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Original Research Article

Field-Based Assessment of Maintenance Practices and Hazard Mitigation in a 20-kV Medium-Voltage Distribution Network: A Case Study of PLN ULP Demak, Indonesia

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ABSTRACT

The reliability and continuity of medium-voltage distribution networks depend on effective maintenance practices and the timely mitigation of physical and environmental hazards. This study evaluated maintenance practices and hazard mitigation in a 20-kV Medium-Voltage Overhead Distribution Network at PT PLN (Persero) ULP Demak, Indonesia. A descriptive field-based case study design was employed using direct observations, semi-structured interviews, and field documentation. Field activities were conducted from 1 February to 10 March 2026 across 12 observation sections. A total of 40 maintenance events were documented and classified into preventive, corrective, and emergency maintenance, while contextual information was obtained from eight purposively selected maintenance personnel. Descriptive analysis and qualitative before–after comparison were used to examine maintenance patterns, hazard conditions, and post-maintenance changes. Preventive maintenance accounted for 24 events (60%), followed by corrective maintenance with 10 events (25%) and emergency maintenance with 6 events (15%). Vegetation and foreign objects, particularly kites, were recurring physical hazards requiring field intervention. Vegetation pruning, foreign-object removal, equipment inspection, and corrective maintenance were associated with observed reductions or removal of identified physical hazards. The study contributes field-based evidence linking hazard identification, maintenance intervention, post-maintenance inspection, and observed hazard mitigation. However, the findings do not constitute quantitative evidence of improved system-level reliability because longitudinal outage data and reliability indices were not available. The study provides an operational basis for integrating field maintenance records with future feeder-level reliability analysis.

Keywords:
condition-based maintenance; distribution network; field assessment; hazard mitigation; maintenance practices; medium-voltage network; preventive maintenance.

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INTRODUCTION

Background

The reliability of electrical distribution systems is a critical aspect of power-system performance because distribution networks constitute the final stage of electricity delivery to customers (Nireekshana et al., 2025). Interruptions at the distribution level can directly affect service continuity and electricity supply to customers (Kebede, 2023, p. 27). Therefore, distribution utilities need effective maintenance strategies to ensure that network assets remain in an operational condition that supports reliable electricity delivery while controlling maintenance requirements and operational costs. Recent research has demonstrated that maintenance planning and power-system reliability are closely interconnected, with preventive, condition-based, and reliability-centered maintenance approaches increasingly being considered in power-system asset management (Alvarez-Alvarado et al., 2022; Endrenyi et al., 2001).

Medium-voltage distribution networks are particularly important because failures in these networks can interrupt electricity supply to a substantial number of downstream customers (Gitelman et al., 2019, p. 232; Schneider et al., 2006, p. 644). Overhead distribution networks are also exposed to environmental conditions, vegetation growth, foreign objects, weather-related disturbances, and deterioration of network components (Zhao et al., 2025, p. 1; Zhou et al., 2006). Consequently, maintenance activities are required not only to restore failed components but also to identify and mitigate potential failure mechanisms before they develop into network interruptions. Reliability-centered maintenance approaches emphasize the relationship between maintenance actions, component failure behavior, system reliability, and maintenance costs (Bertling et al., 2005; Piasson et al., 2016).

Vegetation management is one of the important maintenance activities in overhead distribution systems because vegetation growing close to conductors can create potential electrical faults and service interruptions. Research on vegetation maintenance has demonstrated that systematic management of vegetation around overhead distribution networks is closely related to network reliability and maintenance costs (Correa-Tamayo et al., 2019). Similarly, statistical analysis of distribution-network outage data has shown that vegetation management can contribute to reducing outages associated with severe weather conditions (Taylor et al., 2022). These findings indicate that vegetation management should not be considered merely as routine field work but also as an element of distribution-network reliability management.

The effectiveness of maintenance also depends on the way maintenance activities are planned, prioritized, and related to the condition of network components. Reliability-centered maintenance approaches have been developed to determine maintenance priorities based on component reliability and failure characteristics (Ardabili et al., 2020; Tjernberg et al., 2005). In addition, long-term maintenance planning for medium-voltage overhead networks has been developed by incorporating interruption causes, reliability indices, maintenance costs, and uncertainties into maintenance decisions (Moghadam et al., 2023; Popović et al., 2025). More recently, condition-based maintenance approaches have incorporated inspection information into maintenance decision-making for electrical distribution systems, allowing maintenance actions to be related more directly to the observed condition of network assets (Olojede et al., 2025, p. 13; Wang et al., 2023).

In the context of the present study, maintenance activities on the 20-kV Medium-Voltage Overhead Distribution Network (SUTM) at PT PLN (Persero) ULP Demak involve several activities, including network inspection, vegetation pruning, removal of foreign objects, equipment condition assessment, and corrective maintenance. Field observations conducted during the study identified vegetation and foreign objects, particularly kites attached to conductors, as potential sources of network disturbances. These observations indicate the importance of preventive maintenance in identifying and controlling physical hazards before they develop into more serious operational problems.

Previous Research

Previous studies on distribution-system maintenance have mainly focused on reliability-centered maintenance, preventive-maintenance optimization, condition-based maintenance, and maintenance planning based on reliability and operational risk (Mirshekali et al., 2024, p. 122558; Piasson et al., 2016, p. 42). These approaches demonstrate that maintenance decisions should be linked to the reliability characteristics and condition of network components rather than being conducted solely as reactive responses to equipment failures.

Bertling et al. (2005) developed a reliability-centered asset maintenance method for power distribution systems that relates maintenance measures to component failure rates, system reliability, and maintenance costs. Their study demonstrated the importance of evaluating maintenance strategies systematically in order to understand their potential effects on distribution-system reliability. Similarly, Piasson et al. (2016) proposed a multiobjective reliability-centered maintenance model for electric distribution systems by considering the trade-off between preventive-maintenance costs and overall system reliability. Their approach incorporated reliability indices, including SAIDI and SAIFI, into the maintenance-planning problem (Aravinthan & Jewell, 2013; Muthana & Ku-Mahamud, 2022, p. 5).

A probabilistic reliability-centered maintenance approach was proposed by Ardabili et al. (2020), in which the reliability of distribution-system components was evaluated using a three-state Markov model. The approach was used to support the prioritization of preventive-maintenance resources based on component reliability. These studies indicate that reliability-centered maintenance provides a systematic framework for connecting component condition, failure probability, maintenance actions, and system-level reliability (Nithin et al., 2022, p. 156; Zeng et al., 2021, p. 1).

Another important research direction is maintenance planning for medium-voltage overhead distribution networks. Moghadam et al. (2023) investigated long-term maintenance planning for a real medium-voltage overhead network while considering uncertainty, interruption causes, maintenance costs, and reliability indicators such as SAIDI, SAIFI, ENS, and AENS. Their study demonstrates the potential of integrating historical interruption data and maintenance planning to improve the efficiency of distribution-network maintenance decisions.

Condition-based maintenance has also received increasing attention in distribution-system research. Wang et al., (2023) proposed an opportunistic condition-based maintenance framework for electrical distribution systems that uses inspection information to support maintenance decisions. Their study demonstrates the potential of linking actual equipment conditions with maintenance policies rather than relying solely on predetermined maintenance schedules.

