-physical smart grid infrastructures [2], [21], [22]. Therefore, there is a growing need for proactive risk assessment frameworks capable of systematically identifying, evaluating, and prioritizing potential risks before significant failures occur [23], [24]. Among the methods widely recognized for addressing uncertainty and supporting complex engineering decision-making are the Delphi Method and Failure Mode and Effects Analysis (FMEA). The Delphi Method facilitates structured expert consensus through iterative evaluations, while FMEA systematically assesses failure severity, occurrence probability, and detection capability through Risk Priority Number (RPN) calculations [19], [25]. The integration of these approaches offers a comprehensive framework that combines expert knowledge with quantitative risk prioritization, enabling more effective risk management within smart electrical distribution networks.

Despite the increasing implementation of smart grid technologies, studies integrating Delphi and FMEA for proactive risk assessment in smart electrical distribution systems remain relatively limited, particularly in developing countries [26]. Existing studies generally focus on either expert-based risk identification or quantitative risk prioritization without establishing an integrated framework capable of addressing both known and emerging risks [19], [20]. Consequently, a research gap remains in developing comprehensive methodologies that support systematic risk identification, validation, prioritization, and mitigation planning within smart electrical distribution environments [19], [27]. This study addresses that gap by proposing an integrated Delphi-FMEA framework that combines structured expert judgment with quantitative risk analysis to improve proactive risk management and decision-making processes [28], [29], [30].

This study aims to develop and implement a Delphi-FMEA framework for proactive risk assessment within the smart electrical distribution network at PT PLN Tello Sector. The proposed framework seeks to identify potential risks through expert consensus, evaluate their criticality using FMEA, and prioritize mitigation strategies based on Risk Priority Number values [19], [27]. By integrating qualitative expert knowledge with quantitative risk assessment techniques, the framework is expected to enhance decision-making effectiveness, improve system reliability, strengthen operational resilience, and support sustainable risk management practices within smart electrical distribution systems.

2. Research and Methodology

2.1 Materials

This study employs an integrated Delphi–FMEA framework to conduct proactive risk assessment in a smart electrical distribution network at PT PLN Tello Sector. Data were collected from 8 experts selected through purposive sampling, consisting of two Senior Distribution Engineers, two Maintenance Supervisors, two Operations Managers, one SCADA Specialist, and one Reliability Engineer, with professional experience ranging from 16 to 22 years. Primary data were obtained through multiple Delphi rounds using structured questionnaires, while secondary data were gathered from maintenance records, outage reports, and operational documents [27], [28]. The collected data were systematically analyzed to identify, evaluate, and prioritize potential risks affecting the reliability and performance of the smart electrical distribution system.

2.2 Experiments

The research framework consists of two integrated stages. The first stage applies the Delphi Method to identify and validate potential risks within the smart electrical distribution network. The second stage utilizes FMEA to evaluate and prioritize the identified risks. In the first Delphi round, experts independently identified potential risks associated with electrical distribution operations, including technical, operational, environmental, communication, and cybersecurity risks. During subsequent rounds, experts reviewed, refined, and reassessed the identified risks until a consensus was achieved [19]. The average score of each risk variable was calculated using the arithmetic mean:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (1)$$

where:

$\bar{x}$= mean expert score
x_i= score assigned by expert i
n= number of experts

The level of consensus among experts was measured using the standard deviation:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (2)$$

where:

σ= standard deviation

A smaller standard deviation indicates stronger agreement among experts. Consensus was considered achieved when the coefficient of variation (CV) was less than 20%.

$$CV = \frac{\sigma}{\bar{x}} \times 100\% \tag{3}$$

The Delphi process continued until stability and convergence of expert opinions were reached. After consensus was achieved, the validated risk factors were analyzed using FMEA. Each identified risk was evaluated according to three criteria: Severity (S), Occurrence (O), and Detection (D). Each criterion was assessed on a scale from 1 to 10 using expert judgment. The Risk Priority Number (RPN) was calculated as:

$$RPN = S \times O \times D \tag{4}$$

Higher RPN values indicate higher-priority risks requiring immediate mitigation actions.

2.3 Product characterization

The final stage involved characterizing and prioritizing risks based on Delphi consensus results and FMEA analysis. Risks were ranked according to their RPN values to identify critical risk categories within the smart electrical distribution network. To determine the relative contribution of each risk category, the Risk Priority Index (RPI) was calculated:

$$RPI = \frac{RPN_i}{\sum_{i=1}^{n} RP\,N_i} \times 100\% \tag{5}$$

where:
RPN_i= Risk Priority Number of risk i
$\sum RPN_i$= Total Risk Priority Numbers

The resulting RPI values were used to classify risks into high, medium, and low-priority categories. High-priority risks were subsequently analyzed to develop mitigation strategies to improve system reliability, operational resilience, and service continuity in the smart electrical distribution network. The overall Delphi-FMEA framework enables systematic identification, assessment, and prioritization of both existing and emerging risks in smart electrical distribution systems [25], [27]. This integrated approach supports proactive decision-making and provides a structured basis for enhancing the reliability and sustainability of electrical distribution operations.

3. Results and Discussion

3.1 Risk Identification in Smart Electrical Distribution Networks Using the Delphi Method

The first stage of the Delphi process was conducted to systematically identify potential risks affecting the performance, reliability, and safety of the smart electrical distribution network at PT PLN Tello Sector. Through three Delphi rounds involving eight experts, 30 risk variables were identified and categorized into four key components: network, facilities, inventory, and planning. The identified risks are potential threats arising from technical failures, operational activities, workplace safety, environmental conditions, and human factors that may affect the continuity and effectiveness of electrical distribution services [13], [14], [20].

