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Integrated Decision Modeling for Telecommunication Site Modernization Using Reliability, Energy Efficiency and Maintenance Performance Data

Salar SeyedAhmadi [1,*]

1- Ph.D. in Telecommunication Engineering (Fields and Waves), Urmia University, Urmia, Iran. Email: salar.seyedahmadi@gmail.com.
* Corresponding Author

Abstract

Telecommunication operators must continuously modernize network infrastructure to maintain service reliability, improve energy efficiency, and control maintenance requirements. However, these objectives do not always align at the individual-site level. A site with satisfactory reliability may consume disproportionate amounts of electricity, while another may demonstrate acceptable energy performance but experience frequent failures or prolonged repair durations. Evaluating these dimensions independently can therefore lead to inconsistent modernization priorities. This study develops an integrated multi-criteria decision framework for prioritizing telecommunication site modernization using reliability, energy efficiency, and maintenance performance indicators. The proposed methodology comprises five stages: evidence identification, indicator specification, data preparation, composite score construction, and sensitivity analysis. Reliability indicators include failure frequency, downtime, and service availability. Energy indicators include absolute electricity consumption and traffic-normalized energy intensity. Maintenance indicators include intervention frequency, mean time to repair, recurring failures, and maintenance expenditure where comparable records are available. The indicators are normalized to a common scale, aggregated within their respective dimensions, and combined using an explicit weighting structure. A separate reliability safeguard is incorporated to prevent critical service deficiencies from being concealed by favorable performance in other dimensions. The methodological framework is informed by published studies of telecommunication base-station failures and radio access network energy consumption. Published aggregate reliability evidence and scenario-based energy calculations are examined to illustrate the distinction between directly reported observations and derived quantities. The analysis does not treat separate published datasets as if they represented the same sites, nor does it generate unsupported site-level observations. Because a harmonized dataset linking reliability, energy, traffic, and maintenance records has not been established, the study does not claim to provide an empirically validated ranking of actual sites. The principal contribution is a transparent and reproducible decision structure that separates operational performance assessment from the selection of a specific modernization intervention. The framework can support preliminary investment screening when implemented with consistent site-level records. Future empirical research should evaluate its ranking stability, compare alternative weighting procedures, and determine whether its priorities correspond to subsequent improvements in reliability, energy performance, and maintenance outcomes.

Keywords: Telecommunication Site Modernization; Reliability Assessment; Energy Efficiency; Maintenance Performance; Multi-Criteria Decision Analysis

1- Introduction

Telecommunication networks constitute essential infrastructure for digital communication, commercial activity, public services, and the exchange of information. Their operational performance depends on the reliability of network equipment, the availability of supporting power systems, the efficiency of electricity consumption, and the effectiveness of maintenance operations. As network architectures evolve and traffic demand changes, operators must determine which sites require modernization, which can remain in service with targeted upgrades, and which may be managed more effectively through maintenance interventions.

Modernization decisions are particularly challenging when network operators manage large numbers of geographically distributed sites. Equipment age alone does not provide a sufficient basis for determining

investment priority. Two sites with similar equipment configurations may exhibit different failure patterns, traffic loads, electricity consumption, and maintenance requirements. A site with frequent interruptions may warrant immediate technical assessment, while another may require attention because of high energy consumption or repeated corrective interventions. A consistent decision process must therefore consider multiple dimensions of operational performance rather than relying on a single indicator.

Reliability is one of the most important dimensions because equipment failures and service interruptions can affect network availability and service continuity. Failure frequency, downtime, availability, and recurring faults provide complementary information about operational conditions. However, aggregate network statistics can conceal substantial differences among individual sites. A network-level failure total cannot establish the failure rate of each station, identify the concentration of repeated failures, or determine whether particular stations require replacement. Site-level prioritization consequently depends on records that link incidents to specific equipment, observation periods, and operational consequences.

The study by Wu et al. [2] examined the spatiotemporal characteristics of telecommunication base-station failure events using records covering 7,725 stations over eight months. The reported study included 4,615 failure events. These figures demonstrate the scale of the analyzed evidence, but aggregate counts alone do not reveal the complete distribution of failures among individual stations. For modernization assessment, the distinction is important: a defensible priority score must be based on the performance of the site being evaluated rather than on an aggregate ratio applied indiscriminately across the network.

Reliability assessment also involves more than counting failures. The duration of an interruption, the recurrence of a particular fault, and the availability of redundant equipment can influence the operational significance of an incident. Two sites with identical failure counts may differ in their total downtime or in the consequences of their interruptions. A modernization framework should therefore preserve the distinction between event frequency and service impact. Where appropriate records are available, both should contribute to the reliability assessment.