Environmental factors, particularly vegetation, have also been examined in relation to distribution-network reliability. Correa-Tamayo et al. (2019) investigated the management and scheduling of vegetation maintenance in overhead distribution systems and considered its relationship with network reliability and maintenance costs. Taylor et al. (2022) further developed a statistical framework to evaluate vegetation management and its effectiveness in reducing power outages during severe weather events. These studies confirm that vegetation management can be considered an important component of distribution-network reliability and resilience strategies.

Overall, previous research has established a strong theoretical and methodological foundation for reliability-centered maintenance, maintenance optimization, condition-based maintenance, and environmental-risk management. Nevertheless, most of these studies emphasize mathematical modeling, optimization, statistical analysis, or historical reliability data. A field-based perspective that explicitly connects observed maintenance activities, physical network hazards, and changes in network condition remains less prominent in the literature.

Research Gap

Although previous studies have extensively examined reliability-centered maintenance, preventive-maintenance optimization, condition-based maintenance, vegetation management, and reliability-index assessment, many existing approaches primarily focus on mathematical models, optimization frameworks, or historical interruption data (Alvarez-Alvarado et al., 2022; Ardabili et al., 2020; Moghadam et al., 2023; Piasson et al., 2016; Wang et al., 2023). These approaches provide valuable tools for strategic maintenance planning, but they provide relatively limited descriptions of how specific maintenance interventions are implemented under actual field conditions.

For overhead medium-voltage distribution networks, this limitation is particularly relevant because the occurrence of environmental hazards can vary from one network location to another. Vegetation encroachment, foreign objects attached to conductors, equipment deterioration, and difficult field access require direct inspection and operational intervention. Although previous research has demonstrated the relationship between vegetation management and distribution-system reliability (Correa-Tamayo et al., 2019; Taylor et al., 2022), there remains a need for field-based studies that document how these hazards are identified, what maintenance actions are performed, and how the physical condition of the network changes following maintenance.

Furthermore, maintenance activities are often classified into preventive and corrective interventions without explicitly linking each intervention to the specific hazard that it addresses. A systematic relationship between hazard identification, maintenance intervention, and post-maintenance network condition can provide a more practical perspective for evaluating maintenance effectiveness at the operational-unit level (Argyroudis et al., 2020, p. 136859; Kaliszewski et al., 2025, p. 22).

Therefore, this study addresses a research gap by integrating field observations of maintenance activities with the identification of environmental and operational hazards and the comparison of network conditions before and after maintenance interventions. The study does not assume that observed physical improvements automatically represent statistically significant improvements in system-level reliability. Instead, it evaluates the operational evidence of hazard reduction and network-condition improvement and discusses its implications for distribution-system reliability. This distinction is important because quantitative claims regarding system-level reliability improvement require additional outage and reliability-index data.

Objective and Contribution

Based on the research gap identified above, this study aims to evaluate maintenance practices implemented on the 20-kV Medium-Voltage Overhead Distribution Network at PT PLN (Persero) ULP Demak. Specifically, the study aims to: 1) Characterize the preventive, corrective, and emergency maintenance activities implemented on the 20-kv distribution network; 2) Identify the major operational and environmental hazards encountered during field maintenance activities, particularly vegetation and foreign objects; 3) Evaluate changes in the observed physical condition of the network before and after maintenance interventions; and 4) Discuss the implications of preventive maintenance for the operational reliability and continuity of electricity distribution.

The contribution of this study is a field-based approach for evaluating maintenance effectiveness by linking network hazards, maintenance interventions, and post-maintenance network conditions. Unlike studies that primarily focus on mathematical optimization or reliability modeling, this research emphasizes the practical implementation of maintenance activities within an actual 20-kV overhead distribution network. The findings are expected to provide practical information for maintenance planning and hazard management at the operational-unit level.

In addition, this study provides a basis for future quantitative reliability assessment by highlighting the importance of integrating field maintenance records with interruption data and established reliability indices. Future research can incorporate indicators such as the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and energy not supplied to quantitatively evaluate the relationship between maintenance activities and distribution-system reliability.

MATERIALS AND METHODS

This study employed a descriptive field-based case study design to assess maintenance practices and physical hazard mitigation in a 20-kV Medium-Voltage Overhead Distribution Network (SUTM) operated within the service area of PT PLN (Persero) Unit Layanan Pelanggan (ULP) Demak.

The case study approach was selected because the research focused on maintenance activities as they occurred under actual field and operational conditions. Rather than estimating the prevalence of maintenance practices across the broader population of Indonesian medium-voltage distribution networks, the study sought to document the characteristics of observed maintenance activities, identify operational and environmental hazards, and examine changes in physical network condition following maintenance interventions.

The study employed three complementary sources of field evidence: direct observation, semi-structured interviews, and field documentation. These sources were triangulated to improve the credibility of the interpretation of maintenance practices and observed network conditions. The overall analytical framework was structured as:

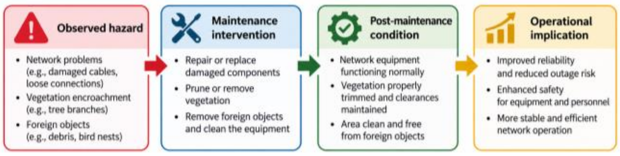

Figure 1. Workflow of Hazard Identification, Maintenance Intervention, Post-Maintenance Condition, and Operational Implications

The study therefore focused on field-level maintenance implementation and physical hazard mitigation, rather than statistical estimation of system-level reliability.

Study Area and Research Object

The study was conducted at PT PLN (Persero) Unit Layanan Pelanggan (ULP) Demak, with the research object being the 20-kV Medium-Voltage Overhead Distribution Network (SUTM) within the operational area covered by the field observations.

The 20-kV network was selected because overhead medium-voltage distribution infrastructure is exposed to environmental and operational conditions that may affect the continuity of electricity distribution. Particular attention was given to physical network components, surrounding environmental conditions, maintenance interventions, and potential hazards encountered during field activities.

The field assessment covered 12 observation sections of the 20-kV distribution network. The term *observation section* was used rather than *observation point* because the assessment concerned sections of the network and their surrounding operational environment rather than isolated geographic points.

The study did not estimate network characteristics that were not available in the field records, such as the total length of the distribution network, total number of feeders, or total number of distribution substations. Consequently, these parameters were not incorporated into the analysis.

Study Period and Field Observation

Field activities were conducted from 1 February to 10 March 2026. The observation period covered 40 effective working/observation days during which maintenance activities and relevant network conditions were documented.

The observation focused on maintenance events occurring within the selected observation sections. During the study period, 40 maintenance events were documented and subsequently classified according to their operational purpose as preventive, corrective, or emergency maintenance.

The observation process was conducted during actual maintenance activities and included documentation of network conditions before intervention, the maintenance action performed, and the observed condition following intervention.