Table 1. Identified Risk Variables in Smart Electrical Distribution Networks

Component	Number of Risks	Percentage (%)	Identified Risk Variables
Network	7	23	Loose cable supports, electric shock to the public, fire from electrical sparks, electromagnetic radiation exposure, equipment failure, maintenance-related electric shock, poor network insulation
Facilities	7	23	Poor workplace design, exposure to extreme weather, inadequate dust control, unsafe public access, injuries from heavy equipment, hazardous chemical exposure, noise-induced hearing loss
Inventory	8	27	Hands caught in machinery, burns from hot tools, non-ergonomic posture injuries, bearing heating burns, falling materials, improper lifting injuries, skin diseases from PPE, injuries from heavy tools
Planning	8	27	Lack of operator training, incorrect machine settings, poor ergonomic planning, dehydration-related fatigue, falls from height, operational setting errors, excessive working hours, inadequate supervision
Total	30	100	Identified risk variables from Delphi Round 1–3

Based on Table 1, the Delphi process identified 30 potential risks distributed across four major components of the smart electrical distribution system. The planning and inventory categories contributed the largest share of risks, each accounting for 27 % (8 risks), followed by network and facilities, each at 23 % (7 risks). Network-related risks were primarily associated with electrical hazards, including electric shock and fire incidents, which accounted for more than 60% of identified network risks [11], [12], [28]. Within the facilities component, environmental and ergonomic issues accounted for nearly 50 % of the identified risks. Inventory risks were largely dominated by mechanical and material-handling hazards, which accounted for approximately 65 % of potential injuries [10]. Furthermore, planning-related risks revealed that human factors, including insufficient training, fatigue, and inadequate supervision, represented more than 70 % of potential operational failures [7]. These findings demonstrate that both technical and human factors play critical roles in shaping the safety, reliability, and resilience of smart electrical distribution networks [5], [6], [19].

3.2 Expert Consensus Analysis in the Delphi Process

The second stage of the Delphi process was conducted to evaluate the level of expert agreement regarding the identified risks in the smart electrical distribution network. Consensus analysis was performed using statistical measures, including the mean, standard deviation (SD), and coefficient of variation (CV), to assess the importance and consistency of expert judgments. Risks with high mean values and low variability were considered valid and suitable for further prioritization using the FMEA framework. The results provide a quantitative basis for validating critical risks affecting system reliability and operational performance.

Table 2. Expert Consensus Results from the Delphi Process

Code	Potential Risk	Mean	SD	CV (%)	Consensus Level
1	Loose cable supports causing injuries and explosions	2.33	0.60	25.75	Moderate
2	Electric shock to people in surrounding areas	1.33	0.60	45.11	Low
3	Fire caused by sparks in distribution networks	3.33	1.20	36.04	Moderate
4	Workers exposed to electric shock during maintenance	4.33	0.60	13.86	High
5	Lack of protection from extreme weather conditions	4.76	0.60	12.61	High
6	Poor workplace design causing musculoskeletal injuries	4.67	1.20	25.70	Moderate
7	Unsafe public access to hazardous areas	1.33	0.60	45.11	Low
8	Hearing impairment due to equipment noise	2.33	1.20	51.50	Low
9	Feet injured by heavy equipment handling	2.67	0.60	22.47	Moderate
10	Burns from hot tools or materials	2.67	0.60	22.47	Moderate
11	Severe hand burns or injuries	2.33	1.20	51.50	Low
12	Hands caught in moving machinery	3.00	1.00	33.33	Moderate
13	Lack of operator training	2.33	0.50	21.46	Moderate
14	Incorrect machine parameter settings	1.67	0.60	35.93	Moderate
15	Worker fatigue due to poor preparation	3.00	1.20	40.00	Moderate
16	Falls from height due to inadequate safety measures	3.34	1.21	36.14	Moderate

Based on Table 2, the Delphi consensus analysis indicates that risk code 5, related to insufficient protection from extreme weather conditions, achieved the highest mean score of 4.76 with a low standard deviation of 0.60 and a CV of 12.61 %, demonstrating strong expert agreement regarding its criticality. Risk code 4 (electrical shock during maintenance activities) and risk code 6 (poor workplace design) followed with mean scores of 4.33 and 4.67, respectively. Conversely, risk codes 2 and 7 recorded the lowest mean values of 1.33, indicating relatively low perceived importance among experts. Overall, most standard deviation values ranged between 0.50 and 1.20, suggesting acceptable consistency across expert evaluations. Approximately 60 % of the identified risks were classified as moderate-to-high importance categories, confirming their relevance for subsequent prioritization and mitigation analysis. These findings are consistent with previous studies demonstrating that Delphi-based consensus methods effectively improve risk identification reliability and support decision-making in complex engineering systems [19], [20], [25], [27].

3.3 Risk Assessment Using the FMEA Method

Following the Delphi consensus process, the identified risks were evaluated using Failure Mode and Effects Analysis (FMEA) to determine their relative criticality within the smart electrical distribution network. Each risk was assessed based on Severity (S), Occurrence (O), and Detection (D) scores. The resulting Risk Priority Number (RPN) was used to prioritize risks requiring immediate mitigation and management attention.

