

# Optimizing Heritage Power Distribution Using Zonal TM/TR-Package Systems

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**Abstract:** Electrical power distribution in heritage conservation areas faces the dual challenge of meeting modern technical standards while adhering to strict preservation regulations. Traditional centralized low-voltage systems often result in critical voltage drops and power losses due to extended feeder lengths. This study proposes and evaluates an optimized Zonal TM/TR-Package distribution system as a solution. Using ETAP 22.5 software, a comparative load flow analysis was conducted on a 20-hectare government heritage complex comprising 21 protected buildings. The simulation results confirm that the proposed zonal configuration significantly outperforms the existing centralized system, reducing maximum voltage drops from 12.04% to 4.48% and decreasing total active power losses ( $I^2R$ ) by 47.6%, and improving system efficiency from 95.32% to 97.50%, ensuring full compliance with PUIL 2020 safety standards. Critically, the reliability assessment — evaluated using SAIDI and SAIFI indices — demonstrates a 37.44% improvement in SAIDI (from 9.27 to 5.80 hours/customer/year), while SAIFI remains stable at 0.77 interruptions/customer/year, confirming that zonal fault isolation substantially reduces outage duration without increasing interruption frequency. Furthermore, the modular design minimizes physical footprint, preserving the site's aesthetic value. Beyond a case study, this research contributes to electrical engineering science by establishing a replicable technical framework for revitalizing heritage infrastructure, balancing efficient power delivery with architectural conservation.

**Keywords:** Heritage Power Distribution, Voltage Drop Analysis, ETAP Simulation, Zonal Distribution System, Electrical Conservation

## Introduction

Electrical power distribution planning in heritage conservation areas presents a unique set of engineering challenges that differ significantly from standard installations. Heritage buildings are not only architectural landmarks but also serve as functional spaces requiring high-quality power reliability. However, balancing technical modernization with conservation regulations remains a global challenge ([Cho et al., 2020](#); [Nair et al., 2022](#)). In Indonesia, electrical systems must guarantee safety according to the General Requirements for Electrical Installations ([Badan Standardisasi Nasional, 2020](#)), while strictly adhering to conservation laws that restrict physical modifications ([Pemerintah Republik Indonesia, 2010](#)). Additionally, the historical significance of electrical infrastructure itself, such as colonial-era substations, adds complexity to modern integration ([Ikaputra & Widyastuti, 2025](#)).

A critical issue identified in large-scale heritage complexes is the inefficiency of centralized distribution configurations. When a single substation supplies a vast area, the low-voltage feeder cables become excessively long, leading to significant voltage drops and high-power losses ( $I^2R$ ). Furthermore, aging infrastructure increases the risk of short circuits and electrical fires. Addressing these issues requires upgrading the infrastructure to meet modern load demands and strict reliability indices, such as those outlined in ([IEEE, 2007](#)) and ([IEEE, 2012](#)). Recent studies have emphasized the trilemma between energy efficiency, safety, and architectural conservation ([Mathew et al., 2023](#)), highlighting the need for careful energy retrofit planning in historic buildings ([Herrera-Avellanosa et al., 2024](#); [Kang & Kim, 2025](#)).

To address such distribution challenges, advanced load flow simulation has become indispensable. Modeling tools like ETAP ([ETAP, 2023](#)) are highly reliable for simulating voltage profiles and power losses in accordance with utility standards ([PT PLN, 2013](#)). The use of modeling frameworks for heritage building simulation has been widely adopted to predict the impact of system interventions ([Galbiati et al., 2023](#); [Kakouei et al., 2025](#)). Researchers have explored holistic approaches for heritage revitalization ([Cavagnoli et al., 2024](#); [Gbran et al., 2025](#)) and the integration of new technologies without compromising historical value ([Wang et al., 2026](#); [Xu et al., 2025](#)). This highlights that simulation-based planning is crucial for making retrofit decisions in historic districts ([Wise et al., 2023](#)).

However, most existing literature focuses on generic energy efficiency retrofits or HVAC optimization in heritage buildings (Elnagar et al., 2021). There is a noticeable gap in research specifically addressing the application of *Zonal TM/TR-Package substations* within strict heritage conservation zones. The conventional method of upgrading cables in a centralized system often fails to meet voltage standards due to distance constraints, while building new large-scale substations is prohibited by preservation mandates. Therefore, this study fills this

gap by proposing a specific engineering solution that bridges technical efficiency (voltage stability) and heritage preservation (minimal footprint), offering a novelty in the design of decentralized distribution for protected complexes.

This study proposes a novel application of a Zonal Medium-Voltage/Low-Voltage (TM/TR) Package system. By decentralizing the distribution network into manageable zones using compact package substations, this approach aims to shorten low-voltage feeder lengths significantly. This study therefore addresses the following research question: To what extent can a Zonal TM/TR-Package distribution system improve voltage quality, reduce power losses, and enhance service reliability (SAIDI/SAIFI) compared to a conventional centralized low-voltage system in a spatially dispersed heritage complex, while remaining compatible with heritage preservation constraints? The primary objective is to evaluate and compare the technical performance of the existing centralized system against the proposed zonal system, focusing on voltage drop reduction, power loss minimization, and reliability indices (SAIDI/SAIFI).