Energy efficiency presents a second major dimension. Telecommunication sites require electricity to operate radio equipment, supporting systems, and other network components. The amount of electricity consumed depends on factors such as equipment configuration, traffic demand, operating conditions, and energy-saving mechanisms. Absolute electricity consumption is important for understanding total energy demand, but it does not independently indicate how efficiently a site supports its traffic volume. Traffic-normalized energy intensity can provide an additional basis for comparing sites when the measurement periods and system boundaries are compatible.

Golard et al. [1] evaluated fourth- and fifth-generation radio access network energy footprints in Belgium using measurement-informed power models and alternative deployment scenarios. Their analysis illustrates the importance of considering network configuration when interpreting energy performance. A site operating under a different configuration or traffic profile may not be directly comparable with another site through absolute consumption alone. The comparison must account for the purpose of the indicator and the conditions under which the measurements or estimates were obtained.

The wider energy implications of telecommunication modernization also require careful interpretation. Williams et al. [3] reviewed operational energy, embodied energy, and indirect effects associated with fifth-generation networks. This distinction is relevant because improving operational energy intensity does not necessarily establish that a modernization intervention reduces the complete lifecycle environmental footprint. Equipment replacement may change operational consumption while introducing additional embodied impacts associated with manufacturing, transportation, and installation. The present framework focuses on operational performance indicators and does not claim to provide a complete lifecycle environmental assessment.

Maintenance performance constitutes a third dimension of modernization decisions. Repeated interventions, long repair durations, recurring faults, and substantial maintenance expenditure may indicate that retaining existing equipment imposes a significant operational burden. However, maintenance records must be interpreted carefully. High intervention frequency may reflect equipment deterioration, but it may also reflect preventive maintenance policies or differences in site accessibility. Similarly, a long repair duration may be caused by spare-parts constraints or logistical delays rather than by the technical condition of the equipment alone.

These considerations show why reliability, energy efficiency, and maintenance performance should not be treated as interchangeable indicators. Reliability describes the frequency and consequences of service-affecting failures; energy efficiency describes electricity use in relation to an appropriate operational reference; and maintenance performance captures the resources and time required to sustain or restore equipment

functionality. Each dimension provides different information about the condition and operational significance of a site.

Assessing these dimensions independently can produce conflicting modernization priorities. A site may have acceptable reliability but relatively high energy intensity. Another may consume less electricity but experience frequent failures and prolonged repair durations. A third may perform adequately across reliability and energy indicators while requiring repeated maintenance interventions. A decision process that considers only one dimension may fail to identify the broader operational burden or may direct investment toward sites that do not represent the most pressing overall concerns.

An integrated decision framework can address this problem by standardizing indicators, defining their relative importance, and combining them into a transparent priority score. Such a framework must also preserve the individual dimension scores so that decision-makers can identify the principal reasons behind a site's ranking. A composite score without an interpretable breakdown may obscure whether a site is prioritized because of reliability problems, energy inefficiency, maintenance burden, or a combination of these factors.

The construction of a composite score nevertheless introduces methodological challenges. Indicators may be measured in different units and may have different directions of preference. Higher failure frequency generally indicates greater modernization concern, whereas higher availability indicates better reliability. Energy intensity may be suitable for comparing relative efficiency, but absolute electricity consumption remains relevant to total energy demand. These indicators must be normalized and interpreted consistently before they can be combined.

Weighting is another important issue. Equal weighting provides a transparent baseline when there is no defensible evidence for assigning different levels of importance to reliability, energy efficiency, and maintenance performance. However, equal weights are a modeling assumption rather than an established universal rule. The appropriate balance may vary according to service requirements, network objectives, energy constraints, and investment priorities. Sensitivity analysis is therefore necessary to determine whether the resulting ranking changes materially when alternative weights are applied.

An additional limitation concerns the compensatory nature of additive decision models. If a site receives a high score for energy efficiency but performs poorly in reliability, a weighted sum may partially offset the reliability deficiency with the favorable energy score. Such compensation may be unacceptable when the site fails a critical operational requirement. A robust framework should therefore distinguish the composite priority score from separate reliability constraints or safeguards established using documented operational criteria.

The literature provides relevant methods for examining these dimensions, but the evidence does not automatically constitute an integrated dataset. Studies may differ in their geographical coverage, observation periods, equipment configurations, analytical units, and measurement boundaries. Combining results from separate publications cannot establish a site-level ranking unless the underlying observations can be linked and made comparable. The distinction between published evidence, model-based estimates, and calculations derived from reported scenarios must therefore remain explicit throughout the analysis.

The central research problem addressed in this study is the absence, within the evidence assembled for this work, of a verified and harmonized site-level dataset linking reliability events, electricity consumption, traffic volume, and maintenance performance over consistent observation periods. Without such data, it is not possible to calculate and validate a common empirical ranking of actual telecommunication sites. Nevertheless, a transparent methodological framework can be developed to define the required indicators, establish the mathematical relationships among them, and specify how ranking stability should be evaluated when suitable operational records become available.

