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Implementation of Early Warning System (EWS) Feature on Mobile Tower Battery in Realtime to Reduce Mobile Tower Downtime

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Abstract

Mobile tower network reliability at PT Antareja Mahada Makmur (AMM), Mifa Jobsite, was partially dependent on battery performance. However, the existing monitoring procedures relied on manual inspections, potentially delaying the detection of voltage drops, particularly during shift transitions. This study aimed to design, implement, and evaluate a real-time early warning system (EWS) for mobile tower batteries using an ESP32 microcontroller, applying the eight-step Quality Control Circle (QCC) methodology and the Plan–Do–Check–Act (PDCA) cycle. Operational records, field observations, team discussions, and cause-and-effect (fishbone) analysis were employed to identify the absence of automated battery monitoring and alert mechanisms as a primary operational issue. The developed system continuously monitored battery voltage and generated automatic notifications when voltage readings fell below 12 V in 12 V operating mode or 24 V in 24 V operating mode. Following implementation, monthly local area network (LAN) availability increased from 92.87% in January 2026 to 99.51% in April and remained at 99.49% in May 2026. Furthermore, no battery-related mobile tower downtime was recorded during the first week of April, compared with documented incidents during the corresponding period in January. These before-and-after findings indicated improvements in operational performance, although the observational design did not establish that the EWS alone caused the increase in network availability. The implementation demonstrated the potential of automated battery monitoring to facilitate earlier fault detection, accelerate maintenance responses, and support network reliability and preventive maintenance practices. Further research involving longer monitoring periods and additional battery health indicators was recommended to evaluate the system's sustained effectiveness and operational reliability.

INTRODUCTION

PT Antareja Mahada Makmur (AMM) supported mining operations at the Mifa Jobsite by providing information and communication technology (ICT) services, including data networking and telecommunications infrastructure (Dananjaya et al., 2024; Hidayatullah et al., 2024; Sitorus et al., 2024). Mobile communication towers played a critical role in maintaining connectivity across geographically dispersed mining areas, making reliable power supply systems and timely

equipment fault detection essential for ensuring operational continuity (Deevela et al., 2024; Uwamahoro et al., 2021). The reliability of these communication networks depended on effective infrastructure maintenance, particularly the continuous monitoring of battery conditions to prevent unexpected service disruptions.

Mobile tower operations relied heavily on battery performance to maintain uninterrupted network connectivity. However, existing maintenance procedures primarily depended on manual inspections and fault reports submitted after operational disruptions had occurred. Consequently, battery voltage could decline without timely detection by the ICT team, particularly during shift transitions when operational responsibilities and technical information were transferred between personnel. These limitations in monitoring procedures increased the likelihood of network interruptions, delayed maintenance responses, and unnecessary field inspections, potentially compromising the reliability and efficiency of telecommunications services.

Operational records from the first week of January 2026 documented five battery voltage drop incidents affecting mobile tower operations, exceeding the established target of zero incidents. These findings highlighted the urgent need for an automated monitoring mechanism capable of detecting battery voltage deterioration before it resulted in network outages. Implementing an effective early warning system was also expected to reduce reliance on repetitive manual inspections at remote tower locations, improve maintenance response times, and establish more consistent operational procedures for addressing battery-related faults.

Previous studies have demonstrated the application of ESP32 microcontrollers in Internet of Things (IoT)-based battery monitoring systems, including automated voltage measurement and notification mechanisms for solar energy and industrial applications (Bachri et al., 2026; Perdana & Irawan, 2026; Rehman et al., 2024; Wahono et al., 2026; Winata & Surantha, 2023). Furthermore, research on telecommunications infrastructure has emphasized the importance of connected monitoring data in supporting preventive and predictive maintenance strategies (Li et al., 2023; Mahmood & Munir, 2020; Ucar et al., 2024). These findings provided a technical foundation for integrating continuous battery voltage monitoring and automated alert mechanisms into mobile telecommunications infrastructure, particularly in operational environments requiring reliable network connectivity.