Maintenance Event Identification and Classification

Each documented maintenance event was treated as an observational unit for descriptive analysis. Maintenance events were classified into three categories according to the primary purpose of the intervention: 1) Preventive maintenance, referring to activities intended to identify, control, or mitigate potential network problems before a disturbance occurs; 2) Corrective maintenance, referring to interventions undertaken to repair or restore network components affected by defects or damage; and 3) Emergency maintenance, referring to rapid interventions undertaken in response to unexpected disturbances requiring immediate operational action. The 40 documented maintenance events consisted of 24 preventive events (60%), 10 corrective events (25%), and 6 emergency events (15%).

Table 1. Classification of observed maintenance events

Maintenance category	Number of events	Percentage
Preventive maintenance	24	60%
Corrective maintenance	10	25%
Emergency maintenance	6	15%
Total	40	100%

The classification was used for descriptive characterization of maintenance activities within the study case. The resulting percentages represent the distribution of the observed events during the study period and are not intended to represent the maintenance distribution of all 20-kV distribution networks.

Participants and Sampling

The qualitative contextual information was obtained through semi-structured interviews with eight personnel who were directly involved in or had operational knowledge of the observed maintenance activities. Participants consisted of: 1) 2 maintenance supervisors, providing information concerning maintenance supervision, operational decision-making, and work coordination; 2) 4 maintenance technicians, providing information concerning technical implementation and field maintenance procedures; and 3) 2 field/operational personnel, providing information concerning field conditions, accessibility, and operational constraints. Participants were selected using purposive sampling. The selection criterion was direct involvement in maintenance activities or sufficient operational knowledge to provide relevant information concerning maintenance procedures and field conditions.

Table 2. Interview participant characteristics

Participant	Number	Primary information provided

category		
Maintenance supervisors	2	Supervision, coordination, and decision-making
Maintenance technicians	4	Technical maintenance implementation
Field/operational personnel	2	Field conditions and operational constraints
Total	8	

Note. The interviews lasted approximately 20–35 minutes per participant.

Data Collection Procedures

Data collection consisted of three complementary activities: direct observation, semi-structured interviews, and documentation.

Direct Observation

Direct observation was conducted during maintenance activities across the 12 observation sections. The observation focused on: a) Type of maintenance activity; b) Network components involved; c) Physical network condition; d) Vegetation conditions; e) Presence of foreign objects; f) Equipment condition; g) Maintenance intervention performed; h) Pre-maintenance condition; i) Post-maintenance condition; j) Implementation of personal protective equipment (ppe) and k3 procedures; and k) Field accessibility and operational constraints.

A total of 40 maintenance events were documented during the observation period. The observation procedure followed the sequence: Pre-maintenance observation → Hazard identification → Maintenance intervention → Post-maintenance observation.

This sequence provided the basis for the subsequent before–after assessment.

Semi-Structured Interviews

Semi-structured interviews were conducted with the eight purposively selected personnel. The interview questions addressed: 1) Routine maintenance procedures; 2) Classification of maintenance activities; 3) Identification of network hazards; 4) Reasons for particular maintenance interventions; 5) Operational constraints; 6) Responses to unexpected network disturbances; 7) Post-maintenance inspection practices; and 8) Considerations affecting maintenance implementation. The interviews were used primarily to provide contextual and explanatory information for the field observations. Interview information was not treated as a separate quantitative dataset.

Field Documentation

Field documentation consisted of photographs and activity records generated during maintenance activities. The documentation was used to support the identification and interpretation of network conditions and maintenance interventions. Photographic and documentary evidence was compared with field observations where applicable. The documentation included evidence related to vegetation conditions, foreign objects, network components, maintenance activities, and post-maintenance conditions. The original manuscript similarly identifies photographs and field records as supporting evidence for maintenance interventions and network conditions.

Data Source Triangulation

Data-source triangulation was employed by comparing information obtained from direct observation, interviews, and field documentation. The triangulation process was designed to determine whether the observed maintenance condition and intervention were supported by contextual information from maintenance personnel and available documentary evidence. For example, when vegetation was identified as a potential hazard during field observation, information from maintenance personnel concerning the reason for pruning was considered together with available photographic or activity documentation. The triangulation structure was:

Observation evidence + Interview evidence + Documentary evidence → Integrated field interpretation

This approach was intended to strengthen the credibility of the descriptive findings without treating the three sources as statistically independent observations.

Identification and Classification of Network Hazards

The field assessment focused on physical and operational conditions that could potentially interfere with the operation of the 20-kV distribution network. The observed hazards were classified into four categories:

Vegetation-Related Hazards: These included trees, branches, or other vegetation growing close to distribution conductors and potentially reducing the required clearance between vegetation and the network.

Foreign Objects: These included kites and other objects attached to, entangled with, or located near distribution conductors.

Equipment-Related Conditions: These included network components requiring inspection, maintenance, repair, or replacement because of observed defects or potential operational problems.

Accessibility Constraints: These referred to field conditions that complicated network inspection or maintenance activities, including locations that were difficult to reach or required additional coordination.

Observation Parameters

To ensure consistency across the 12 observation sections and 40 maintenance events, observations were organized around predefined parameters.

Table 3. Observation parameters and operational definitions

Parameter	Operational focus
Maintenance type	Preventive, corrective, or emergency
Network component	Conductor, insulator, pole, connection, and related components
Vegetation condition	Presence and proximity of vegetation to the network
Foreign objects	Presence and type of objects attached to or near the network
Equipment condition	Observable condition requiring inspection, repair, or replacement
Maintenance intervention	Action undertaken in response to the observed condition
Pre-maintenance condition	Physical condition before intervention
Post-maintenance condition	Physical condition after intervention
Safety implementation	PPE and K3 implementation
Accessibility	Field conditions affecting inspection or maintenance

These parameters are consistent with the observation framework in the original manuscript, which includes maintenance type, network components, vegetation, foreign objects, equipment condition, intervention, pre- and post-maintenance conditions, safety, and field constraints.

Assessment of Maintenance Outcomes

Maintenance outcomes were assessed through a qualitative before–after comparison. For each relevant maintenance event, the physical condition observed before intervention was compared with the condition observed after the intervention. The assessment used three principal outcome categories: 1) Hazard removed — the identified physical hazard was no longer observed after intervention; 2) Hazard reduced — the hazard remained partially present but its observed exposure or extent was reduced; and 3) Hazard remained — the identified condition remained substantially unchanged following the intervention.

The assessment also considered whether the affected network component had been inspected or subjected to additional maintenance following the primary intervention. For example, vegetation identified near conductors before intervention was compared with the surrounding vegetation condition after pruning. Similarly, foreign objects observed on the network before intervention were compared with the network condition after object removal. This assessment framework follows the original manuscript's before–after approach.

Data Analysis

The study used descriptive analysis to summarize the observed maintenance practices and field conditions.

The analysis was conducted in four stages.

Stage 1: Maintenance Classification:
All 40 maintenance events were classified as preventive, corrective, or emergency maintenance. Frequency and percentage were calculated for each category using:

$$P_i = \frac{n_i}{N} X\ 100\%$$

where:
P_i = percentage of maintenance category ii;
n_i = number of events in category ii; and
N = total number of observed maintenance events. For the present study, N=40

Stage 2: Hazard Classification:
Observed hazards were categorized into vegetation, foreign objects, equipment-related conditions, and accessibility constraints.