Accordingly, this study develops an integrated decision framework for prioritizing telecommunication site modernization through reliability, energy efficiency, and maintenance performance. The framework standardizes the selected indicators, aggregates them within three dimensions, and combines the dimension-specific scores into a composite priority measure. It also incorporates a separate reliability safeguard and sensitivity analysis to address the limitations of purely additive ranking procedures.

The study has three objectives. First, it defines a set of operational indicators suitable for assessing the modernization needs of telecommunication sites. Second, it develops a reproducible multi-criteria procedure for integrating the indicators while preserving the contribution of each dimension. Third, it specifies a sensitivity-analysis procedure for examining the stability of modernization priorities under alternative weighting assumptions.

The study addresses three research questions:

1. How can reliability, energy-efficiency, and maintenance-performance indicators be standardized and integrated into a common telecommunication site modernization framework?
2. How can the proposed model preserve critical reliability requirements while producing an interpretable composite priority score?
3. How can sensitivity analysis be used to assess the stability of modernization priorities when the relative importance of the assessment dimensions changes?

The contribution is methodological rather than a claim of completed empirical optimization. The framework establishes a structured basis for preliminary investment screening, while actual site rankings and claims about modernization outcomes require linked operational data and subsequent empirical validation.

The remainder of the article presents the relevant literature and research gap, describes the proposed methodology, examines the available published evidence and derived calculations, discusses the implications and limitations of the framework, and concludes with directions for future empirical research.

2- Literature Review and Research Gap

2.1. Reliability Assessment in Telecommunication Networks

Reliability assessment is a fundamental component of telecommunication network management because service interruptions can affect network availability, operational continuity, and the quality of services delivered to users. Conventional reliability indicators, including failure frequency, downtime, and availability, provide useful information about operational performance. However, these indicators may not fully capture differences in failure patterns, network configuration, and the consequences of individual incidents.

Li et al. [4] investigated the prediction of wireless telecommunication service reliability using distribution regression. Their work provides a methodological basis for considering the distribution of reliability outcomes rather than relying exclusively on a single average estimate. This distinction is relevant to modernization decisions because sites with similar average performance may exhibit different levels of variability or exposure to service degradation.

Wu et al. [2] examined the spatiotemporal characteristics of base-station failure events. Their research highlights the importance of considering how failures are distributed across locations and time periods. In an operational decision framework, this perspective supports the use of site-level records and consistent observation windows when calculating failure-related indicators. Aggregate network statistics alone cannot identify the specific stations that should receive modernization priority.

Reliability assessment can also extend beyond individual equipment failures to encompass the resilience of the wider cellular network. Liang and Li [11] examined holistic resilience and reliability measures for cellular telecommunication networks. This broader perspective suggests that modernization decisions should consider the relationship between individual-site performance and network-level service continuity. Nevertheless, network resilience measures and site-level reliability indicators represent different analytical levels and should not be combined without an explicit definition of their relationship.

Another source of reliability information is the analysis of alarms and equipment logs. Massaro et al. [12] investigated network hardware fault prediction through layered treatment of alarm logs. Such approaches are relevant because equipment alarms and recurring fault patterns may provide early indications of deterioration or impending failures. Within the proposed framework, alarm-based indicators can complement conventional failure counts when their definitions, timestamps, and relationships with confirmed incidents are sufficiently reliable.

Ahmed et al. [10] examined a multivariate machine-learning approach to predicting power failures at base transceiver stations. Power-system reliability is particularly relevant because failures in supporting infrastructure may interrupt communication services even when radio equipment remains functional. This evidence supports distinguishing power-related failures from other failure categories when operational records permit such classification.

Collectively, these studies indicate that reliability assessment can benefit from multiple sources of operational evidence, including recorded failures, service interruptions, alarms, and power-system events. However, predictive reliability models and descriptive reliability indicators serve different purposes. A model that predicts failure probability does not automatically establish the optimal modernization intervention. The

proposed framework therefore treats reliability indicators as inputs to decision prioritization rather than as direct estimates of investment effectiveness.

2.2. Energy Efficiency and Power Consumption Modeling

Energy efficiency is an important consideration in radio access network planning because equipment configuration, traffic demand, and energy-saving operating modes influence electricity consumption. Comparisons among sites, however, require careful selection of measurement boundaries and performance indicators.

Golard et al. [1] evaluated the energy footprint of fourth- and fifth-generation radio access networks using measurement-informed models and alternative deployment scenarios. Their work provides a basis for examining energy intensity under different network configurations. Williams et al. [3] emphasized the importance of distinguishing operational energy from embodied energy and indirect effects when evaluating the broader energy implications of fifth-generation networks. These perspectives indicate that the scope of an energy assessment must be defined before its results are used to support modernization decisions.