Table 3. FMEA Risk Assessment Results

Code	Severity (S)	Occurrence (O)	Detection (D)	RPN
1	6	4	5	120
2	4	2	4	32
3	8	4	5	160
4	9	5	4	180
5	9	6	5	270
6	8	5	4	160
7	4	2	4	32
8	5	4	4	80
9	6	4	4	96
10	6	4	4	96
11	7	4	5	140
12	7	5	4	140
13	6	4	5	120
14	5	3	4	60
15	7	4	4	112
16	8	5	5	200

Based on Table 3, the FMEA assessment identified risk code 5 as the most critical risk with the highest RPN value of 270, resulting from a severity score of 9, occurrence score of 6, and detection score of 5. This was followed by risk code 16 with an RPN of 200 and risk code 4 with an RPN of 180. Risks coded 3 and 6 each recorded an RPN of 160, indicating significant impacts on system reliability and safety. Conversely, risks coded 2 and 7 had the lowest RPN values of 32. Overall, five risks (31.25%) exhibited RPN values above 150, highlighting the need for immediate mitigation and proactive risk management strategies within the smart electrical distribution network [19], [20], [25], [27].

3.4 Risk Prioritization Based on Risk Priority Number (RPN)

Following the FMEA assessment, risk prioritization was conducted using the Risk Priority Number (RPN) to identify the most critical risks within the smart electrical distribution network. Risks with higher RPN values indicate greater potential impacts on system reliability, operational continuity, and worker safety. This ranking process enables decision-makers to focus mitigation efforts on the most significant risks and allocate resources more effectively. The prioritized risks provide a foundation for developing proactive risk management strategies and improving the resilience of the electrical distribution system.

Table 4. Risk Ranking Based on Risk Priority Number (RPN)

Rank	Code	RPN	Priority Level
1	5	270	Very High
2	16	200	High
3	4	180	High
4	3	160	High
5	6	160	High
6	11	140	Medium
7	12	140	Medium
8	1	120	Medium
9	13	120	Medium
10	15	112	Medium

Rank	Code	RPN	Priority Level
11	9	96	Medium
12	10	96	Medium
13	8	80	Medium
14	14	60	Medium
15	2	32	Low
16	7	32	Low

Based on Table 4, the risk ranking results indicate that risk code 5, related to inadequate protection from extreme weather conditions, obtained the highest RPN value of 270 and was classified as the most critical risk within the smart electrical distribution network. This was followed by risk code 16 (falls from height due to inadequate safety measures), with an RPN of 200, and risk code 4 (electrical shock during maintenance activities), with an RPN of 180. Furthermore, risk codes 3 and 6 each recorded an RPN of 160, highlighting significant concerns regarding fire incidents and poor workplace design. The five highest-ranked risks collectively account for approximately 44% of the total cumulative RPN, demonstrating that a limited number of risks contribute disproportionately to the system's overall vulnerability. Conversely, risk codes 2 and 7 exhibited the lowest RPN values of 32, indicating relatively lower priority levels [18], [19], [20]. To further visualize the distribution and cumulative contribution of these prioritized risks, a Pareto diagram is presented in Figure 1, illustrating the critical risks that require immediate mitigation and management attention.

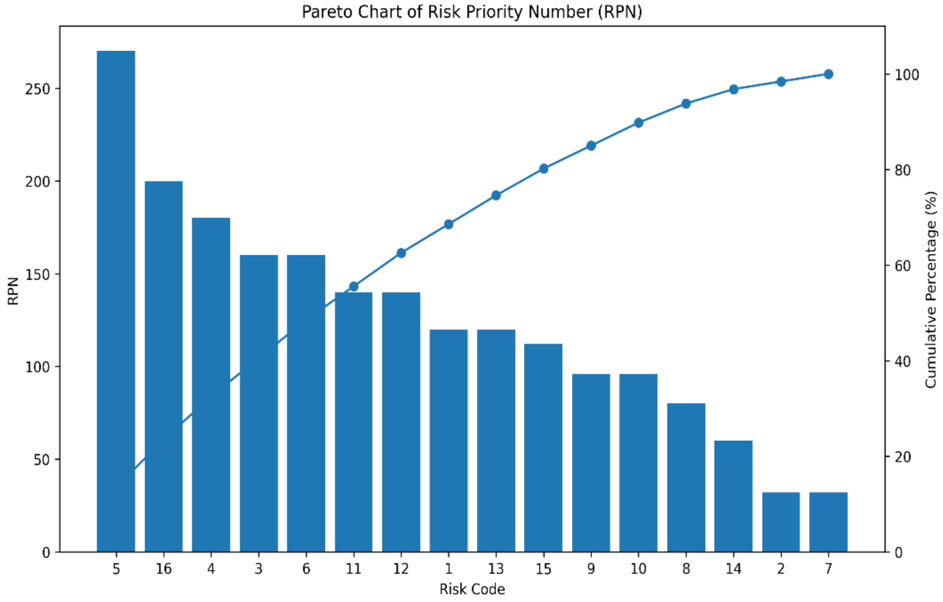

Figure 1. Pareto Chart of Risk Priority Number (RPN)

The Pareto chart was developed to visualize the distribution of Risk Priority Number (RPN) values and identify the most critical risks contributing to the overall vulnerability of the smart electrical distribution network. Risks are ranked from highest to lowest RPN to facilitate prioritization and decision-making for mitigation planning [19], [20], [27], [28].