Stage 3: Before–After Comparison:
The physical condition before and after maintenance intervention was compared qualitatively to determine whether the identified hazard was removed, reduced, or remained.

Stage 4: Integrated Interpretation:
Observation results, interview information, and documentary evidence were integrated to interpret the operational implications of maintenance interventions. The analytical framework was therefore:

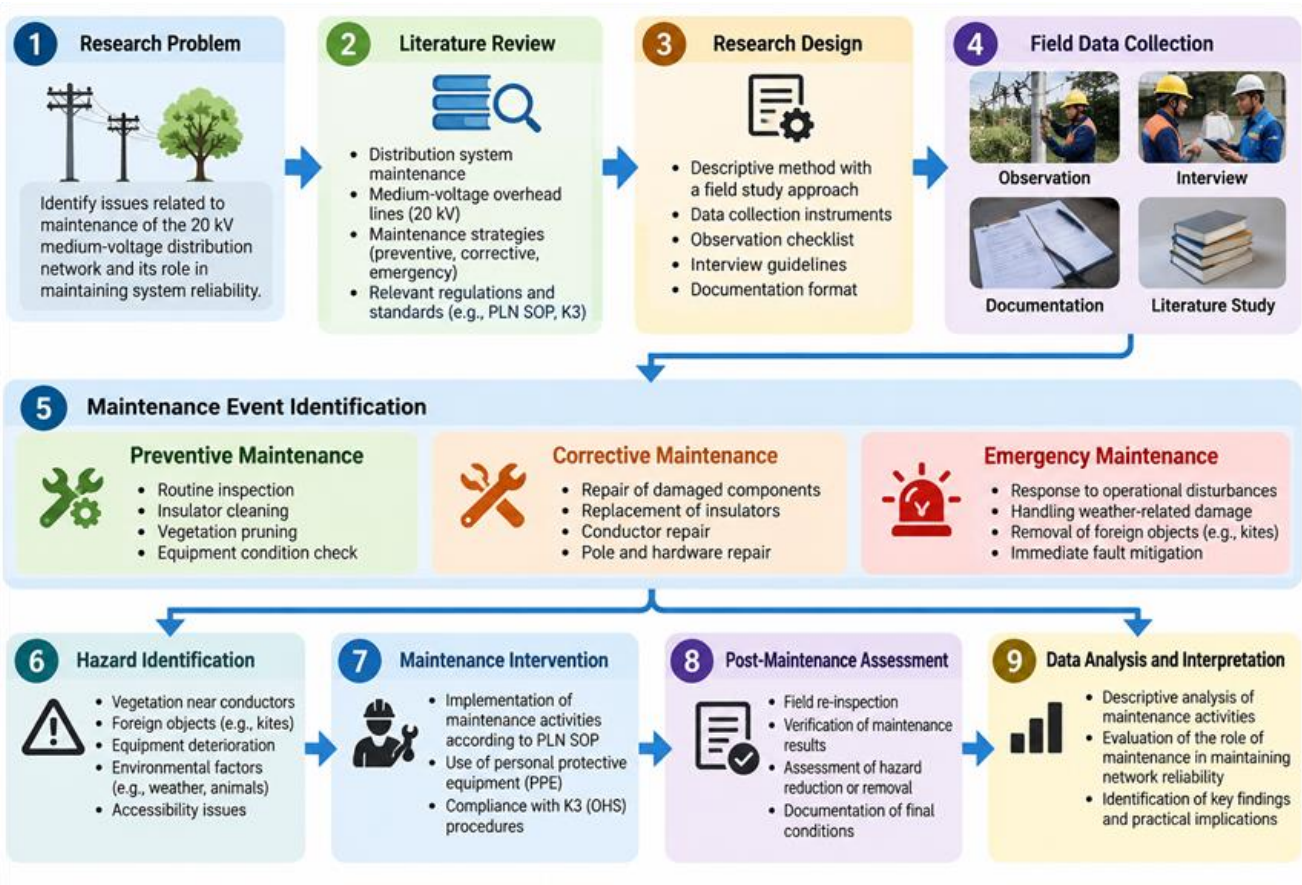

Figure 1. Field-Based Research and Maintenance Assessment Workflow

No inferential statistical testing was conducted because the study was designed as a descriptive field-based case study and the observed maintenance events were not treated as a probability sample of the wider population of 20-kV distribution networks.

Reliability Interpretation

A methodological distinction was maintained between observed hazard mitigation and system-level distribution reliability. The removal or reduction of a physical hazard following maintenance was interpreted as evidence of observed maintenance effectiveness at the asset or field level. However, this observation was not interpreted as direct statistical evidence of an improvement in overall distribution-system reliability. System-level reliability requires quantitative information concerning interruption frequency, interruption duration, affected customers, and feeder-level performance. Indicators such as SAIFI, SAIDI, CAIDI, ENS, and AENS would require appropriate historical and longitudinal data.

The present study therefore uses *reliability* primarily in an operational sense: maintaining network continuity and reducing identifiable physical disturbance mechanisms. This distinction is important because the original manuscript itself recognizes that the available data are insufficient to calculate system-level reliability indicators.

Occupational Health and Safety Procedures

Because maintenance activities on 20-kV distribution networks involve electrical, mechanical, and environmental hazards, occupational health and safety procedures were included in the field observations. The assessment documented the implementation of personal protective equipment (PPE) and K3 procedures during maintenance activities. Safety observations were used to provide operational context for the maintenance process. They were not used to calculate an independent safety-performance score or to establish the effectiveness of the organization's occupational safety system.

Ethical Considerations

The study received ethical approval from the Lembaga Penelitian Universitas Islam Sultan Agung (UNISSULA) under reference number FT/LR-26-02.4421. The research procedures were conducted in accordance with the applicable institutional ethical requirements for field-based research. Participation in the interviews was voluntary, and the informants were informed about the purpose and general procedures of the study. Information obtained through interviews, field observations, and supporting documentation was used exclusively for research purposes. Confidentiality of informant identities and operational information related to the electricity distribution network was maintained throughout the research and reporting process. The study did not involve experimental intervention on human participants or manipulation of the electrical distribution system. Field observations and documentation were conducted without interfering with routine maintenance operations or compromising occupational safety procedures. All field activities followed the applicable safety requirements established at the research site.

Data Confidentiality and Organizational Considerations

Because the study was conducted within an operational electricity-distribution environment, information that could disclose sensitive operational details was treated with appropriate confidentiality. The analysis focuses on maintenance practices, observable physical hazards, and field-level maintenance outcomes rather than confidential operational parameters or security-sensitive information. Photographs and other documentary materials included in the final manuscript should be screened to ensure that they do not disclose confidential information or identifiable individuals without appropriate permission.