Huttunen et al. [5] investigated base-station energy use in dense urban and suburban environments. Their research is relevant to the interpretation of consumption across different deployment contexts. Sites serving different traffic loads or operating under different network conditions may not be directly comparable through absolute electricity consumption alone.

Piovesan et al. [7] examined machine-learning and analytical power-consumption models for fifth-generation base stations. Such models can support the estimation and interpretation of power demand under different operating conditions. Nevertheless, the suitability of a model for site prioritization depends on the availability of appropriate inputs and the consistency between modeled conditions and the sites being assessed.

Aggarwal and Selvamuthu [8] investigated energy analysis using semi-Markov modeling for base stations in fifth-generation networks. Modeling approaches that account for changes in operating states can be relevant when assessing equipment behavior under different traffic and energy-saving conditions. Model-derived energy estimates should, however, remain distinguishable from direct measurements, particularly when the assessment supports investment decisions.

Bellin et al. [9] examined power consumption in the softwarized fifth-generation core using a measurement-based approach. Although core-network energy consumption differs from radio-site energy consumption, this study illustrates the importance of defining the system boundary when comparing energy indicators. A site-level modernization framework should not combine core-network measurements with radio access network measurements unless the distinction is explicitly accounted for.

Zimmermann [13] investigated a hybrid boosted approach inspired by a mixture of experts for predicting fifth-generation energy consumption. Predictive approaches may help estimate energy demand when measurements are incomplete or operating conditions vary. Their applicability must nevertheless be established before their outputs are used in an operational ranking.

Sorrentino et al. [6] developed and experimentally assessed a multi-annual energy-monitoring tool to support energy intelligence and management in the telecommunications industry. Their work reinforces the value of systematic energy monitoring over time. Longitudinal records can help distinguish persistent energy inefficiency from temporary variation and provide a more defensible basis for assessing modernization opportunities.

Collectively, these studies support the inclusion of energy intensity, absolute electricity consumption, and relevant configuration information in modernization assessment. They also highlight a methodological requirement: measured energy values, modeled estimates, and scenario-derived calculations must be identified separately. Otherwise, a decision model may appear quantitatively precise while combining evidence that is not directly comparable.

2.3. Maintenance Performance and Operational Decision Support

Maintenance performance is closely related to reliability because repair practices influence equipment availability and the duration of service interruptions. Nevertheless, maintenance burden cannot be inferred reliably from failure frequency alone. Two sites with similar failure counts may differ substantially in repair duration, intervention complexity, spare-parts availability, and maintenance expenditure.

The analysis of alarm logs by Massaro et al. [12] provides a connection between fault detection and maintenance planning. When alarm events can be linked to confirmed failures and subsequent interventions,

they may support the identification of recurring problems and help distinguish isolated incidents from persistent equipment issues.

The power-failure prediction approach examined by Ahmed et al. [10] is also relevant to maintenance planning because early identification of power-system vulnerabilities may support preventive intervention. However, predictive performance and maintenance effectiveness should not be treated as equivalent. A model may identify elevated failure risk without establishing whether equipment replacement, component repair, or changes in maintenance procedures would produce the greatest operational benefit.

Reliability and resilience studies [2,11] further suggest that operational performance should be interpreted within the broader context of service continuity. For maintenance assessment, this means that intervention frequency and repair duration should be considered alongside the operational consequences of failures. Where possible, records should distinguish preventive interventions, corrective repairs, repeated faults, and major equipment replacements.

Despite the relevance of these indicators, maintenance performance is difficult to compare across sites unless organizations use consistent definitions and recording procedures. Differences in maintenance policies, reporting practices, and site accessibility can influence observed intervention counts and repair durations. Consequently, maintenance indicators should be normalized and interpreted cautiously, and missing maintenance records should not be treated as evidence of good performance.

The proposed framework incorporates maintenance performance as a separate decision dimension. Its role is to ensure that sites requiring repeated interventions or experiencing prolonged restoration periods are not assessed exclusively through reliability and energy indicators. However, the framework does not assume that high maintenance burden necessarily implies that complete site modernization is the preferred response. Intervention selection requires a subsequent engineering and economic assessment.

2.4. Multi-Criteria Decision Modeling for Site Modernization

The reviewed literature provides evidence that reliability, energy consumption, and maintenance-related information can be analyzed using different statistical and engineering methods. Reliability studies investigate failure occurrence and service continuity; energy studies examine consumption under alternative configurations; and alarm-based approaches support fault identification and prediction. These methods contribute valuable but distinct information.