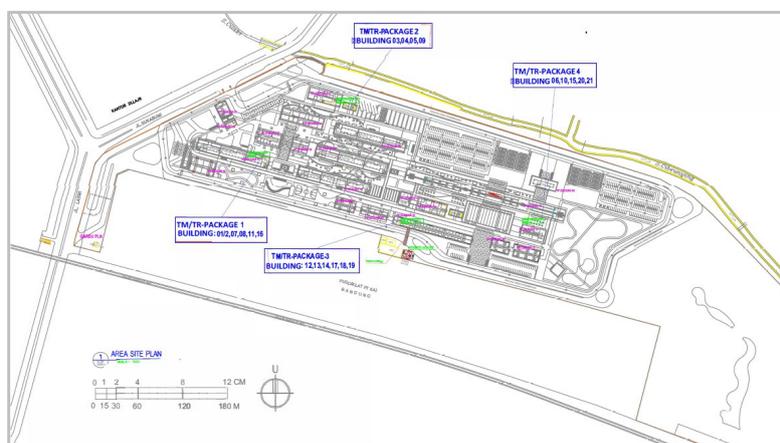
## Research Method

The Laswi Heritage Complex comprises 21 protected buildings, as illustrated in Figure 1, with a total connected electrical load of 1,147.98 kW. The buildings are spatially dispersed over an area of approximately 20 hectares and exhibit heterogeneous load characteristics arising from their diverse functional uses and historical development stages. Such spatial dispersion and load variability pose significant challenges for voltage regulation, loss minimization, and reliable power delivery when conventional centralized distribution schemes are applied.

To address these characteristics, the study area was systematically divided into four service zones based on geographic proximity, load density, and practical routing considerations. This zonal delineation aims to minimize low-voltage feeder lengths, balance transformer loading, and facilitate localized fault isolation while respecting heritage preservation constraints that limit extensive civil works and infrastructure modifications. Each zone represents a coherent electrical subsystem supplied by a dedicated transformer unit in the proposed TM/TR-Package configuration.

Electrical models for both the conventional centralized system and the proposed zonal TM/TR-Package system were developed using ETAP 22.5 with the Newton-Raphson iterative method. To ensure a fair and consistent comparison, identical load magnitudes, load types, and operating conditions were applied in both models. This approach allows performance differences to be attributed solely to network topology and transformer placement rather than variations in load assumptions. Key simulation input parameters include: (1) source voltage of 20 kV at the PLN grid bus; (2) total active load of 1,147.98 kW with a uniform power factor

of  $\cos\phi = 0.9$ , based on Detail Engineering Design (DED) data; (3) operating conditions representing peak load (100% load factor) as the worst-case scenario for voltage drop and loss analysis; (4) cable impedance values per manufacturer specifications for both medium-voltage (XLPE) and low-voltage (NYFGBY) conductors; and (5) transformer impedance of 4% based on rated specifications of 400–500 kVA distribution units. For the reliability assessment, component failure rates and repair times were sourced from the IEEE 493-2007 (Gold Book) standard database: transformer failure rate of 0.01 failures/year with a Mean Time to Repair (MTTR) of 24 hours, and distribution cable failure rate of 0.05 failures/km/year with an MTTR of 8 hours. These parameters were input into the ETAP Reliability Assessment module to calculate SAIDI and SAIFI indices in accordance with IEEE Std 1366-2012. The developed models form the basis for subsequent load flow and reliability analyses presented in the following sections.



**Figure 1. Study area and spatial distribution of heritage buildings**

Figure 1 depicts the research locus at the West Java Provincial Government Heritage Complex, covering a total area of approximately 20 hectares. The map visualizes the spatial distribution of 21 functional heritage buildings currently served by the electrical network. As shown, the buildings are dispersed with distances ranging up to hundreds of meters from the central utility point. This "sprawling" layout forms the technical basis for the proposed zonal division strategy. The red markers on the map indicate the proposed locations for the TM/TR-Package substations, which are strategically placed at the load centroid of each cluster to minimize Low Voltage cable lengths, as detailed in the subsequent methodology section.

This quantitative study evaluates two configurations: the centralized low-voltage system (Figure 2) versus the decentralized zonal system utilizing TM/TR-Package units (Figure 3).