Methodological Scope and Study Boundaries

The methodological scope of this study is limited to the observed maintenance activities and network sections during the study period. The 40 maintenance events and 12 observation sections constitute the empirical scope of the case study, rather than a statistical sample intended to represent all PLN distribution networks or all Indonesian 20-kV networks. Accordingly, the findings are interpreted as case-specific field evidence concerning maintenance implementation and physical hazard mitigation. The study does not attempt to: 1) estimate the reliability of all 20-kV distribution networks; 2) calculate changes in SAIFI or SAIDI; 3) establish causal relationships between maintenance and outage reduction; 4) statistically generalize the observed maintenance distribution to other PLN operational units; or 5) quantify the economic cost-effectiveness of maintenance activities. These boundaries ensure that the methodological claims remain consistent with the data collected.

RESULTS

Overview of the Field Observation

Field observations were conducted from 1 February to 10 March 2026 across 12 observation sections of the 20-kV Medium-Voltage Overhead Distribution Network at PT PLN (Persero) ULP Demak. During the observation period, 40 maintenance events were documented and classified according to their primary operational purpose. The observed maintenance events consisted of 24 preventive maintenance events (60%), 10 corrective maintenance events (25%), and 6 emergency maintenance events (15%). Preventive maintenance therefore constituted the largest category among the maintenance events documented during the study period.

Table 4. Distribution of observed maintenance events

Maintenance category	Number of events	Percentage
Preventive maintenance	24	60%
Corrective maintenance	10	25%
Emergency maintenance	6	15%
Total	40	100%

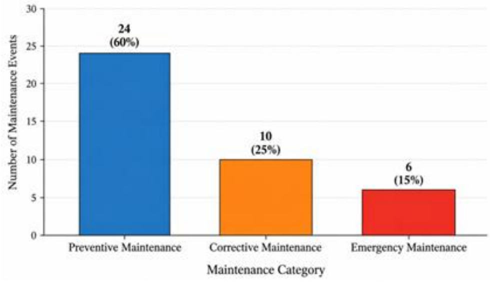

Figure 2. Distribution of Observed Maintenance Events by Category

The distribution provides a descriptive representation of the maintenance activities observed within the study case. The 60% proportion of preventive maintenance should be interpreted specifically within the 40 observed events and the study period, rather than as an estimate of the maintenance distribution across other PLN operational units or Indonesian 20-kV distribution networks.

Characteristics of Interview Participants

To complement the field observations, semi-structured interviews were conducted with **eight personnel** who had direct involvement in or operational knowledge of network maintenance. The participants consisted of two maintenance supervisors, four maintenance technicians, and two field/operational personnel.

Table 5. Characteristics of interview participants

Participant category	Number	Percentage
Maintenance supervisors	2	25.0%
Maintenance technicians	4	50.0%
Field/operational personnel	2	25.0%
Total	8	100%

Each interview lasted approximately 20–35 minutes. The interviews addressed maintenance procedures, hazard identification, operational constraints, maintenance decision-making, and post-maintenance inspection practices.

The interview findings were used primarily to provide contextual information for interpreting the observed maintenance activities rather than as a separate quantitative dataset.

Distribution and Characteristics of Maintenance Activities

he 40 documented maintenance events comprised three operational categories: preventive, corrective, and emergency maintenance. The classification was based on the primary operational purpose of each intervention, as defined in the Methods section. Preventive maintenance included activities intended to identify, control, or mitigate potential network problems before they developed into operational disturbances. The preventive activities observed in the field included network inspection, insulator cleaning, vegetation pruning, connection inspection, equipment-condition checking, and removal of identified potential hazards. Corrective maintenance involved interventions undertaken after defects or damage had been identified. The observed corrective activities included replacement of damaged insulators, conductor repair, and pole repair. These interventions were directed toward restoring or maintaining the physical condition of affected network components.

Emergency maintenance involved rapid intervention following unexpected disturbances that required immediate operational action to restore or stabilize network operation. Unlike preventive and corrective maintenance, emergency activities were characterized primarily by the need for timely field response to an unexpected operational condition. The field documentation provided direct visual evidence of several maintenance activities undertaken during the observation period. In particular, the documented activities included network intervention, vegetation pruning in the vicinity of the distribution network, and removal of foreign objects from the SUTM conductors. These activities illustrate how field maintenance was implemented in response to observed physical and environmental conditions.

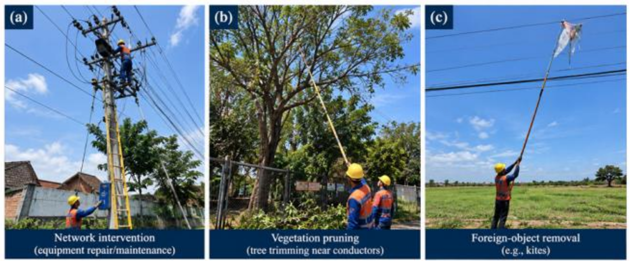

Figure 3. Field Evidence of Maintenance and Hazard Mitigation. (a) Network intervention, (b) vegetation pruning near the 20-kV distribution network, and (c) foreign-object removal from the SUTM conductors.

The visual evidence complements the descriptive field observations by demonstrating the physical implementation of maintenance interventions. Network intervention represents maintenance activity directed toward the network infrastructure, while vegetation pruning addresses an environmental condition surrounding the overhead distribution network. Foreign-object removal represents an intervention directed toward an external physical hazard that could interfere with the network environment. Taken together, the observations indicate that maintenance activities were not limited to responses to equipment defects. Field interventions also addressed environmental and physical conditions identified during inspection. This finding supports the field-based maintenance perspective of the study, in which maintenance activities are interpreted in relation to observed network conditions and identifiable hazards.

Environmental and Operational Hazards

Four principal categories of environmental and operational conditions were identified during field observations: 1) vegetation-related hazards; 2) foreign objects; 3) equipment-related conditions; and 4) accessibility constraints.

Table 6. Observed hazard categories and corresponding maintenance responses

Hazard/condition	Field observation	Maintenance response
Vegetation	Vegetation or branches located near the distribution network	Vegetation pruning
Foreign objects	Kites or other objects attached to or near conductors	Removal of foreign objects
Equipment condition	Components requiring inspection, repair, or	Inspection, repair, or

	replacement	replacement
Accessibility constraint	Network sections difficult to reach	Additional planning and coordination

Vegetation and foreign objects were repeatedly identified as important physical conditions requiring field intervention. Vegetation was observed in locations where branches could potentially approach or contact distribution conductors.

Foreign objects, particularly kites, were also observed attached to or entangled with network conductors. Following identification, the objects were removed and the affected network section was inspected. Accessibility constraints were observed in some network sections where field conditions made inspection or maintenance more difficult and required additional planning or coordination. The identification of these hazard categories is consistent with the original field observations reported in the manuscript.

Preventive Maintenance and Early Hazard Identification

Of the 40 documented maintenance events, 24 events (60%) were classified as preventive maintenance. Preventive interventions were primarily associated with early identification and control of potential hazards. Network inspection, vegetation pruning, foreign-object removal, and equipment-condition assessment were conducted before the identified physical conditions developed into more serious operational problems. The observed preventive activities indicate that maintenance operations included not only responses to existing equipment defects but also interventions directed toward controlling environmental and physical conditions surrounding the network.