The central decision challenge is to combine these dimensions without losing their individual meanings. A site may exhibit high reliability but poor energy efficiency, or relatively low energy consumption but substantial maintenance burden. A decision model based on only one dimension may therefore produce priorities that do not reflect the full operational context.

The proposed framework addresses this issue through a hierarchical multi-criteria structure. Individual indicators are normalized, aggregated within their respective dimensions, and combined into a composite modernization priority score. The separate dimension scores remain visible so that decision-makers can distinguish the principal factors contributing to a site's ranking.

This approach requires explicit treatment of weighting assumptions. Equal weighting can provide a transparent baseline when no defensible empirical basis exists for assigning different weights. However, equal weights should not be interpreted as evidence that the three dimensions are equally important in every operational context. Sensitivity analysis is therefore necessary to establish whether the resulting ranking changes materially under alternative weight configurations.

The framework also distinguishes relative priority from intervention selection. A composite score can identify sites that warrant closer investigation, but it cannot independently determine whether a site should undergo complete replacement, component-level upgrading, or continued maintenance. Such decisions require additional information about technical feasibility, lifecycle costs, service requirements, and expected operational outcomes.

2.5. Research Gap and Contribution

The reviewed studies address important aspects of telecommunication reliability, energy consumption, fault prediction, and maintenance-related information. However, these contributions do not, by themselves, establish an integrated site-level prioritization procedure using a common dataset spanning all three dimensions.

The principal research gap is methodological and operational. Reliability, energy efficiency, and maintenance performance are frequently represented through different indicators, measurement periods, and analytical

approaches. Without a consistent integration procedure, decision-makers may struggle to compare sites transparently or determine why one site should receive modernization investment before another.

This study addresses the gap by proposing a structured framework with five components:

1. A defined set of reliability, energy-efficiency, and maintenance indicators.
2. A normalization procedure that places eligible indicators on a common scale.
3. A hierarchical weighting structure that distinguishes dimension-level and indicator-level importance.
4. A composite modernization priority score accompanied by a separate reliability safeguard.
5. Sensitivity analysis to assess the stability of priorities under alternative weighting assumptions.

The contribution is the specification of a reproducible decision methodology, not the claim that an empirically optimal ranking has already been established. The absence of a verified, harmonized site-level dataset limits the study's ability to calculate actual site rankings or validate the model against subsequent operational outcomes. Future empirical implementation should therefore use linked reliability, energy, traffic, and maintenance records to determine whether the proposed framework improves modernization screening.

3- Research Methodology

3.1. Research Design

This study adopts a quantitative, evidence-based decision-modeling design to develop a structured method for prioritizing telecommunication sites for modernization. The proposed framework integrates three assessment dimensions: reliability, energy efficiency, and maintenance performance. Its purpose is to transform operational indicators into a comparable priority score while retaining the contribution of each dimension to the final decision.

The research design comprises five analytical stages: evidence identification, indicator specification, data preparation, multi-criteria score construction, and sensitivity analysis. These stages separate the selection of relevant performance measures from the mathematical operations used to combine them. This separation is important because the indicators may differ in measurement units, observation periods, and operational significance.

The reliability component is informed by Wu et al. [2], who analyzed telecommunication base-station failures while accounting for station-specific heterogeneity and spatial dependence. The energy component draws on Golard et al. [1], who developed measurement-informed power models for fourth-generation base stations and evaluated alternative fourth- and fifth-generation radio access network scenarios. These studies support the selection and interpretation of the proposed indicators, but their underlying observations are not treated as a single integrated dataset.

The analytical unit for a full empirical implementation is the individual telecommunication site. Each site should be assessed over a consistent observation period using linked reliability, electricity consumption, traffic, and maintenance records. Where site-level observations are unavailable, the methodology can still be specified and its mathematical properties examined, but a ranking of actual sites cannot be claimed without the corresponding data.

The intended output is a ranked list of modernization candidates accompanied by dimension-specific scores and a sensitivity assessment. The ranking is a decision-support result rather than a substitute for engineering feasibility studies or financial appraisal.

3.2. Data Sources and Evidence Preparation

The study adopts a secondary-evidence strategy based on peer-reviewed international journal publications. Evidence preparation establishes defensible indicator definitions and identifies which measurements can be incorporated into the decision model without combining incompatible observations.

The first principal source is the reliability study by Wu et al. [2]. Their investigation covered eight months of failure records from 7,725 base stations and reported 4,615 failure events. The study provides a basis for defining reliability indicators and recognizing differences in failure behavior across sites. However, the complete site-level dataset cannot be assumed to be publicly available. The reported study characteristics can be used as published evidence, but individual-site failure rates must not be inferred without the underlying records.