Despite these technological developments, previous research had not adequately addressed the integration of ESP32-based battery voltage monitoring with structured operational improvement methodologies, particularly within shift-transition procedures at mining-site telecommunications facilities. Existing studies primarily emphasized technical monitoring capabilities, while limited attention was given to the organizational processes required to ensure timely responses to automated alerts and evaluate their operational outcomes. Accordingly, the identified research gap concerned the integration of an automated voltage monitoring system with the eight-step Quality Control Circle (QCC) methodology to improve maintenance coordination, standardize fault response procedures, and assess network reliability using operational performance indicators (Aliyudin & Setijadi, 2026; Nemer & Vieira, 2018; Sari & Nurwathi, 2023; Setiawan et al., 2025; Sumasto et al., 2024; Wang et al., 2013).

The novelty of this study was its integration of automated battery voltage threshold monitoring for 12 V and 24 V operating modes with the Plan–Do–Check–Act (PDCA) cycle (Deming, 1986; Yuliarty et al., 2024), root-cause analysis (Rahman et al., 2025), standardized maintenance responses, and comparative assessments of network availability before and after system

implementation. Unlike approaches focusing exclusively on technological functionality, this study incorporated technical monitoring and organizational improvement processes within a unified operational framework. Changes in network availability were evaluated as observational performance outcomes rather than definitive causal effects attributable solely to the implemented early warning system, given the absence of a controlled experimental design.

Accordingly, this study aimed to identify the primary causes of battery-related mobile tower downtime, design and implement an ESP32-based real-time early warning system (EWS), and evaluate changes in network availability following implementation. The study also examined operational implications using the Quality, Cost, Delivery, Safety, and Morale (QCDSM) framework to assess potential improvements in maintenance efficiency and service reliability. The findings were expected to provide practical guidance for ICT personnel in implementing cost-effective battery monitoring solutions, improving early fault detection, and standardizing maintenance response procedures. Furthermore, the study sought to establish a foundation for subsequent evaluations involving longer monitoring periods and additional battery health indicators to assess the system's sustained effectiveness and operational reliability.

METHOD

This study employed a case study approach using the eight-step Quality Control Circle (QCC) methodology, structured around the Plan–Do–Check–Act (PDCA) cycle. The research procedures comprised problem identification and data collection, root-cause analysis, solution development, improvement planning, implementation, effectiveness evaluation, standardization, and identification of subsequent improvement priorities.

Data were collected from local area network (LAN) availability records, battery-related mobile tower downtime reports covering January to May 2026, field observations, and team brainstorming sessions concerning existing battery monitoring procedures. Root causes were identified using Ishikawa cause-and-effect diagrams, focusing on human, methodological, and equipment-related factors (Ishikawa, 1985). Improvement targets were established using the SMART framework, while implementation activities included equipment procurement, system design, programming, installation, and functional testing.

The proposed technical solution was developed using an ESP32 microcontroller-based battery voltage monitoring system with wireless network (Wi-Fi) connectivity and automated alert capabilities. The system design drew on previous applications of Internet of Things (IoT)-based battery monitoring technologies in solar energy systems (Bachri et al., 2026; Wahono et al., 2026) and industrial equipment monitoring with automated notifications (Perdana & Irawan, 2026). System performance was evaluated by comparing LAN availability and the frequency of battery-related mobile tower downtime before and after implementation during the January–May 2026 observation period. Additional operational impacts were assessed using the Quality, Cost, Delivery, Safety, and Morale (QCDSM) framework.

RESULTS AND DISCUSSION

Problem Identification and Goal Setting

At the data collection stage, it was identified that monitoring the condition of mobile tower batteries in existing conditions still relied entirely on manual checking, without recorded voltage data history or dashboard monitoring. This condition was reflected in the occurrence of mobile

tower downtime due to batteries recorded in Week 1 of January 2026, with the number of battery drop incidents in the initial observation period reaching five incidents from the zero target. Based on these gaps, the team set improvement targets using the SMART framework as presented in Table 2.

Table 2. Setting improvement goals based on SMART criteria

SMART Criteria	Goal Formulation
Specific	Implements ESP32-based mobile tower battery voltage monitoring system with real-time notifications to detect voltage drops below 12V (12V mode) and 24V (24V mode)
Measurable	Reduces mobile tower downtime due to battery detection delays by ±90%
Achievable	Targets can be achieved by utilizing IoT technology (ESP32) for automatic monitoring and real-time notifications without the reliance on manual checking
Realistic	Supports increased operational reliability of mobile tower networks and reduces downtime, especially during change shifts
Time-based	Implementation and evaluation will be carried out within three months, February-April 2026

Source: QCC project target setting reported in the manuscript.