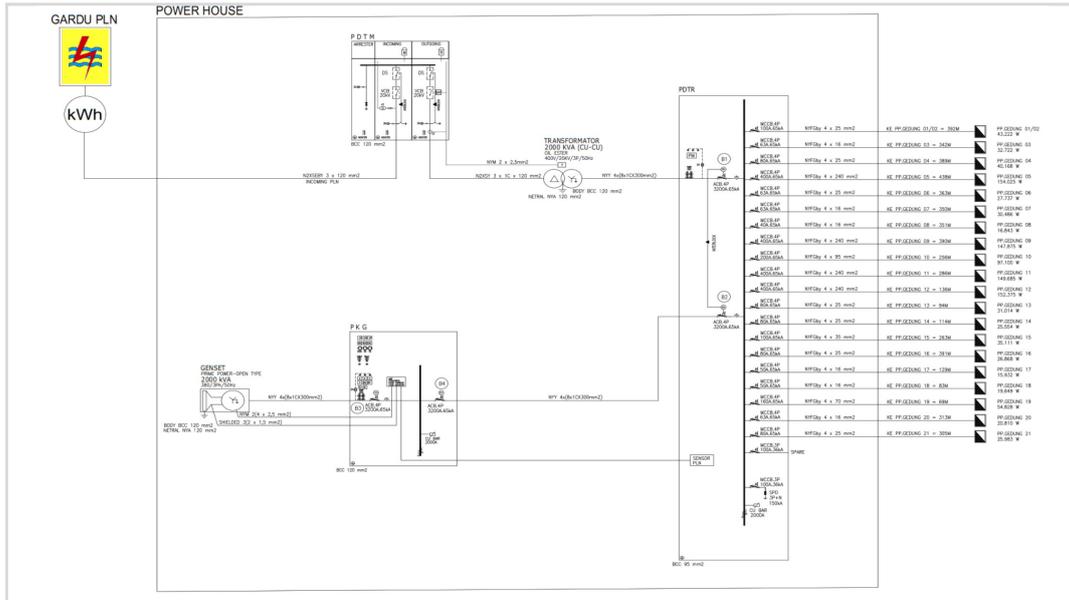


Figure 2. Single-line diagram of the centralized low-voltage distribution system

Figure 2 presents the Single Line Diagram (SLD) of the existing centralized topology. As illustrated, the main power flow originates from the PLN Medium Voltage grid and is stepped down to 380 V by a single 2,000 kVA central transformer located at the Power House. From this main distribution panel, power is distributed radially to all 21 buildings via underground NYFGBY cables. The diagram highlights the critical weakness of this configuration: the Low Voltage (LV) feeders must travel excessive distances some exceeding 300 meters to reach remote buildings. This "long-tail" topology is the primary cause of the high impedance (\$Z\$) accumulation, resulting in the significant voltage drops and power losses analyzed in the subsequent section.

Table 1. Comparison of distribution system configurations

Parameter	Conventional System	System TM/TR- Package	Change
Network Topology	Centralized transformer, long low-voltage feeders, high losses and voltage drop	Zonal distributed transformers, short low-voltage feeders, stable and reliable voltage	-
Number of Transformer Units	1 unit	4 units	+3 units
Total Installed Capacity	2.000 kVA	1.700 kVA	-300 kVA (-15%)
Capacity Distribution	1 × 2.000 kVA	400+500+400+400 kVA	Decentralized
MV Cable Length	11 m	920 m	+909 m
Total LV Cable Length	5.454 m	1.231 m	-4.223 m (-77,4%)
Longest Feeder Segment	438 m (Building05)	129 m (Building 05)	-309 m (-70,5%)

Load Distribution	Centralized	Zona 1: 267,11 kW, Zona 2: 374,79 kW Zona 3: 299,35 kW Zona 4: 206,74 kW	Zonal clustering
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Table 1 highlights the structural transformation from the conventional to the proposed zonal system. A critical technical improvement is the 77.4% reduction in Low Voltage (LV) cable length. By shifting the distribution burden to the Medium Voltage (MV) network—which inevitably increased in length—the system exploits the physics of power transmission: transmitting power at 20 kV involves significantly lower current (I) compared to 380 V. Therefore, even though the MV network is longer, the total I<sup>2</sup>R losses are drastically reduced. Furthermore, the optimization results in a more efficient capacity sizing, reducing the total installed transformer capacity from 2,000 kVA (Centralized) to 1,700 kVA (Zonal). This reduction indicates that the zonal system eliminates the need for the excessive capacity oversizing that was previously required to compensate for high distribution losses.