3.5 Root Cause Analysis of Priority Risks in Smart Electrical Distribution Networks

Following the risk prioritization stage, a root cause analysis was conducted to identify the underlying factors contributing to the highest-priority risks within the smart electrical distribution network. The analysis categorized the causes into six major dimensions: human, equipment, method, environment, technology, and communication. This approach provides a systematic understanding of the factors influencing operational failures and supports the development of effective mitigation strategies to improve system reliability, safety performance, and operational resilience.

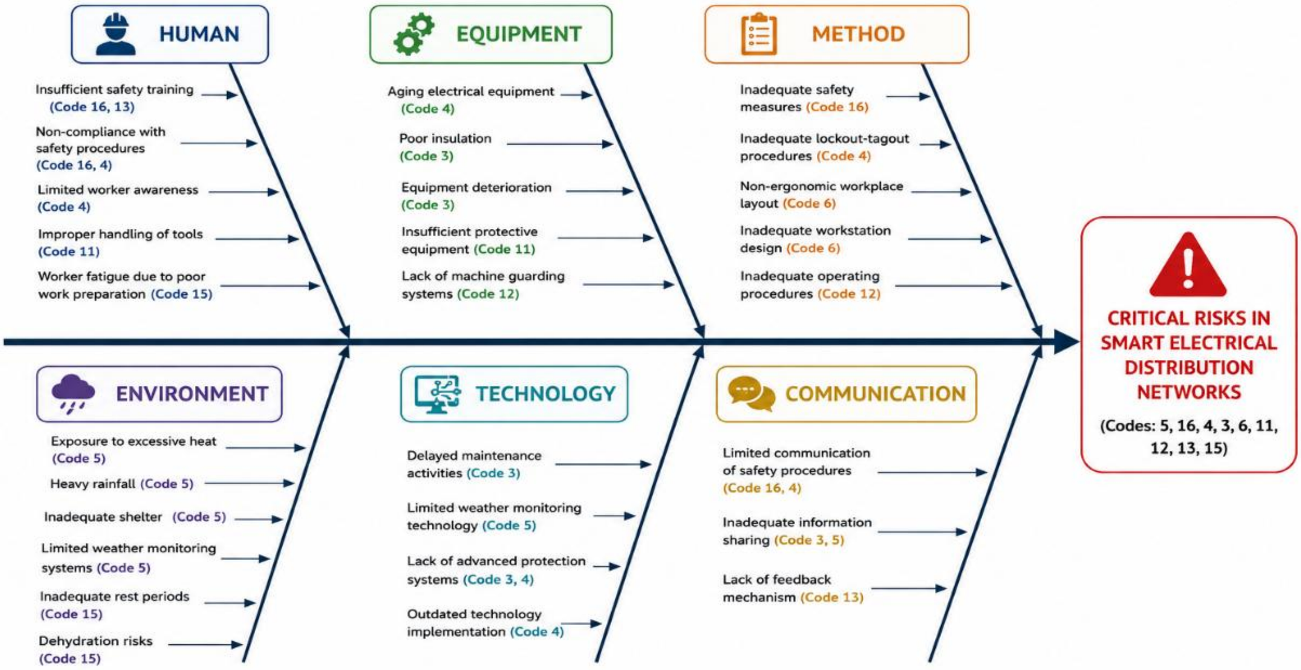

Figure 3. Fishbone Diagram of Priority Risk Causes in Smart Electrical Distribution Networks

Table 5. Root Cause Analysis of Critical Risks

Risk Code	Critical Risk	Root Cause Category	Identified Root Causes
5	Lack of protection from extreme weather conditions	Environment	Exposure to excessive heat, heavy rainfall, inadequate shelter, limited weather monitoring systems
16	Falls from height due to inadequate safety measures	Human / Method	Insufficient safety training, non-compliance with safety procedures, inadequate use of personal protective equipment
4	Electric shock during maintenance activities	Equipment / Human	Aging electrical equipment, inadequate lockout-tagout procedures, limited worker awareness
3	Fire caused by sparks in distribution networks	Equipment / Technology	Poor insulation, equipment deterioration, delayed maintenance activities
6	Poor workplace design causing musculoskeletal injuries	Method / Environment	Non-ergonomic workplace layout, inadequate workstation design, poor task planning
11	Severe hand burns or injuries	Human / Equipment	Improper handling of tools, insufficient protective equipment
12	Hands caught in moving machinery	Equipment / Method	Lack of machine guarding systems, inadequate operating procedures
13	Lack of operator training	Human	Insufficient technical training programs, limited competency development
15	Worker fatigue due to poor work preparation	Human / Environment	Excessive workload, inadequate rest periods, dehydration risks

Based on Table 5, the analysis indicates that human-related factors constitute the dominant source of critical risks, contributing to approximately 30% of the identified root causes. These factors include inadequate training, insufficient safety awareness, operator fatigue, and non-compliance with operational procedures, all of which have been recognized as major contributors to operational failures in complex engineering systems [25], [27], [28]. Equipment-related issues account for approximately 25% of the critical causes, primarily due to aging infrastructure, equipment deterioration, and inadequate maintenance practices, which significantly affect system reliability and service continuity [20]. Method-related factors contribute around 20%, reflecting weaknesses in standard operating procedures and safety management systems. Environmental factors, including extreme weather exposure and workplace conditions, account for approximately 15% of the identified causes, while technology and communication factors collectively contribute about 10%, highlighting the growing importance of digital infrastructure reliability and information exchange in smart distribution networks [19], [31]. These findings demonstrate that the majority of high-priority risks originate from human and equipment-related deficiencies, emphasizing the need for enhanced training programs, preventive maintenance strategies, and stronger safety management practices to improve system reliability, operational resilience, and safety performance [25], [27], [28].