Vegetation management was particularly relevant because vegetation growth represents a recurring environmental condition around overhead distribution networks. Similarly, foreign-object removal addressed external objects that could interfere with the physical operating environment of the network. The finding that preventive maintenance constituted 60% of the observed maintenance events provides quantitative descriptive support for the field observation that preventive intervention represented a substantial component of maintenance activities during the study period.

Before–After Changes in Network Condition

A qualitative before–after assessment was conducted to examine changes in observed network conditions following maintenance intervention.

Table 7. Before–after assessment of network conditions

Parameter	Before maintenance	Intervention	After maintenance	Observed outcome
Vegetation	Vegetation potentially approaching the conductor	Vegetation pruning	Affected vegetation cleared/reduced	Hazard reduced
Foreign objects	Kites/objects present	Object removal	Foreign objects no longer observed at affected section	Hazard removed
Equipment condition	Condition requiring inspection or intervention	Inspection/maintenance	Condition checked following intervention	Condition verified
Network hazard	Identified physical hazard present	Hazard mitigation	Identified hazard reduced or removed	Hazard mitigation observed
Network condition	Maintenance intervention required	Maintenance performed	Improved observed physical condition	Physical condition improved

The before–after observations showed that the identified physical hazards were addressed following the corresponding maintenance intervention.

For vegetation-related conditions, vegetation located near the distribution network was pruned, resulting in a visibly clearer area around the affected network section. For foreign objects, kites or other objects identified before intervention were removed, and the affected section was subsequently inspected. Equipment-related conditions were addressed through inspection and, where necessary, corrective intervention. The findings demonstrate changes in observed physical condition following maintenance, but they do not quantify the magnitude of change in electrical reliability.

Maintenance Intervention and Hazard-Control Pathway

The field observations demonstrated a consistent operational sequence between hazard identification and maintenance intervention.

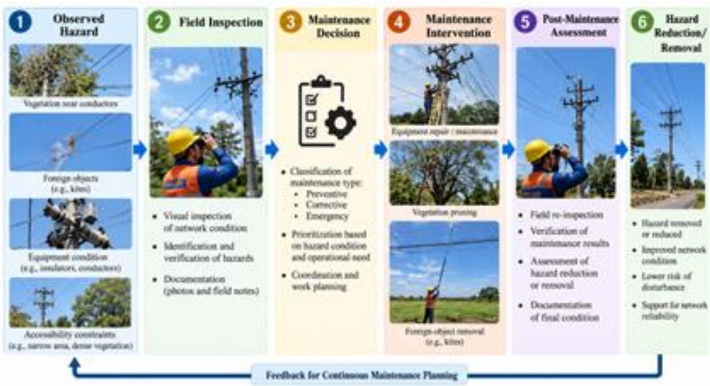

Figure 4. Field-Based Hazard Mitigation and Maintenance Pathway

Figure 4. Field-Based Hazard Mitigation and Maintenance Pathway. The figure illustrates the field-based process from hazard identification and inspection to maintenance decision, intervention, post-maintenance assessment, and observed hazard reduction or removal in the 20-kV medium-voltage distribution network.

This pathway was particularly evident for vegetation and foreign-object hazards. For vegetation, the sequence consisted of identifying vegetation near the network, performing pruning, and subsequently examining the affected section. For foreign objects, the sequence involved identification of the object, removal, and inspection of the affected network section. The observed sequence demonstrates that field maintenance activities were directly associated with identifiable physical conditions rather than being limited to predetermined maintenance actions.

Safety Implementation During Maintenance

The field observations also documented implementation of occupational health and safety procedures during maintenance activities. Maintenance personnel were observed using personal protective equipment (PPE) and following applicable K3 procedures during network inspection, vegetation management, equipment intervention, and other maintenance activities.

The observed implementation of PPE and K3 procedures formed part of the operational process accompanying maintenance activities.

However, because the study did not employ a quantitative safety-performance instrument, these observations are presented as evidence of safety-procedure implementation, rather than as a quantitative assessment of occupational safety performance. This distinction is consistent with the methodological boundary established in the manuscript.

Integrated Findings from Observation, Interviews, and Documentation

Integration of the three data sources—field observations, interviews, and documentation—provided a consistent description of the maintenance process. Field observations identified the physical conditions requiring intervention. Interviews provided contextual information concerning maintenance procedures, field constraints, and operational responses. Photographs and field documentation provided supporting evidence of maintenance activities and changes in physical network conditions. The combined evidence indicates that maintenance activities at the observed PLN ULP Demak network involved a recurring cycle of: **Inspection → hazard identification → intervention → post-intervention inspection.**

The field evidence particularly emphasized vegetation management, foreign-object removal, equipment inspection, and corrective intervention where physical defects were identified.

DISCUSSION

Preventive Maintenance as the Main Maintenance Pattern

The present study documented 40 maintenance events across 12 observation sections of the 20-kV Medium-Voltage Overhead Distribution Network at PLN ULP Demak. Preventive maintenance accounted for 24 events (60%), while corrective and emergency maintenance accounted for 10 (25%) and 6 (15%) events, respectively. This distribution indicates that, within the observed case and study period, maintenance activities were substantially oriented toward identifying and controlling potential problems before they developed into more serious operational disturbances.

The predominance of preventive maintenance is consistent with the broader development of maintenance strategies in electrical distribution systems, in which utilities increasingly combine preventive, condition-based, and reliability-centered approaches (Bostani et al., 2018, p. 2; Piasson et al., 2016, p. 42). Reliability-centered maintenance emphasizes the relationship between maintenance actions, component failure behavior, system reliability, and maintenance costs.

The present finding adds a field-level perspective to this body of research. Whereas previous studies have frequently addressed maintenance through reliability models, optimization approaches, or historical interruption data, the present study documents how preventive maintenance is implemented in actual field conditions (Ragma et al., 2026; Simard et al., 2023). The observed activities—including network inspection, vegetation pruning, foreign-object removal, and equipment-condition checking—represent practical mechanisms through which potential disturbance sources are identified and controlled (Mălinescu & Virca, 2022, p. 251; Mortensen et al., 2024, p. 5).

Nevertheless, the 60% proportion should not be interpreted as a general representation of preventive maintenance across PLN or Indonesian 20-kV distribution networks. It describes the 40 maintenance events observed during the specific study period and within the selected observation sections.

Field-Based Maintenance Provides an Operational Link Between Hazard and Intervention

An important finding of this study is the observable relationship between hazard identification and maintenance intervention. The field observations demonstrated a recurring sequence in which a physical or environmental condition was identified, an intervention was performed, and the affected network section was subsequently inspected. This sequence can be represented as:

Hazard identification → Maintenance intervention → Post-maintenance inspection → Observed hazard mitigation

The finding provides an operational perspective that complements reliability-centered maintenance research. Previous studies have developed quantitative approaches to connect maintenance decisions with component failure rates, reliability indices, and maintenance costs (Petropoulos et al., 2023, p. 526; Zio & Compare, 2012, p. 55).