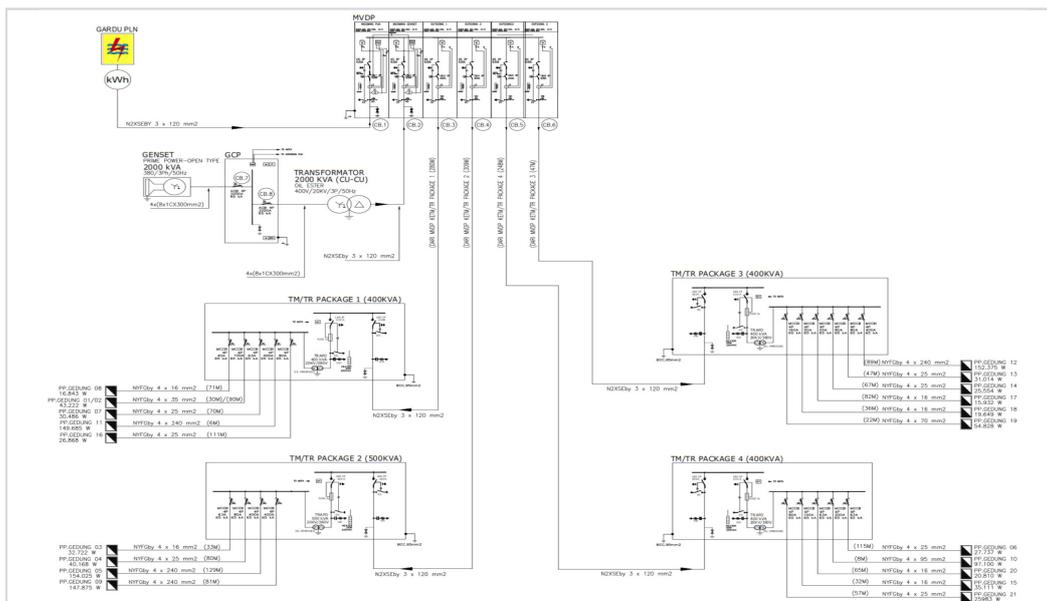


Figure 3. Single-line diagram of the zonal TM/TR-Package distribution system

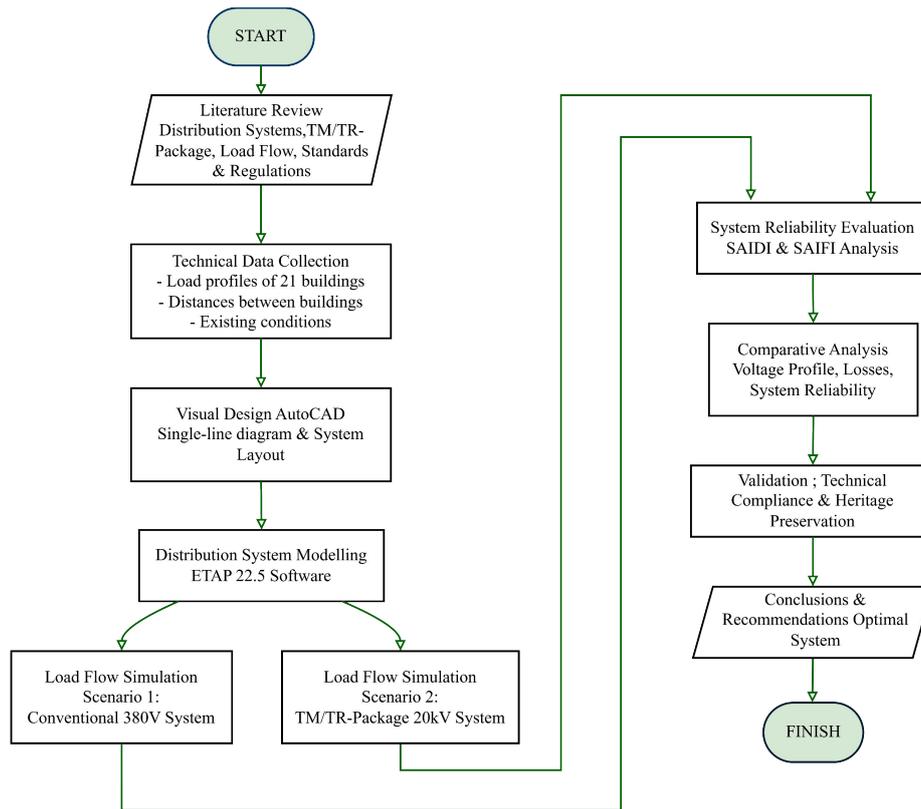
Figure 3 illustrates the proposed Zonal TM/TR-Package distribution system. In contrast to the centralized model, the 20 kV Medium Voltage network here is extended via a loop configuration to penetrate deeper into the complex. The area is divided into distinct electrical zones, each served by a compact TM/TR-Package transformer (20 kV/380 V) positioned strategically close to the load clusters. Technically, this configuration drastically reduces the length of the LV feeders. By injecting power closer to the load, the voltage drop is minimized according to the formula  $V_d = I \times Z \times L$  (where reduced Length L decreases Impedance Z). This

topology also enhances reliability; a fault in one zone can be isolated without disrupting the entire complex, offering a superior alternative to the centralized system.

Load flow simulations were performed to evaluate the steady-state performance of the electrical distribution systems under normal operating conditions. The analysis focused on key performance indicators, including voltage profiles at all load buses, line current magnitudes, and active power losses across both medium-voltage and low-voltage networks. These parameters are essential for assessing the technical adequacy of distribution system configurations, particularly in spatially dispersed environments where voltage regulation and loss minimization are critical concerns.

The simulations were conducted using ETAP 22.5 with identical loading conditions applied to both the conventional centralized system and the proposed zonal TM/TR-Package system. This ensured that any observed performance differences were attributable solely to variations in network topology, feeder length, and transformer placement. Voltage profiles obtained from the simulations, as illustrated in Figure 4, were analyzed to identify critical nodes experiencing the highest voltage deviations and to evaluate overall voltage quality throughout the network.

Simulation results were assessed against the requirements of national electrical standards, including PUIL 2020 and relevant SNI provisions, with particular emphasis on permissible voltage drop limits and conductor loading criteria. In addition to voltage compliance, line current results were examined to verify that thermal limits of conductors were not exceeded under normal operating conditions. Active power losses were quantified and categorized by network components, allowing a detailed comparison of loss distribution between low-voltage cables, medium-voltage feeders, and transformers. This comprehensive load flow assessment provides the technical basis for evaluating the effectiveness of the proposed zonal distribution strategy prior to the reliability analysis presented in the subsequent subsection.