The second principal source is the energy study by Golard et al. [1]. Their research used on-site measurements to develop power models for fourth-generation base stations and evaluated alternative deployment scenarios for fourth- and fifth-generation radio access networks in Belgium. The study distinguishes traffic-independent power demand from traffic-dependent consumption and examines the effects of network configuration and energy-saving operating modes.

Evidence preparation follows four principles:

1. Traceability: every empirical value must be linked to its original publication, measurement period, and reported unit.
2. Measurement consistency: indicators can be compared across sites only when their definitions and observation periods are sufficiently compatible.
3. Separation of evidence types: direct observations, published model estimates, and calculations generated by the proposed framework must be identified separately.
4. Explicit treatment of missing data: unavailable measurements must not be replaced with invented site-level observations.

Maintenance performance requires particular attention because the principal reliability and energy studies do not provide a complete common dataset covering repair duration, maintenance expenditure, and intervention frequency for every site. These indicators are therefore included in the framework as required variables for a full operational implementation. They are not presented as empirically measured values unless the underlying observations can be verified.

This evidence structure permits the development of an integrated decision model while preserving the distinction between the empirical basis of the indicators and the availability of data needed to calculate site-specific priorities.

3.3. Definition of Decision Criteria

The framework contains three primary criteria and a set of supporting indicators. Each indicator is selected according to its operational relevance, interpretability, and relationship with modernization requirements.

3.3.1. Reliability Assessment

Reliability assessment focuses on the occurrence and consequences of service-affecting failures. The proposed indicators are failure frequency, total service interruption duration, service availability, and recurrence of failures where individual events can be linked to the corresponding site.

Failure frequency is calculated as:

$F_i = N_i / T_i$

where N_i represents the number of qualifying failure events at site *i*, and T_i is the observation duration expressed in a consistent time unit.

When interruption and operating-time records are available, site availability can be expressed as:

$A_i = [(T_i - D_i) / T_i] \times 100$

where D_i is the total qualifying downtime during observation period T_i. This expression assumes that downtime events are measured consistently and that overlapping interruptions are not counted more than once.

Higher failure frequency and longer downtime indicate greater operational concern, whereas higher availability indicates better performance. Their direction must therefore be standardized before aggregation.

3.3.2. Energy-Efficiency Assessment

Energy assessment considers both absolute electricity demand and the amount of traffic supported by that demand. The proposed indicators include electricity consumption during the observation period, energy intensity per unit of traffic, estimated fixed power demand where supported by an appropriate model, and equipment configuration where it can be documented consistently.

Energy intensity is calculated as:

$EI_i = E_i / V_i$

where E_i is the electricity consumed by site *i*, measured in kilowatt-hours, and V_i is the corresponding traffic volume measured in gigabytes. The resulting unit is kWh/GB.

This indicator is meaningful only when energy and traffic cover the same period and the measurement boundary is consistent. A lower value indicates less electricity consumed per unit of traffic, but it does not independently establish that the site is a suitable candidate for modernization. Absolute electricity consumption, network configuration, and service requirements must also be considered.

3.3.3. Maintenance-Performance Assessment

Maintenance performance is represented through the burden of recurring interventions and the time required to restore service. The proposed indicators are maintenance intervention frequency, mean time to repair, recurring failures associated with the same component or failure category, and maintenance expenditure where consistently recorded.

Mean time to repair is expressed as:

$$MTTR_i = (\Sigma_{j=1}^{mi} t_{ij}) / m_i$$

where t_{ij} is the repair duration for intervention *j* at site *i*, and m_i is the number of eligible completed repairs.

A high intervention frequency or long repair duration may indicate a substantial maintenance burden. Nevertheless, neither indicator proves that replacement is preferable to continued maintenance. Their interpretation must account for preventive maintenance practices, failure severity, site accessibility, and the nature of the intervention.

The final set of indicators will be restricted to measurements that are sufficiently comparable for the intended analysis. If a particular maintenance variable cannot be supported by accessible evidence, it will remain part of the framework's specification rather than being assigned an invented empirical value.

3.4. Indicator Normalization and Construction of the Decision Matrix

The indicators differ in measurement units, numerical ranges, and operational interpretation. Failure frequency is expressed as a rate, electricity consumption is measured in kilowatt-hours, and repair duration is measured in units of time. These indicators cannot be aggregated directly without first converting them into comparable scales.

The proposed methodology uses min–max normalization to transform each eligible indicator into a dimensionless value between zero and one. The normalized decision matrix is represented as:

$$X = [x_{ij}]_{nxm}$$

where *n* is the number of assessed sites, *m* is the number of indicators, and x_{ij} is the observed value of indicator *j* for site *i*.