Causal Analysis and Determination of Dominant Causal Causes

The cause-and-effect analysis of the problem of "high mobile tower downtime during change shift" was carried out using a fishbone diagram (Ishikawa, 1985) in three categories: Method, Man, and Machine, as summarized in Table 3.

Table 3. Analysis of the cause and effect of high mobile tower downtime during change shift

Categories	Identified Causes	Root Causes
Method	Monitoring is still done manually; battery checks are not real-time; teams still rely on direct checks to the location	There is no monitoring system and EWS (early warning system)
Man	The team is not aware of the actual condition of the battery; does not receive information on the condition of the battery; there is no notification when the battery drops	There is no monitoring system and EWS (early warning system)
Machine	The battery voltage drops below the device's power specifications; the battery performance decreases; the mobile tower often runs out of power; the battery condition is not monitored in realtime	There is no monitoring system and EWS (early warning system)

Source: QCC team fishbone and root-cause analysis.

The results of the analysis showed that the three categories — Method, Man, and Machine — consistently boiled down to the same root cause, namely the lack of a monitoring system and an early warning system (EWS) to monitor the condition of the mobile tower battery in real-time. Without these systems, the ICT team did not obtain early information about the decline in battery voltage, so treatment was only carried out after the downtime actually occurred, especially at critical moments such as shift changes. These findings became the basis for the team to focus on the development of an automated monitoring system based on IoT technology, in line with a cause-effect analysis approach that emphasizes the importance of addressing the root of structural problems rather than dealing with the symptoms of each event separately.

Determination of Solution

Based on the dominant root causes, the team developed and assessed several alternative technical solutions — including strengthening SOPs for manual checks during change shifts,

procurement of commercial monitoring devices from third parties, and developing microcontroller-based self-monitoring systems — taking into account the criteria of implementation cost, speed of implementation, and ease of integration with existing network infrastructure. The selected solution is the implementation of an ESP32-based mobile tower battery monitoring system with real-time notifications, considering that these microcontrollers offer integrated Wi-Fi connectivity, relatively low device costs, and high programming flexibility to support the needs of continuous battery voltage monitoring (Bachri et al., 2026; Perdana & Irawan, 2026). This solution is also considered to be most aligned with the technical competence of the internal ICT team, so that it can be developed and maintained independently without long-term dependence on external vendors.

Improvement Plan and Implementation

The implementation of the solution is carried out through five main stages, namely: (1) procurement of equipment in the form of ESP32 modules and voltage sensors; (2) the design of a monitoring system that integrates ESP32 with the voltage sensor at the mobile tower battery measurement point; (3) the programming (coding) of a real-time notification system that sends automatic alerts when the battery voltage is below the threshold of 12V (12V mode) or 24V (24V mode); (4) the installation of monitoring devices on mobile tower units in the field; and (5) testing and validation of the system, including the test of the notification function and the stability test of the network connection on the installed device.

The developed system is integrated with a monitoring dashboard so that the battery condition of the entire mobile tower can be monitored centrally by the ICT team. This implementation provides benefits on three main aspects as summarized in Table 4: operational aspects, response and maintenance aspects, and internal aspects of the ICT Department.

Table 4. Benefits of implementing ESP32-based mobile tower battery monitoring system

Aspects	Benefits of Implementing ESP32-Based Monitoring System
Operational	Monitor the condition of the mobile tower battery in real-time; automatically detect voltage drop (12V/24V); reduce downtime due to detection delays
Response & Maintenance	Provide real-time notifications as early warnings; speed up handling response before a disturbance occurs; support a more preventive maintenance system
Internal ICT	Reduce reliance on manual monitoring; increase team awareness of battery conditions; facilitate centralized control and supervision of mobile towers

Source: Project implementation analysis reported in the manuscript.

The implementation of the system also has a positive impact on related stakeholders. For all departments (All Dept), this system provides centralized mobile tower monitoring in real-time, faster response through automatic notifications, and reduced downtime that supports operational continuity. For AMM Site Mifa employees in general, this implementation provides more stable and reliable network availability, transparent and real-time information on mobile tower conditions, and reduces the need for manual checks to the location so that the ICT team's work activities become safer and more efficient.