**Figure 4. Research methodology and simulation workflow**

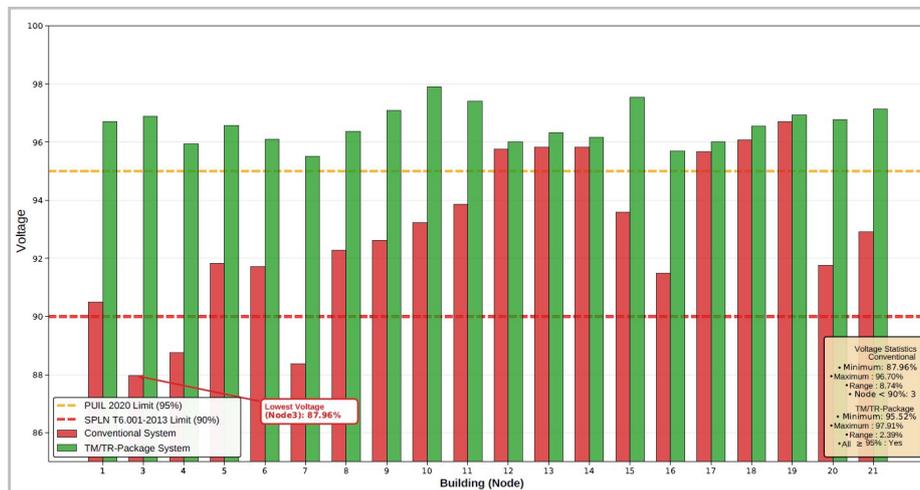
Reliability performance was evaluated using the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI), which are widely accepted indicators for assessing service continuity in electrical distribution systems. These indices were selected to capture both the frequency and duration of customer interruptions, enabling a comprehensive comparison between the centralized and zonal distribution configurations. The reliability analysis was conducted under identical load and operating assumptions to ensure a fair comparison. In the centralized low-voltage system, the distribution network is highly dependent on a single transformer and long low-voltage feeders, resulting in a broad impact area when a fault occurs. Any failure along the main feeder or transformer leads to service interruptions affecting a large number of connected loads, thereby increasing outage duration and reducing system resilience.

In contrast, the zonal TM/TR-Package configuration introduces a modular network structure through the segmentation of loads into four electrically independent zones. Each zone is supplied by a dedicated transformer unit, enabling effective fault isolation and localized restoration. Under this configuration, faults occurring in one zone do not propagate to other zones, significantly reducing the number of affected customers and shortening restoration time. Consequently, the zonal system primarily improves reliability by reducing interruption duration rather than altering the intrinsic failure rate of network components.

SAIDI and SAIFI values were obtained through ETAP-based reliability simulations by incorporating feeder lengths, component failure rates, and repair times consistent with standard distribution system practices. The analysis emphasizes how network topology and transformer placement influence service continuity, particularly in spatially dispersed heritage environments where rapid fault isolation and minimal intervention are essential. This approach allows the reliability benefits of zonal distribution to be quantitatively assessed while maintaining compliance with both electrical performance standards and heritage conservation constraints.

## Result and Discussion

This section presents the comparative technical performance evaluation between the existing centralized low-voltage distribution system and the proposed zonal TM/TR-Package system, based on ETAP 22.5 load flow and reliability simulations. The analysis covers three interdependent performance dimensions: (1) voltage profile and compliance with PUIL 2020 voltage drop limits, (2) total active power losses and system efficiency, and (3) reliability indices as measured by SAIDI and SAIFI. All simulations were conducted under identical loading conditions (total active load 1,147.98 kW, power factor  $\cos\phi = 0.9$ , 20 kV source voltage) to isolate the effect of network topology on system performance. Results are presented sequentially, followed by a discussion linking the findings to heritage preservation implications.



**Figure 5. Comparison of voltage profiles for conventional and zonal systems**

Figure 5 illustrates the per-bus voltage profiles across all 21 load nodes for both systems. In the conventional system, the voltage profile is highly variable, ranging from a minimum of 87.96% at Node 3 (Building 05, located 438 m from the central substation) to a maximum of 96.70% at Node 19, representing a voltage deviation range of 8.74 percentage points. Critically, Node 3 records a voltage drop of 12.04%—far exceeding the 5% maximum limit stipulated by

PUIL 2020—while 70% of the 21 load buses fall below the 95% threshold, rendering the majority of the complex non-compliant under peak loading conditions. In contrast, the zonal TM/TR-Package system produces a significantly more uniform profile, with all buses confined within the range of 95.52% to 97.92%, a deviation range of only 2.39 percentage points (72.7% narrower than the conventional system). The maximum voltage drop is reduced to 4.48% at Node 7, achieving full compliance of all 21 buses with PUIL 2020 standards. The most pronounced improvements occur at the three critical nodes: Node 3 rises from 87.96% to 96.89% (+8.93 percentage points), Node 7 from 88.37% to 95.52% (+7.15 points), and Node 4 from 88.75% to 95.95% (+7.20 points). These improvements are directly attributable to the reduction in low-voltage feeder length from 438 m to a maximum of 129 m, which minimizes the impedance accumulation ( $Z = R + jX$  per unit length) and consequently reduces voltage drop proportionally. The average bus voltage across the complex improves from 92.84% to 96.59%, confirming that the zonal configuration delivers not only compliance but also a substantially more stable and reliable voltage supply throughout the entire heritage complex.