For indicators where higher values indicate greater modernization need, such as failure frequency, downtime, and repair duration, the normalized score is:

$$z_{ij} = (x_{ij} - x_{jmin}) / (x_{jmax} - x_{jmin})$$

For indicators where higher values represent better performance, such as service availability, the direction is reversed:

$$z_{ij} = (x_{jmax} - x_{ij}) / (x_{jmax} - x_{jmin})$$

In both expressions, z_{ij} represents the normalized modernization-need score, and the minimum and maximum values are calculated across the eligible sites in the assessment population. A score closer to one indicates a greater relative modernization concern for that indicator, whereas a score closer to zero indicates a lower relative concern.

This approach makes indicators comparable in scale while preserving their intended direction. However, normalization is population-dependent: a site's score may change when the assessment population changes, even if its underlying operational performance remains constant. Accordingly, the set of sites and the observation period must be defined before calculating the scores.

When all sites have identical values for a particular indicator, the denominator becomes zero. Such an indicator cannot distinguish among the assessed sites and should not be used to create artificial ranking differences. It should instead be excluded from discrimination for that assessment, with the treatment documented.

Missing observations require a separate rule. A site should not automatically receive a favorable score because its failure, energy, or maintenance records are incomplete. The preferred procedure is to assess data completeness first, calculate scores only for eligible observations, and disclose any exclusions or justified imputation. Any imputation must be documented and subjected to sensitivity testing.

The normalized matrix provides the mathematical foundation for combining the three assessment dimensions into a composite modernization priority score.

3.5. Weighting of Assessment Criteria

The three primary dimensions do not necessarily have equal importance in every operating environment. A network serving critical services may place greater emphasis on reliability, whereas an operator facing substantial electricity costs may assign greater importance to energy performance. Maintenance burden may also become a dominant consideration when repeated interventions consume engineering resources or prolong service restoration.

The proposed model assigns a weight to each assessment dimension:

$w_r + w_e + w_m = 1$

where w_r, w_e, and w_m denote the weights assigned to reliability, energy efficiency, and maintenance performance, respectively. Each weight is nonnegative and represents the relative contribution of its corresponding dimension to the overall modernization priority score.

For the baseline model, equal weighting can be used as a transparent reference configuration:

$w_r = w_e = w_m = 1/3$

Equal weighting is a modeling assumption, not an empirically established finding about the relative importance of the three dimensions. It provides a neutral starting point when there is insufficient evidence to justify a different set of weights. Alternative weighting configurations must subsequently be examined to determine whether the ranking is sensitive to the decision-maker's priorities.

Within each dimension, indicator weights are also required if more than one indicator is used. Let \(v_{jk}\) represent the weight of indicator *k* within assessment dimension *j*. The weights within each dimension satisfy:

$\Sigma_{k=1}^{\varphi j} v_{jk} = 1$

where $^{\varphi j}$ is the number of eligible indicators assigned to dimension *j*.

The score for each dimension is calculated as:

$D_{ij} = \Sigma_{k=1}^{\varphi j} v_{jk} z_{ijk}$

where D_{ij} is the dimension-specific modernization-need score for site *i*, and z_{ijk} is the normalized value of indicator *k* for that site.

This hierarchical structure prevents a dimension from receiving an unintended increase in importance simply because it contains more indicators. For example, if reliability includes four indicators and energy efficiency includes two, their contributions to the final score remain controlled by their dimension-level weights rather than by the number of measurements available.

The weighting procedure should be documented before interpreting the rankings. If expert judgments or operational priorities are used to establish weights, the source of those judgments and the weighting procedure must be reported. Where such evidence is unavailable, equal weighting should remain the baseline, with alternative weights used only for sensitivity analysis.

3.6. Integrated Modernization Priority Model

The composite modernization priority score is calculated by combining the three dimension-specific scores:

$P_i = w_r D_{ir} + w_e D_{ie} + w_m D_{im}$

where P_i is the composite priority score for site *i*, and D_{ir}, D_{ie}, and D_{im} are its normalized reliability, energy, and maintenance scores.

Provided that all dimension scores lie between zero and one and the weights sum to one, the composite score also lies between zero and one.

Sites can then be ordered in descending priority-score order. A higher score indicates a greater relative need for modernization under the specified criteria and weights.

The model is deliberately additive because it is interpretable and straightforward to implement using standard spreadsheet software. Nevertheless, an additive score permits compensation between dimensions: a favorable energy score can partially offset a poor reliability score. This may be inappropriate when a site has a critical reliability deficiency that must not be offset by strong performance elsewhere.

To address this limitation, the study proposes a reliability safeguard. Sites that exceed a separately established critical threshold for interruption duration or another validated reliability measure can be flagged for mandatory technical review regardless of their composite score. The threshold must be justified using operational requirements or documented standards; it must not be selected retrospectively merely to produce a preferred ranking.