In contrast, the present study focuses on the intermediate field-level process through which maintenance is implemented. This distinction is important because reliability improvement does not occur independently of physical maintenance actions. Before system-level reliability can be evaluated quantitatively, the physical mechanisms that may contribute to disturbances must first be identified and controlled (Endrenyi, 2001; Vogl et al., 2016, p. 94). The contribution of the present study therefore lies in documenting this field-level pathway rather than claiming a statistically measured reliability improvement.

Vegetation Management as a Recurring Environmental Maintenance Requirement

Vegetation was one of the recurring environmental conditions identified during field observations. Branches and vegetation located close to the distribution network were treated as potential hazards and addressed through pruning. This observation is consistent with previous research identifying vegetation management as an important component of overhead distribution-system maintenance. Correa-Tamayo et al. (2019) examined vegetation-management scheduling in relation to maintenance resources, costs, and network reliability, while Taylor et al. (2022) used historical data to examine the relationship between vegetation management and power outages during severe weather events.

The present study provides a different type of evidence. It does not quantify the relationship between vegetation and outage frequency; instead, it documents the physical maintenance mechanism through which vegetation exposure is controlled. This distinction is important. The observation that vegetation was pruned demonstrates that a physical hazard was identified and addressed, but it does not demonstrate that the intervention produced a measurable reduction in SAIFI, SAIDI, or outage duration. Accordingly, vegetation management in this study is best interpreted as asset-level hazard mitigation rather than direct quantitative evidence of system-level reliability improvement. The recurring nature of vegetation-related maintenance also indicates a potential opportunity for more systematic maintenance planning. Information concerning vegetation location, recurrence, growth characteristics, network criticality, and previous disturbance history could potentially be incorporated into risk-informed maintenance prioritization (Pacevicius et al., 2024; Zhao et al., 2025, p. 1). Such an approach is consistent with the direction of reliability-centered and risk-based maintenance research.

Foreign Objects Represent an Additional Maintenance Challenge

In addition to vegetation, foreign objects—particularly kites—were identified during field activities. These objects required removal followed by inspection of the affected network section. The finding highlights that maintenance requirements are not determined exclusively by the deterioration of electrical components. External environmental and human-related factors can also create physical conditions requiring intervention. This observation is relevant to maintenance planning because different disturbance mechanisms require different preventive responses. Vegetation hazards may require scheduled pruning, whereas foreign objects may require inspection, removal, and potentially additional public-awareness or environmental-management measures (Ji et al., 2017, p. 1356; Mortensen et al., 2024, p. 8).

Previous research has demonstrated the value of explicitly considering interruption causes in maintenance planning. Moghadam et al. (2023), for example, incorporated different interruption mechanisms into long-term maintenance planning for a real medium-voltage overhead network and connected these mechanisms with reliability indicators such as SAIFI, SAIDI, ENS, and AENS. The present study does not establish the contribution of kites or other foreign objects to actual network outages. Their significance in this study is therefore operational: they represent identifiable physical hazards that required intervention. Quantifying their contribution to network interruptions would require integration of the field observations with historical outage records.

Before–After Changes Demonstrate Physical Hazard Mitigation

The before–after assessment showed observable improvement in the physical condition of affected network sections following maintenance. Vegetation that was potentially approaching conductors was pruned, foreign objects were removed, and equipment conditions were inspected after intervention. These findings demonstrate that the observed maintenance activities addressed the specific physical conditions identified during field inspection. The result is consistent with the fundamental principle of reliability-centered maintenance, in which maintenance interventions are intended to reduce exposure to failure mechanisms. Previous research has established quantitative relationships between maintenance measures, component failure behavior, and reliability performance (Arno et al., 2015; Liu et al., 2023). However, the present study provides only qualitative before–after evidence. A physical hazard being removed does not necessarily imply that the probability of a system interruption has decreased by a measurable amount. For example, removing vegetation from one network section may reduce exposure at that location while other components, weather events, equipment failures, switching operations, or unrelated disturbance mechanisms continue to influence feeder-level reliability. Therefore, the observed improvement should be interpreted as improved physical network condition and reduced exposure to identified hazards, rather than as direct evidence of increased system reliability.

Relationship Between Maintenance Intervention and Distribution-System Reliability

The findings support a conceptual relationship between maintenance intervention and distribution-system reliability, but this relationship should be interpreted within the limits of the available evidence.

The observed interventions reduced identifiable physical exposure to potential disturbance mechanisms. In operational terms, inspection, vegetation pruning, foreign-object removal, and equipment checking provide mechanisms through which maintenance can contribute to the continuity of distribution-network operation. Previous quantitative studies provide stronger evidence for linking maintenance with reliability performance. Piasson et al. (2016, p. 41) incorporated SAIDI and SAIFI into a preventive-maintenance optimization framework, while Moghadam et al. incorporated SAIDI, SAIFI, ENS, and AENS into long-term maintenance planning.

Research in the Indonesian context has similarly demonstrated the potential to connect maintenance strategies with measurable distribution-system performance using indicators such as SAIFI, SAIDI, energy not supplied, feeder disturbance, and overall equipment effectiveness. Compared with these studies, the present research contributes field-based evidence of how maintenance is implemented and how identified physical hazards change following intervention. Its contribution is therefore complementary rather than a replacement for quantitative reliability analysis.

Implications for Condition-Based and Risk-Informed Maintenance

The observation of recurring vegetation, foreign objects, equipment conditions, and accessibility constraints indicates that routine field inspection can potentially generate valuable information for condition- and risk-informed maintenance. Condition-based maintenance approaches emphasize the use of inspection information to determine when and where maintenance should be performed. Wang et al. (2023)developed an opportunistic condition-based maintenance framework in which observed equipment conditions were incorporated into maintenance decisions. The present findings suggest that field maintenance records at PLN ULP Demak could potentially be structured into a database containing: Location of the hazard; Hazard type; Recurrence; Affected network component; Maintenance action; Date of intervention; Post-maintenance condition; and Subsequent disturbance history.

Such information could support a transition from a purely activity-oriented maintenance system toward a more evidence-based process:

Routine inspection → Hazard identification → Risk evaluation → Maintenance prioritization → Reliability monitoring

The present study does not implement such an optimization model. Rather, it provides the field-observation basis for its potential development.

Integration of Field Evidence and Reliability Data

One implication emerging from the study is the importance of integrating field maintenance information with system-level reliability data. The current field observations identify what physical hazards were encountered and how they were addressed, while reliability records would be required to determine whether and to what extent these interventions influence network performance over time. An integrated dataset could combine:

Table 8. Integrated Field Maintenance and System Reliability Data Framework

Field maintenance data	Reliability data
Maintenance date	Outage date
Location/section	Feeder
Hazard type	Outage cause
Maintenance category	Outage duration
Intervention	Number of affected customers
Post-maintenance condition	SAIFI
Recurrence	SAIDI
Equipment condition	CAIDI/ENS

Such integration would allow future research to move beyond descriptive evidence toward quantitative evaluation of maintenance effectiveness.

This is particularly important because reliability is a system-level property and cannot be adequately assessed from a single physical maintenance event. The original study appropriately recognizes that quantitative reliability assessment requires historical interruption frequency, duration, affected customers, and feeder-level performance data.