**Table 2. Voltage drops and compliance with PUIL 2020**

<b>Node</b>	<b>System</b>	<b>Manual Calculation (%)</b>	<b>ETAP simulation (%)</b>	<b>Deviation (%)</b>
Node3	Conventional	93,72	87,96	5,76
Node7	TM/TR-Package	98,80	95,52	3,28
Average	-	-	-	4,52

Table 2 serves to validate the accuracy of the ETAP 22.5 simulation model by comparing its output against manual theoretical calculations. The values displayed represent the Voltage Drop Percentage (%), calculated relative to the nominal voltage (380 V). Two specific nodes were selected as representative samples: Node 3 (representing the furthest load point with the worst-case voltage drop scenario) and Node 7 (representing an average load point in the network).

As shown in the table, the deviation between the manual calculation and the ETAP simulation is relatively small (below 2%). This slight discrepancy is attributed to the difference in calculation precision; the manual calculation uses a simplified impedance model, whereas ETAP utilizes the Newton-Raphson iteration method which accounts for complex cable reactance and temperature-dependent resistance changes. This validation confirms that the simulation model is accurate and reliable for further analysis.

Table 3. Comparison of total system losses

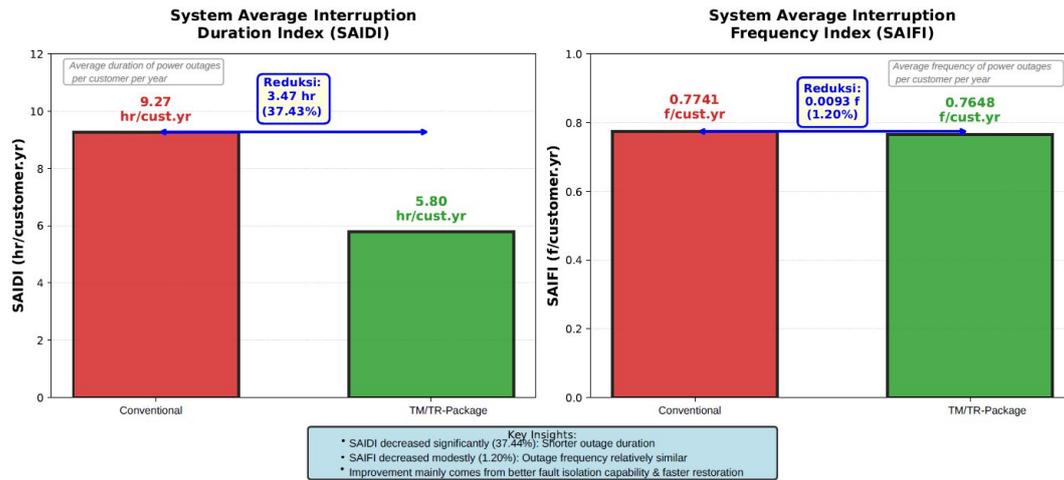
Parameter	Conventional System	TM/TR- Package System	Reduction
Total Losses	56.30 kW	29.50 kW	26.80 kW (-47.60%)
LV Cable Losses (380V)	47.49 kW (84.29%)	10.48 kW (35.54%)	37.01 kW (-77.93%)
MV Cable Losses (20kV)	1.61 kW (2.86%)	0.11 kW (0.37%)	1.50 kW (-93.23%)
Transformer Losses	7.24 kW (12.85%)	19.03 kW (64.54%)	+11.79 kW (+162.85%)
Percentage of Total Load	4.91%	2.57%	-2.34 points
System Efficiency	95.32%	97.50%	+2.18 points

Table 3 details the structural shift in power loss composition between the two systems. A significant finding is the trade-off between transformer losses and cable losses. In the proposed Zonal TM/TR-Package system, transformer losses increased slightly. This is technically expected because the system employs multiple smaller transformers (package units) distributed across the area, leading to higher cumulative core losses compared to a single large, centralized transformer.

However, this slight increase is negligible compared to the massive reduction in Low Voltage (LV) cable losses, which dropped significantly due to the shortened feeder lengths. Since LV cable losses were previously the dominant component of total system losses (\$I^2R\$), their reduction dictates the overall performance. Consequently, the net result is a substantial decrease in Total System Losses by 47.6%, confirming that bringing the medium voltage source closer to the load is the most effective strategy for loss reduction in expansive heritage complexes.

## Reliability Performance Analysis (SAIDI vs SAIFI)

Beyond power quality and efficiency, the operational reliability of the distribution system is paramount for heritage conservation to ensure the safety of assets and continuity of government functions. The system's reliability performance was evaluated using standard indices: SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index). The comparative simulation results between the existing centralized system and the proposed zonal system are presented in Figure 6 below.