3.6 Mitigation Strategies and the Proposed Delphi–FMEA Framework

Based on the Delphi and FMEA analyses, mitigation strategies were developed to address the critical risks identified in the smart electrical distribution network. The proposed mitigation measures focus on reducing the likelihood and impact of high-priority risks while enhancing system reliability, operational safety, and service continuity. Furthermore, an integrated Delphi–FMEA framework is proposed to support proactive decision-making by combining expert-based risk identification with systematic risk prioritization and mitigation planning [27], [28]. This framework enables utility operators to anticipate potential disruptions, allocate resources efficiently, and strengthen the resilience of smart electrical distribution networks.

Table 6. Recommended Mitigation Strategies for Critical Risks

Risk Code	RPN	Mitigation Strategy	Expected Outcome
5	270	Install weather monitoring systems, improve protective shelters, implement climate adaptation plans	Reduced weather-related disruptions and improved worker safety
16	200	Conduct regular safety training, enforce PPE compliance, improve fall protection systems	Reduced workplace accidents and injuries
4	180	Strengthen lockout-tagout procedures, improve electrical safety training, replace aging equipment	Reduced electrical hazards and maintenance incidents
3	160	Enhance preventive maintenance, improve insulation systems, conduct periodic inspections	Reduced fire risks and equipment failures
6	160	Implement ergonomic workplace improvements and workstation redesign	Improved worker productivity and reduced injury rates
11	140	Provide advanced protective equipment and safety awareness programs	Reduced hand injury incidents
12	140	Install machine guards and strengthen operational procedures	Improved machinery safety
13	120	Develop competency-based training and certification programs	Enhanced operator capability and operational reliability
15	112	Improve work scheduling and hydration management programs	Reduced fatigue-related operational errors

Based on Table 6, the proposed mitigation strategies primarily focus on addressing the highest-priority risks identified through the Delphi-FMEA analysis. Risk code 5, related to inadequate protection from extreme weather conditions (RPN = 270), requires the implementation of weather monitoring systems, climate adaptation measures, and improved protective facilities to minimize operational disruptions. Risk code 16, associated with falls from height (RPN = 200), and risk code 4, involving electrical shock during maintenance activities (RPN = 180), emphasize the importance of comprehensive safety training, strict compliance with personal protective equipment (PPE), and enhanced lockout-tagout procedures [20], [25], [27], [28]. Furthermore, risks related to fire incidents and poor workplace design, each with an RPN value of 160, necessitate preventive maintenance programs, equipment inspections, and ergonomic workplace improvements [27]. The top five critical risks account for approximately 44 % of the cumulative RPN, indicating that targeted mitigation efforts can substantially reduce overall system vulnerability. Previous studies have demonstrated that proactive maintenance, workforce competency development, and safety management systems significantly improve operational reliability and reduce failure occurrence in power distribution networks [19], [20]. Therefore, implementing these mitigation strategies is expected to enhance system resilience, improve worker safety, and strengthen the reliability of smart electrical distribution operations.

The proposed Delphi-FMEA framework was developed to provide a systematic and proactive approach for identifying, evaluating, prioritizing, and mitigating risks within smart electrical distribution networks. The framework integrates expert judgment and quantitative risk assessment to support effective decision-making and improve system reliability.

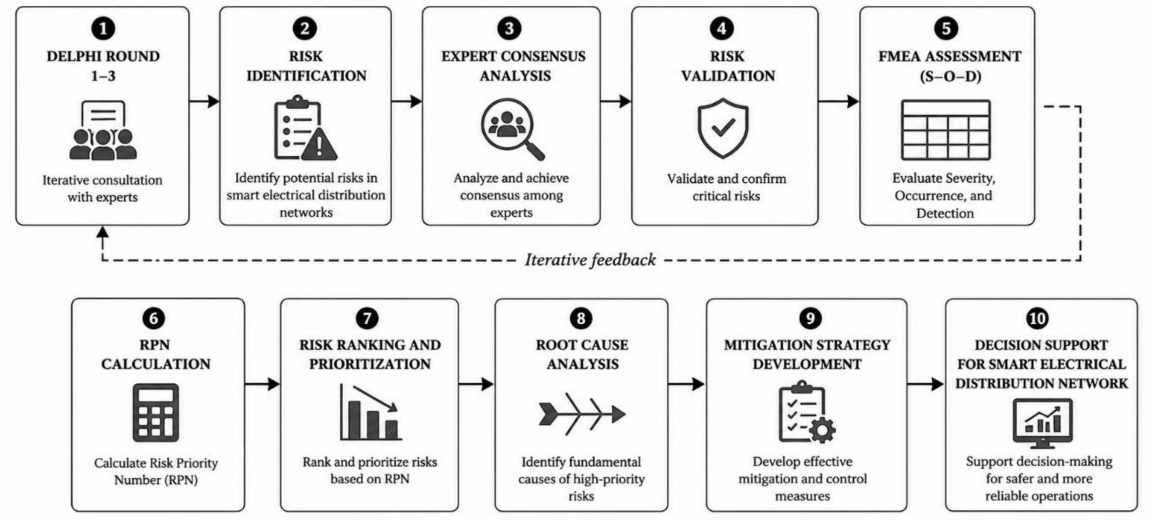

Figure 4. Proposed Delphi-FMEA Framework for Proactive Risk Assessment

Based on Figure 4, the proposed framework begins with three iterative Delphi rounds involving eight experts to identify and validate potential risks affecting the smart electrical distribution network. The identified risks are subsequently evaluated through expert consensus analysis and risk validation before being assessed using the FMEA method. The FMEA stage measures each risk according to Severity (S), Occurrence (O), and Detection (D) criteria to generate Risk Priority Number (RPN) values. Risks are then ranked and prioritized according to their criticality levels. The framework further incorporates root cause analysis to determine the underlying sources of critical risks and supports the development of targeted mitigation strategies [25], [27]. By integrating qualitative expert knowledge with quantitative risk assessment, the framework enables proactive decision-making, enhances operational reliability, improves safety performance, and strengthens the resilience of smart electrical distribution networks.