Safety as an Integral Component of Maintenance Implementation

The study also documented PPE use and K3 implementation during maintenance activities. This observation is relevant because medium-voltage maintenance involves electrical, mechanical, and environmental hazards. Maintenance effectiveness should therefore not be considered solely in terms of whether a physical network hazard is removed. Maintenance activities must also be conducted within appropriate safety procedures. The present study, however, does not independently evaluate occupational safety performance. K3 observations are therefore interpreted as part of the operational context of maintenance rather than as evidence of a quantified improvement in safety performance.

Practical Implications for PLN ULP Demak

The findings have several practical implications for maintenance management at the operational-unit level. First, the recurring identification of vegetation and foreign objects suggests that environmental hazard monitoring should remain an important component of routine 20-kV SUTM inspection. Second, the observed 60% share of preventive maintenance indicates that early identification and intervention formed a substantial part of the documented maintenance activities during the study period. Third, maintenance records could be strengthened by consistently recording the location, hazard type, recurrence, intervention, and post-maintenance condition of each maintenance event. Fourth, the integration of maintenance records with feeder-level interruption data would provide a stronger basis for evaluating whether particular interventions are associated with measurable changes in reliability performance. Finally, technologies such as sensors, digital inspection systems, and UAV/drone-based inspection could potentially improve the systematic collection of network-condition information. However, their effectiveness should be established empirically rather than assumed.

Theoretical and Practical Contribution

The theoretical contribution of this study lies in strengthening the field-level understanding of the relationship between maintenance intervention and physical hazard mitigation in medium-voltage overhead distribution networks. The study complements reliability-centered and condition-based maintenance literature by emphasizing the operational stage that precedes quantitative reliability measurement:

Observed condition → Maintenance decision → Physical intervention → Post-maintenance condition

From a practical perspective, the study demonstrates how routine field observations can be structured into information that may subsequently support risk-informed maintenance prioritization. The contribution should therefore be understood as a field-based empirical case study, rather than as a statistical reliability model.

Limitations and Interpretation of the Findings

Several limitations should be considered when interpreting the findings. First, the study was conducted within a single operational unit, PLN ULP Demak, and involved 12 observation sections. Therefore, the findings should not be statistically generalized to all 20-kV distribution networks. Second, the analysis involved 40 observed maintenance events. Although this provides a structured basis for descriptive case analysis, the events were not selected as a probability sample of the broader population of maintenance activities. Third, the before–after assessment was primarily qualitative. Consequently, it demonstrates changes in observed physical conditions but does not establish the magnitude of changes in electrical reliability. Fourth, the study did not include sufficient longitudinal outage data to calculate or compare SAIFI, SAIDI, CAIDI, ENS, or AENS.

These limitations define the appropriate interpretation of the findings: the study provides evidence of maintenance implementation and physical hazard mitigation, while quantitative system-level reliability assessment remains a subject for future research. The original manuscript similarly identifies the absence of network-wide asset statistics, interruption records, and quantitative reliability indicators as important limitations.

Recommended Future Research

Future research should extend the present field-based approach by integrating maintenance observations with longitudinal reliability and operational datasets. A stronger quantitative design could combine: Maintenance-event records; Hazard recurrence; Feeder characteristics; Outage frequency; Outage duration; Affected customers; Saifi; Saidi; Caidi; Ens/aens; and Maintenance costs.

Such a dataset would enable researchers to examine whether specific preventive interventions are associated with measurable changes in feeder-level reliability over time. A longitudinal design would also make it possible to evaluate whether recurring hazards—particularly vegetation and foreign objects—are associated with subsequent disturbance events and whether targeted preventive intervention changes their recurrence.

CONCLUSION

This study examined maintenance practices and hazard mitigation in the 20-kV Medium-Voltage Overhead Distribution Network (SUTM) at PLN ULP Demak using a field-based descriptive case-study approach. Based on observations across 12 network sections and 40 identified maintenance events, three categories of maintenance activities were documented: preventive, corrective, and emergency maintenance. Preventive maintenance accounted for 24 events (60%), followed by corrective maintenance with 10 events (25%) and emergency maintenance with 6 events (15%). Within the scope of this case study, the distribution of activities indicates that preventive intervention constituted the main observed maintenance pattern.

The field observations identified vegetation and foreign objects, particularly objects such as kites, as recurring environmental hazards requiring maintenance attention. Equipment condition and accessibility were also relevant operational considerations. Maintenance interventions—including vegetation pruning, removal of foreign objects, equipment inspection, and corrective repair—were associated with observable reductions or removal of physical hazards. The before–after assessment therefore provides field-level evidence of physical hazard mitigation following maintenance intervention.

A key contribution of this study is the empirical description of the operational pathway from hazard identification → maintenance intervention → post-maintenance inspection → observed hazard mitigation. This pathway demonstrates how field maintenance activities can provide an operational basis for condition-based and risk-informed maintenance practices in medium-voltage distribution networks. The findings also indicate the importance of systematically documenting environmental hazards, maintenance actions, component conditions, and post-maintenance conditions to support subsequent reliability analysis.

However, the findings should not be interpreted as quantitative evidence of improvement in system-level electrical reliability. The study did not include sufficient longitudinal outage data to calculate reliability indices such as SAIFI, SAIDI, CAIDI, or ENS. In addition, the study was limited to one PLN operational unit, 12 observation sections, and 40 maintenance events, with purposive rather than probability sampling. Consequently, the results primarily describe field-level maintenance practices and observed physical hazard mitigation within the study context.

Future research should integrate field maintenance records with feeder-level reliability data, including outage frequency and duration, affected customers, feeder characteristics, maintenance costs, and reliability indices. Such integration would allow the relationship between maintenance interventions, hazard recurrence, and measurable distribution-system reliability to be evaluated quantitatively.

DECLARATION

Ethical Approval

This study received ethical approval from the Research and Community Service Institute of Universitas Islam Sultan Agung (Lembaga Penelitian UNISSULA) under approval/reference number FT/LR-26-02.4421. The study was conducted in accordance with the applicable institutional ethical requirements and procedures for field-based research. Participation in interviews was conducted on a voluntary basis, and information obtained from participants and field observations was used solely for research purposes. Operational information obtained from the study site was treated confidentially and presented in accordance with applicable institutional requirements.

Consent to Participate

Informed consent was obtained from the interview participants before the interviews were conducted.

Author Contributions (CRediT)

Mohammad David Kurniawan: Conceptualization, methodology, field investigation, data collection, formal analysis, and original manuscript preparation.

Ida Widihastuti: Supervision, methodological review, interpretation of findings, and critical revision of the manuscript.

Both authors reviewed and approved the final version of the manuscript.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The data supporting the findings of this study are subject to applicable organizational and confidentiality restrictions. Non-confidential data may be made available by the corresponding author upon reasonable request and with permission from the relevant organization.

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During the preparation of this manuscript, generative artificial intelligence tools were used to assist with language refinement and manuscript structuring. The authors reviewed and verified the scientific content, interpretation, references, and final manuscript and take full responsibility for the accuracy and integrity of the published work. No confidential organizational, personal, or participant information was intentionally entered into generative artificial intelligence tools.

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