Evaluation of Improvement Results

Evaluation of target achievement was carried out by comparing LAN availability data before and after the implementation of the monitoring system. Table 5 presents monthly network availability data in the January–May 2026 period.

Table 5. Monthly LAN network availability for the period January–May 2026

Month	Actual LAN Availability (%)	Remarks
January 2026	92,87	Condition before full implementation; there was a battery down event in Week 1
February 2026	95,34	Early period of implementation of the ESP32 monitoring system
March 2026	98,64	The monitoring system is running and starting to show improvement in availability
April 2026	99,51	No battery downs were found in Week 1, April 2026
May 2026	99,49	Availability remains at a level above 99% post-implementation

Source: AMM Site Mifa monthly LAN availability records reported in the manuscript.

The data in Table 5 show a consistent trend of increasing availability, from 92.87% in January 2026 to above 99% in April and May 2026. More specific success indicators are shown in the comparison of Week 1 conditions: in Week 1 January 2026, there were recorded mobile tower downs due to battery conditions, while in Week 1 April 2026 — after the ESP32-based monitoring system was fully operational — no more battery downs were found. Supporting data for weekly LAN KPIs (W1–W24) also showed a similar pattern, with actual achievements gradually exceeding the achievement target of 95% since the middle of the implementation period. Based on these results, the team concluded that the implementation of an ESP32-based monitoring system proved effective in reducing mobile tower downtime through early warning of battery voltage drops.

Impact evaluation was also carried out on the five dimensions of Quality, Cost, Delivery, Safety, and Morale (QCDSM), as summarized in Table 6. In the Quality aspect, real-time monitoring increases the overall reliability of the mobile tower network. In the Cost aspect, the system helps reduce the potential for losses due to downtime and the risk of more severe battery damage if low voltage conditions are left for a long time; The potential for lost costs in existing conditions arises when the battery too often experiences a voltage drop below the threshold, which accelerates the decline in battery health and long-term battery storage. In the Delivery aspect, the team's response becomes faster so that downtime decreases. In the Safety aspect, reducing the need for manual checks to the location also avoids the risk of human error and exposure to less safe field conditions. In the Morale aspect, the team's awareness of the condition of the mobile tower battery increases, so that teamwork becomes more effective and directed.

Table 6. Impact of implementation on the dimensions of Quality, Cost, Delivery, Safety, and Morale (QCDSM)

QCDSM Dimensions	The Impact of the Implementation of ESP32-Based Monitoring System
Quality	Real-time monitoring improves the reliability of the mobile tower network
Cost	Reduces potential downtime and risk of long-term battery damage due to repeated drop voltages
Delivery	Faster handling response so that downtime duration decreases
Safety	Reduce manual checks to the site to avoid the risk of human error
Morale	ICT team's awareness of battery condition increases, teamwork is more effective

Source: QCC team QCDSM assessment reported in the manuscript.

Standardization

Based on the results of the implementation and evaluation, the team set a new standard in the process of monitoring the condition of mobile tower batteries using an ESP32-based system with real-time notifications as an early warning system. The points of the new standard include: monitoring of battery condition is carried out in real-time using the ESP32 system; automatic notifications are sent when the voltage is below standard (<12V in 12V mode and <24V in 24V mode); the team is required to respond to notifications within a maximum of 10 minutes; manual monitoring is no longer used as the main method, but as a backup; and monitoring data is documented and used as a basis for evaluation and continuous preventive maintenance.

The standard operating procedure (SOP) that is set includes five steps: (1) the ESP32 system is activated and connected to the network; (2) the sensor reads the battery voltage continuously; (3) if the voltage is below the threshold, the system automatically sends a notification; (4) the team receives a notification and immediately takes action to handle it; and (5) the handling results are recorded as evaluation data. This standardization aims to ensure that the battery monitoring system runs consistently, increase the team's response speed, and prevent repeated downtime in the mobile tower due to delays in detecting battery conditions.

As a continuation of the continuous improvement cycle, the QCC ICT team set the next theme, namely "Hybrid Shield: Multi-Source Power Protection System for Continuous Uptime Server", which is directed to expand the scope of monitoring and power protection not only on mobile tower batteries, but also on the server infrastructure that is the backbone of ICT services at the MIFA AMM Site.