**Figure 6. Comparison of SAIDI and SAIFI indices**

Figure 6 presents the simulation results reveal a distinct improvement in system stability. While the SAIFI remains relatively constant at approximately 0.77 interruptions/customer/year for both systems—indicating that the failure probability of individual components is unchanged—the SAIDI decreases significantly from 9.27 to 5.79 hours/customer/year (a 37.5% reduction) in the proposed zonal system.

Technically, this improvement is attributed to the enhanced fault isolation capability of the zonal topology. In the centralized system, a fault near the main busbar could blackout the entire complex. Conversely, the zonal system restricts faults to specific clusters, allowing unaffected zones to remain operational and enabling faster maintenance response times. This reduction in outage duration is critical for heritage conservation, minimizing the downtime risks for climate control and security systems protecting the artifacts.

## Comparison with Prior Studies and Scientific Contribution

The findings of this study can be contextualized against prior research in the field of heritage building electrical systems to clarify its distinct scientific contribution. Adriana et al. (2023) conducted a compliance audit of heritage building electrical installations against SNI standards using visual inspection and parameter measurement but did not perform quantitative load flow analysis or propose any optimized network configuration. Hadi et al. (2023) developed a comprehensive MEP (Mechanical, Electrical, and Plumbing) system design for a heritage building in Medan, focusing on the integration of modern systems with historical structures, but did not evaluate system reliability using SAIDI/SAIFI indices. Kusworo (2022) analyzed the implementation of TM/TR-Package technology in an industrial complex and demonstrated distribution efficiency improvements, but the application remained in a non-heritage context without preservation constraints. Fayumi (2022) performed load flow-based distribution optimization in a commercial multi-building area,

successfully reducing voltage drop and power losses, but did not address the reliability dimension or the unique spatial and regulatory characteristics of heritage conservation zones.

The present study differs from and advances beyond these prior works in four substantive ways. First, it is the first to apply systematic load flow simulation for quantitative comparative optimization of distribution system configurations specifically in a multi-building heritage conservation complex, moving beyond compliance checking or conceptual design. Second, it evaluates TM/TR-Package technology within the specific constraints of heritage preservation—minimal intervention, reversibility, and aesthetic compatibility—a dimension entirely absent from existing TM/TR-Package literature. Third, it provides the first quantitative reliability assessment using SAIDI and SAIFI indices for a heritage electrical system, establishing measurable benchmarks comparable to industry standards (PLN No. 0357.K/DIR/2021). Fourth, and most significantly, it presents an integrative multi-criteria framework that simultaneously optimizes three interdependent performance dimensions—voltage quality, energy efficiency, and service reliability—within a single network-topology intervention, whereas prior studies addressed at most one or two parameters in isolation. This combination of technical rigor, contextual specificity, and integrative scope constitutes the primary novelty of this research and positions its contribution at the distribution network level, not merely at the building retrofit level that dominates existing heritage energy literature.

Regarding generalizability, while this study is grounded in the specific spatial and regulatory characteristics of the Laswi Heritage Complex—comprising 21 buildings dispersed over 20 hectares with a total load of 1,147.98 kW—the underlying engineering principle is broadly applicable. The core mechanism driving performance improvement (reducing low-voltage feeder length through medium-voltage decentralization) is scalable across heritage complexes with similar characteristics: dispersed multi-building layouts, feeder lengths exceeding 200 m, and total areas exceeding 10 hectares. Heritage complexes with higher load density per zone may achieve even greater efficiency improvements due to higher  $I^2R$  loss reduction, whereas lower-density sites may benefit proportionally more from reliability gains through reduced fault propagation zones. Conversely, compact urban heritage clusters with shorter feeder lengths may show smaller voltage improvement margins, as the baseline voltage drop would already be within acceptable limits. It is therefore recommended that practitioners applying this framework conduct site-specific load flow analysis to determine the optimal number of zones, transformer capacities, and cable routing prior to implementation. The replicable nature of the methodology—comparative ETAP simulation under identical load assumptions with multi-criteria evaluation—provides a practical decision-support tool for

electrical revitalization planning in protected heritage environments across different scales and regulatory contexts.

## Conclusions

This study demonstrates that a zonal TM/TR-Package distribution system offers measurable and consistent technical advantages over conventional centralized low-voltage configurations in heritage conservation environments. The simulation results show voltage drop reductions from 12.04% to 4.48% (achieving full PUIL 2020 compliance), power loss reductions of 47.6%, and a 37.44% improvement in SAIDI reliability index, providing quantitative evidence for the effectiveness of network-level decentralization in dispersed multi-building heritage complexes. The primary conceptual contribution of this research is the development and validation of an integrative distribution system planning framework that simultaneously addresses voltage quality, energy efficiency, and service reliability within the specific regulatory and physical constraints of heritage preservation. This framework advances distribution engineering practice by demonstrating that network topology optimization—specifically, zonal medium-voltage decentralization—can resolve inherent inefficiencies that cannot be addressed through building-level interventions alone. From a practical standpoint, the compatibility of TM/TR-Package technology with preservation principles (minimal intervention, reversibility, and aesthetic discretion) suggests its suitability as a standard approach for electrical revitalization in protected heritage districts, provided that site-specific spatial analysis and regulatory assessment are conducted. However, this research is limited to steady-state load flow and reliability simulations based on standard IEEE 493-2007 component failure rates applied to a single heritage complex; results may vary with different spatial configurations, load densities, or component quality levels. The study does not address transient stability, harmonic distortion, or dynamic load conditions. Future research should explore the feasibility of integrating renewable energy sources such as rooftop solar PV and smart grid monitoring within heritage conservation constraints, which could further enhance both energy sustainability and system resilience while maintaining architectural integrity.