3.7 Discussion: Advancing Proactive Risk Management Through the Delphi–FMEA Framework in Smart Electrical Distribution Networks

The findings of this study demonstrate that the integration of the Delphi-FMEA provides a systematic and proactive approach for identifying, evaluating, and prioritizing risks within smart electrical distribution networks. Through three Delphi rounds, 30 potential risk variables were identified across four major components, namely network, facilities, inventory, and planning. The results revealed that planning and inventory risks each contributed 27% of the total identified risks, while network and facilities risks accounted for 23% each. These findings indicate that risk exposure in smart distribution systems extends beyond technical infrastructure and is significantly influenced by human, organizational, and operational factors. Similar observations have been reported in previous studies, which emphasize that the increasing complexity of smart grid systems requires integrated risk management approaches capable of addressing both technical and socio-organizational dimensions [16], [18], [19].

The Delphi consensus analysis further validated the identified risks by measuring expert agreement through mean values, standard deviation, and coefficient of variation. Risk code 5, associated with insufficient protection from extreme weather conditions, achieved the highest mean score (4.76), followed by poor workplace design (4.67) and electrical hazards during maintenance activities (4.33). These results highlight the growing influence of environmental and occupational safety risks on the performance of electrical distribution systems. The findings support previous research indicating that climate-related disturbances, workforce safety issues, and aging infrastructure are among the most significant challenges affecting utility reliability and operational continuity [12], [13], [19]. Moreover, the relatively low variability among expert responses confirms the effectiveness of the Delphi method in achieving consensus under conditions of uncertainty and limited historical data [27].

The FMEA results revealed that environmental and occupational risks dominate the risk landscape of the smart electrical distribution network. Risk code 5 obtained the highest RPN value of 270, followed by falls from height (RPN = 200) and electrical shock during maintenance operations (RPN = 180). These three risks alone represent a substantial proportion of the overall system vulnerability. The Pareto analysis further demonstrated that the five highest-priority risks contribute approximately 44 % of the cumulative RPN, confirming the Pareto principle that a limited number of critical risks account for the majority of potential system disruptions. These findings are consistent with previous studies showing that prioritizing high-impact risks enables utilities to allocate resources more efficiently and improve the effectiveness of risk mitigation programs [19], [27], [28]. Consequently, focusing on a small number of critical risks can generate significant improvements in system reliability and safety performance.

The proposed Delphi–FMEA framework offers practical implications for PT PLN and other utility operators seeking to strengthen proactive risk management practices. The framework combines expert knowledge, structured risk assessment, root cause analysis, and mitigation planning into a unified decision-support process. Root cause analysis identified human-related factors as the dominant contributors to critical risks (approximately 30 %), followed by equipment-related factors (25%), method-related factors (20 %), environmental factors (15 %), and technology and communication factors (10 %). These results emphasize the importance of workforce competency development, preventive maintenance programs, safety management systems, and climate resilience initiatives. By integrating these elements into a proactive risk management framework, utilities can improve operational resilience, reduce service interruptions, and enhance the long-term sustainability of smart electrical distribution networks [19], [25], [27], [28].

4. Conclusion

This study successfully developed and implemented an integrated Delphi-FMEA framework for proactive risk assessment in the smart electrical distribution network at PT PLN Tello Sector. Through three Delphi rounds involving eight experts with 16-22 years of professional experience, a total of 30 potential risk variables were identified across four key components: network, facilities, inventory, and planning. The results revealed that planning and inventory contributed the highest proportion of identified risks, each accounting for 27 %, while network and facilities represented 23 % respectively. The Delphi consensus analysis confirmed the validity of the identified risks through mean, standard deviation, and coefficient of variation assessments. The FMEA evaluation demonstrated that the most critical risk was inadequate protection from extreme weather conditions, which obtained the highest Risk Priority Number (RPN) of 270. This was followed by falls from height (RPN = 200) and electrical shock during maintenance activities (RPN = 180). Pareto analysis further showed that the five highest-priority risks contributed approximately 44 % of the cumulative risk exposure, indicating that a limited number of critical risks account for a substantial portion of system vulnerability. Root cause analysis revealed that human-related factors were the dominant contributors (30 %), followed by equipment-related factors (25 %), method-related factors (20 %), environmental factors (15 %), and technology and communication factors (10 %). The proposed Delphi-FMEA framework provides a structured decision-support tool for identifying, evaluating, and prioritizing risks before failures occur. Its implementation can enhance system reliability, improve operational resilience, strengthen safety performance, and support sustainable risk management practices in smart electrical distribution networks. Future studies are recommended to integrate real-time monitoring, predictive analytics, and artificial intelligence techniques to further improve proactive risk assessment and decision-making capabilities.