Discussion and Comparison with Previous Studies

The findings of this study are consistent with a number of previous studies that show the effectiveness of the ESP32 microcontroller as the basis of a real-time battery monitoring system in various application domains, ranging from solar power systems (Bachri et al., 2026; Wahono et al., 2026) to battery monitoring systems on industrial equipment with automatic notifications through messaging applications (Perdana & Irawan, 2026). A common pattern in these studies is the ability of ESP32 to detect battery voltage drops early and send notifications to operators without the need for intensive manual checks, as also evidenced by the implementation of the mobile tower battery EWS system in this study. Compared to conventional manual monitoring approaches, IoT-based systems have been consistently proven to be able to accelerate detection and response times to degraded battery conditions, thereby directly contributing to a reduction in infrastructure downtime.

In the broader context of the telecommunications industry, the application of predictive and preventive maintenance approaches based on IoT and big data has also been proven to help network operators control the time and cost of maintaining Radio Access Network (RAN) infrastructure, including power supply devices such as batteries (Mahmood & Munir, 2020). This research strengthens this evidence in the specific context of mobile tower operations in mining environments, which have unique characteristics in the form of dispersed, dynamic work areas, and have limited access compared to telecommunication infrastructure in urban areas. The main contribution of this research lies in the integration of the QCC-PDCA methodology with IoT-based technical solutions developed independently by the in-house team, so that the resulting solutions are not only technically effective, but also low cost and easy to maintain without long-term dependence on external vendors.

This research has a number of limitations that need to be considered in application and follow-up research. First, the evaluation of the success of the new system covers a five-month period (January–May 2026), so the long-term sustainability of the system's performance, including the resistance of the ESP32 device to extreme mining environmental conditions (dust, humidity, and vibration), needs to be continuously monitored. Second, the currently developed system focuses on monitoring battery voltage as the main parameter, while other supporting parameters such as battery temperature, charging current, and quantitatively estimated battery state-of-health have not been explicitly covered, as has been applied to several other more comprehensive IoT battery monitoring systems (Bachri et al., 2026). Third, the success of the system also depends on the team's discipline in responding to notifications according to the set time standard (≤10 minutes), so compliance aspects with the new SOPs need to be continuously evaluated through periodic audits so that the benefits of the system can be maintained consistently.

CONCLUSION

The implementation of the eight-step Quality Control Circle (QCC) methodology, integrated with the Plan–Do–Check–Act (PDCA) cycle, successfully identified the primary factors contributing to mobile tower downtime during shift transitions, particularly the absence of an automated battery monitoring system and a real-time early warning system (EWS). The implementation of an ESP32-based battery monitoring system with automated real-time notifications was associated with improved local area network (LAN) availability, which increased from 92.87% in January 2026 to over 99% in April and May 2026. Furthermore, no battery-related mobile tower downtime incidents were recorded during the first week of April 2026, compared with documented incidents during the first week of January 2026. These findings indicated improvements in operational reliability and maintenance responsiveness, although the observed changes could not be attributed exclusively to the implemented system without further controlled evaluation. The intervention also demonstrated potential operational benefits across the Quality, Cost, Delivery, Safety, and Morale (QCDSM) dimensions within the Information and Communication Technology (ICT) Department at PT Antareja Mahada Makmur (AMM), Mifa Jobsite.

Based on these findings, several recommendations were proposed to strengthen the sustainability and effectiveness of the implemented system. First, the ESP32-based battery monitoring system should be standardized and progressively deployed across mobile towers at other jobsites with comparable operational characteristics, following appropriate technical validation. Second, future system enhancements should incorporate additional battery health indicators, including temperature, charging current, and state-of-health (SOH) estimation, to support more comprehensive condition monitoring and predictive maintenance strategies. Third, the ICT Quality Control Circle team should continue its improvement initiatives by exploring the proposed project, "Hybrid Shield: Multi-Source Power Protection System for Continuous Server Uptime," to extend power protection capabilities across critical ICT infrastructure. Finally, periodic compliance audits of standard operating procedures (SOPs) for alert acknowledgment, incident escalation, and maintenance responses should be conducted to ensure consistent system operation, timely corrective actions, and sustained improvements in network reliability.

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