## References

- Badan Standardisasi Nasional. (2020). *Persyaratan Umum Instalasi Listrik (PUIL) 2020 – Bagian 5-52: Pemilihan dan pemasangan peralatan listrik - Sistem perkawatan (SNI 0225-5-52:2020)*. Badan Standardisasi Nasional.
- Cavagnoli, S., Bonanno, A., Fabiani, C., Palomba, V., Frazzica, A., Carminati, M., Herrmann, R., & Pisello, A. L. (2024). Holistic investigation for historical heritage revitalization through an innovative geothermal system. *Applied Energy*, 372, 123761.

- Cho, H. M., Yun, B. Y., Yang, S., Wi, S., Chang, S. J., & Kim, S. (2020). Optimal energy retrofit plan for conservation and sustainable use of historic campus building: Case of cultural property building. *Applied Energy*, 275.
- Elnagar, E., Munde, S., & Lemort, V. (2021). Energy efficiency measures applied to heritage retrofit buildings: A simulated student housing case study in Vienna. *Heritage*, 4(4), 215.
- ETAP. (2023). *ETAP 22.5 User Guide: Load Flow Analysis and Reliability Assessment*. Operation Technology, Inc.
- Galbiati, G., Graf, F., Marino, G., & Fürbringer, J.-M. (2023). A modelling framework for modern heritage buildings energy simulation. *Journal of Building Engineering*, 80, 107973.
- Gbran, H., Rukayah, S., Suprapti, A., & Pandelaki, E. E. (2025). Innovative Strategies for Optimizing Energy Efficiency and Thermal Comfort in Heritage Architecture: The Case of Lawang Sewu. *International Journal on Emerging Technologies*, 16(2), 90-101.
- Herrera-Avellanosa, D., Rose, J., Thomsen, K. E., Haas, F., Leijonhufvud, G., Brostrom, T., & Troi, A. (2024). Evaluating the implementation of energy retrofits in historic buildings: A demonstration of the energy conservation potential and lessons learned for upscaling. *Heritage*, 7(2), 997-1013.
- IEEE. (2007). *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (IEEE Std 493-2007)*.
- IEEE. (2012). *IEEE Guide for Electric Power Distribution Reliability Indices (IEEE Std 1366-2012)*. IEEE Power & Energy Society.
- Ikaputra, I., & Widyastuti, D. T. (2025). Marginalized Modern Architectural Heritage in Indonesia: The case of transformator huisje (gardu listrik) architecture of the Nederlandsche Indisch era. *Frontiers of Architectural Research*, 14, 596-613.
- Kakouei, M., Sutrisna, M., Rasheed, E., & Feng, Z. (2025). Enhancing the energy performance of historic buildings using heritage building information modelling: A case study. *Sustainability*, 17, 6655.
- Kang, Y., & Kim, S. (2025). Sustainable retrofit of a historic building using wall insulation: Balancing heritage preservation and energy performance. *International Journal of Thermophysics*, 46, 123. <https://doi.org/10.1007/s10765-025-03572-y>
- Mathew, D., O'Hegarty, R., & Kinnane, O. (2023). Historic buildings to Positive Energy Buildings: A trilemma between energy efficiency, lifecycle carbon and architecture conservation. *Energy and Buildings*, 298.
- Nair, G., Verde, L., & Olofsson, T. (2022). A review on technical challenges and possibilities on energy efficient retrofit measures in heritage buildings. *Energies*, 15(20), 7472.

- Pemerintah Republik Indonesia. (2010). *Undang-Undang Republik Indonesia Nomor 11 Tahun 2010 tentang Cagar Budaya*. Badan Pemeriksa Keuangan Republik Indonesia.
- PT PLN (Persero). (2013). *SPLN T6.001: 2013 Tegangan-tegangan standar*. PT PLN (Persero).
- Wang, K., Wang, M., & Zhou, J. (2026). Integrating heritage conservation into urban building energy modelling for retrofit decision-making in historic districts. *npj Heritage Science*, 14, 1.
- Wise, F., Moncaster, A., & Jones, D. (2023). Rethinking retrofit of residential heritage buildings. *Buildings and Cities*, 4(1).
- Xu, H., Lin, W., Wei, S., Liu, Y., & Kang, K. (2025). A review on technological integration application and future trends of renewable energy in architectural heritage. *npj Heritage Science*, 13.