Author contributions: Riska Iva Riana designed the research, conducted the analysis, and wrote the manuscript. Yan Herdianzah contributed to data collection and validation and provided critical revisions to the manuscript. Both authors were involved in interpreting the results and approved the final version of the manuscript.

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Conflict of Interest: The authors confirm that this study was conducted independently, without any financial, commercial, or personal interests that could influence the research results or interpretations.

5. References

[1] A. A. Zúñiga, A. Baleia, J. Fernandes, and P. J. D. C. Branco, “Classical Failure Modes and Effects Analysis in the Context of Smart Grid Cyber-Physical Systems,” *Energies (Basel).*, vol. 13, no. 5, p. 1215, Mar. 2020, doi: 10.3390/en13051215

[2] S. K. Akula and H. Salehfar, “Risk-based Classical Failure Mode and Effect Analysis (FMEA) of Microgrid Cyber-physical Energy Systems,” in *2021 North American Power Symposium (NAPS)*, IEEE, Nov. 2021, pp. 1–6. doi: 10.1109/NAPS52732.2021.9654717

[3] V. O. Otitolaiye and F. S. Abd Aziz, “Understanding the Mechanism Through Which Safety Management Systems Influence Safety Performance in Nigerian Power and Electricity Distribution Companies,” *Safety*, vol. 11, no. 4, p. 98, Oct. 2025, doi: 10.3390/safety11040098

[4] D. F. Silalahi, A. Blakers, and C. Cheng, “100% Renewable Electricity in Indonesia,” *Energies (Basel).*, vol. 17, no. 1, p. 3, Dec. 2023, doi: 10.3390/en17010003

[5] L. M. N. Gabriel, J. A. Adebisi, L. N. P. Ndjuluwa, and D. K. Chembe, “Investigation of smart grid technologies deployment for energy reliability enhancement in electricity distribution networks,” *Franklin Open*, vol. 10, p. 100227, Mar. 2025, doi: 10.1016/j.fraope.2025.100227

[6] E. Yaghoubi, E. Yaghoubi, M. R. Maghami, and M. Z. Jahromi, “Comprehensive technical risk indices and advanced methodologies for power system risk management,” *Electric Power Systems Research*, vol. 244, p. 111534, Jul. 2025, doi: 10.1016/j.epsr.2025.111534

[7] M. Aghahadi, A. Bosisio, M. Merlo, A. Berizzi, A. Pegoiani, and S. Forciniti, “Digitalization Processes in Distribution Grids: A Comprehensive Review of Strategies and Challenges,” *Applied Sciences*, vol. 14, no. 11, p. 4528, May 2024, doi: 10.3390/app14114528

[8] Z. Li, P. Du, and T. Li, “Comprehensive Risk Assessment of Smart Energy Information Security: An Enhanced MCDM-Based Approach,” *Sustainability*, vol. 17, no. 8, p. 3417, Apr. 2025, doi: 10.3390/su17083417

[9] J. Gallegos, P. Arévalo, C. Montaleza, and F. Jurado, “Sustainable Electrification—Advances and Challenges in Electrical-Distribution Networks: A Review,” *Sustainability*, vol. 16, no. 2, p. 698, Jan. 2024, doi: 10.3390/su16020698

[10] M. Rouholamini, C. Wang, S. Magableh, and X. Wang, “Resiliency of electric power distribution networks: a review,” *Journal of Infrastructure Preservation and Resilience*, vol. 6, no. 1, p. 39, Nov. 2025, doi: 10.1186/s43065-025-00154-y

[11] Y. Chen *et al.*, “Fortifying Smart Grids: A Holistic Assessment Strategy against Cyber Attacks and Physical Threats for Intelligent Electronic Devices,” *Computers, Materials & Continua*, vol. 80, no. 2, pp. 2579–2609, 2024, doi: 10.32604/cmc.2024.053230

[12] A. A. Zúñiga, A. Baleia, J. Fernandes, and P. J. D. C. Branco, “Classical Failure Modes and Effects Analysis in the Context of Smart Grid Cyber-Physical Systems,” *Energies (Basel).*, vol. 13, no. 5, p. 1215, Mar. 2020, doi: 10.3390/en13051215

[13] Y. Yang, X. Zhao, T. Han, M. Xu, and C. Li, “Enhancing Operational Risk Management in Distribution Networks: A Comprehensive Framework,” *Fluctuation and Noise Letters*, vol. 23, no. 05, p. 2450044, Oct. 2024, doi: 10.1142/S0219477524500445

[14] A. Ghasempour, “Internet of Things in Smart Grid: Architecture, Applications, Services, Key Technologies, and Challenges,” *Inventions*, vol. 4, no. 1, p. 22, Mar. 2019, doi: 10.3390/inventions4010022

[15] K. H. Mohd Azmi, N. A. Mohamed Radzi, N. A. Azhar, F. S. Samidi, I. Thaqifah Zulkifli, and A. M. Zainal, “Active Electric Distribution Network: Applications, Challenges, and Opportunities,” *IEEE Access*, vol. 10, pp. 134655–134689, 2022, doi: 10.1109/ACCESS.2022.3229328

[16] M. Kiasari, M. Ghaffari, and H. Aly, “A Comprehensive Review of the Current Status of Smart Grid Technologies for Renewable Energies Integration and Future Trends: The Role of Machine Learning and Energy Storage Systems,” *Energies (Basel).*, vol. 17, no. 16, p. 4128, Aug. 2024, doi: 10.3390/en17164128

[17] M. A. Husnoo, A. Anwar, N. Hosseinzadeh, S. N. Islam, A. N. Mahmood, and R. Doss, “False data injection threats in active distribution systems: A comprehensive survey,” *Future Generation Computer Systems*, vol. 140, pp. 344–364, Mar. 2023, doi: 10.1016/j.future.2022.10.021

[18] P. Smith, E. Piatkowska, E. Widl, F. P. Andren, and T. I. Strasser, “Towards a Systematic Approach for Smart Grid Hazard Analysis and Experiment Specification,” in *2020 IEEE 18th International Conference on Industrial Informatics (INDIN)*, IEEE, Jul. 2020, pp. 333–339. doi: 10.1109/INDIN45582.2020.9442080

[19] W. Phokee, S. Chaiklieng, P. Boriwan, T. Phoka, J. Vanoirbeek, and S. Chatpun, “A Cascading Delphi Method-Based FMEA Risk Assessment Framework for Surgical Instrument Design: A Case Study of a Fetoscope,” *Applied Sciences*, vol. 15, no. 11, p. 6203, May 2025, doi: 10.3390/app15116203

[20] P. Zandi, M. Rahmani, M. Khanian, and A. Mosavi, “Agricultural Risk Management Using Fuzzy TOPSIS Analytical Hierarchy Process (AHP) and Failure Mode and Effects Analysis (FMEA),” *Agriculture*, vol. 10, no. 11, p. 504, Oct. 2020, doi: 10.3390/agriculture10110504

[21] A. Fole, K. N. Safitri, Erniyani, and B. Sufrian, “Hybrid AHP TOPSIS Approach for Evaluating Green Supply Chain Management Barriers in the Poultry Processing Industry,” *Cognitia : International Engineering Journal*, vol. 2, no. 1, pp. 11–22, 2025, doi: 10.63288/ciej.v2i1.17

[22] A. Fole, T. Alisyahbana, N. I. Safutra, Muh. Ridzwan, and Alifah Dwi Wulandari Putri, “An Evaluation of Supply Chain Reliability Strategies in the Garment Industry Based on the SCOR 14.0 Racetrack Framework,” *Cognitia : International Engineering Journal*, vol. 1, no. 3, pp. 92–106, Dec. 2025, doi: 10.63288/ciej.v1i3.11

[23] B. Salah, M. Alnahhal, and M. Ali, “Risk prioritization using a modified FMEA analysis in industry 4.0,” *Journal of Engineering Research*, vol. 11, no. 4, pp. 460–468, Dec. 2023, doi: 10.1016/j.jer.2023.07.001

[24] A. Al-Refaie and H. Aljundi, “Fuzzy FMEA-Resilience Approach for Maintenance Planning in a Plastics Industry ,” *Int. J. Progn. Health Manag.*, vol. 15, no. 2, Jul. 2024, doi: 10.36001/ijphm.2024.v15i2.3851

[25] Y. Ren, F. Deichsel, V. Hopf, J. Seiler, A. Kaup, and P. Beckerle, “Networked Systems Diagnostics: A Fusion of Failure Mode and Effects Analysis and a Delphi Expert Study,” in *2024 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, IEEE, Oct. 2024, pp. 2041–2046. doi: 10.1109/SMC54092.2024.10831721

[26] A. Mohammed, A. Al-Baqami, A. Alshibani, L. A. Hadidi, A. Ghaithan, and A. Al-Abbas, “An integrated gray relational analysis – FMEA approach for risk assessment of petrochemical projects during the design stage,” *Journal of Modelling in Management*, vol. 21, no. 4, pp. 1325–1351, May 2026, doi: 10.1108/JM2-04-2025-0167

[27] S. Ebrahimi, K. Vachal, and J. Szmerekovsky, “A Delphi-FMEA model to assess county-level speeding crash risk in North Dakota,” *Transp. Res. Interdiscip. Perspect.*, vol. 16, p. 100688, Dec. 2022, doi: 10.1016/j.trip.2022.100688

[28] J. Lim, E. Oey, and M. Simbung, “Integrating FTA, FMEA and Delphi technique in addressing major defects for high rise residential complex - a lesson learned from a large-scale apartment project,” *International Journal of Structural Engineering*, vol. 14, no. 3, pp. 314–340, 2024, doi: 10.1504/IJSTRUCTE.2024.139804

[29] R. I. Riana, T. Immawan, and Y. Herdianzah, “Supply Chain Risk Management for Waste Management Strategy Using House of Risk,” *Metode : Jurnal Teknik Industri*, vol. 11, no. 1, pp. 138–147, Mar. 2025, doi: 10.33506/mt.v11i1.4149

[30] Y. Herdianzah, A. D. Wahyuni P, C. A. Chalik, B. Febriyanti, and N. A. K. Fitri, “Optimizing Banana Chips Production Planning in MSMEs Through the Goal Programming Approach,” *Cognitia : International Engineering Journal*, vol. 1, no. 2, pp. 58–68, Aug. 2025, doi: 10.63288/ciej.v1i2.7

[31] B. Hanum, “Quality Control Analysis of Metal Baseplate Finishing Process Using Statistical Process Control (SPC) and Failure Mode and Effect Analysis (FMEA): A Case Study of an Indonesian Company,” *International Journal of Scientific and Academic Research*, vol. 02, no. 06, pp. 09–18, 2022, doi: 10.54756/IJSAR.2022.V2.i6.2