The model therefore produces two complementary outputs: a relative priority ranking based on the integrated score and a separate flag identifying sites that require review under critical reliability conditions. This distinction supports transparent decision-making without treating the composite score as a substitute for engineering judgment.

The model also does not directly estimate investment return. A high priority score identifies where further assessment may be warranted, but determining whether replacement, component upgrading, or continued maintenance is the preferred intervention requires cost and performance information beyond the core three-dimensional score.

3.7. Sensitivity Analysis and Ranking Stability

A modernization ranking may change when the weights assigned to reliability, energy efficiency, and maintenance performance change. Sensitivity analysis is therefore required to assess whether the resulting priorities are robust to plausible differences in decision preferences.

The analysis begins with the equal-weight baseline. Alternative configurations then increase the relative importance of one dimension while reducing the weights assigned to the others, subject to the requirement that all weights remain nonnegative and sum to one.

For each configuration, the composite score is recalculated and the sites are reordered. The comparison examines changes in the rank assigned to each site, changes in the highest-priority group, sites whose priority remains consistently high, and sites whose ranking depends strongly on the selected weights.

Ranking agreement can be measured using Spearman's rank correlation coefficient:

$$\rho = 1 - [6\Sigma_{i=1}^{n} d_i^2 / (n(n^2 - 1))]$$

where d_i is the difference between the two rankings assigned to site *i*, and *n* is the number of sites. This expression applies when the rankings contain no tied ranks; appropriate tie-adjusted calculations are required otherwise.

A coefficient closer to one indicates stronger agreement between the compared rankings. However, correlation alone does not establish that the same sites occupy the highest-priority positions. The analysis should therefore also examine top-ranked site overlap and changes in individual rank positions.

A second sensitivity analysis can assess the effect of changes in indicator values and data completeness. Where repeated observations are available, uncertainty in estimated failure rates or energy intensity can be examined using suitable resampling or interval-estimation procedures. Such analyses should only be conducted when the data structure supports the assumptions of the selected method.

No numerical sensitivity results are reported at this stage because the underlying observations needed to calculate site-level scores have not been established. The sensitivity framework defines how ranking stability will be evaluated; it does not, by itself, demonstrate that the proposed model has achieved empirical robustness.

3.8. Methodological Validation and Reproducibility

The final methodological stage evaluates the internal consistency and practical interpretability of the proposed framework. Validation focuses on the correctness of the calculations, the traceability of indicator definitions, the consistency of normalization, and the stability of rankings under alternative weighting assumptions.

The implementation should satisfy the following requirements:

- Every empirical observation must have a traceable source and a documented measurement period.
- Indicator definitions and units must remain consistent across the assessment population.
- The direction of each normalized indicator must reflect its relationship with modernization need.
- Criterion and indicator weights must satisfy their mathematical constraints.
- The composite score must be reproducible from the reported inputs and equations.
- Missing data and any exclusions must be disclosed.
- Sensitivity results must be distinguished from the baseline ranking.
- Critical reliability concerns must be assessed separately where a validated threshold is available.

The framework can be implemented using a spreadsheet or a statistical computing environment. Its mathematical structure does not require proprietary software, although a full empirical application requires access to sufficiently comparable site-level records.

The principal limitation is the availability of a common dataset that links reliability events, electricity consumption, traffic volume, and maintenance interventions for the same sites and observation periods. Published studies support the selection of the indicators and the formulation of the model, but they do not automatically provide this complete combination of measurements. Accordingly, the present methodology establishes a reproducible decision framework, while the strength of any empirical claims depends on the data that can actually be extracted and verified.

4- Results

4.1. Empirical Evidence and Data Availability

The evidence reviewed in this study supports the relevance of reliability and energy-efficiency indicators for telecommunication site modernization. However, the available studies do not establish a single harmonized dataset containing reliability events, electricity consumption, traffic volume, and maintenance performance for the same sites and observation periods. The results are therefore organized into published empirical evidence, calculations derived from published scenarios, and the methodological implications of integrating these dimensions.

Wu et al. [2] analyzed eight months of failure records covering 7,725 telecommunication base stations and reported 4,615 failure events. These aggregate figures provide evidence of the scale of the observed failure data but do not disclose the failure distribution of every individual station in the aggregate summary.

Golard et al. [1] investigated the energy footprint of fourth- and fifth-generation radio access networks using measurement-informed power models and alternative deployment scenarios. Their findings provide a basis for discussing traffic-normalized energy intensity and the potential implications of energy-saving operating modes. However, the scenario estimates cannot be interpreted as direct measurements from the same stations examined by Wu et al. [2].

The availability and analytical role of the evidence are summarized in Table 1.

Table 1. Availability of evidence for the three modernization assessment dimensions

Assessment dimension	Evidence available	Analytical role	Principal limitation
Reliability	Published base-station failure records and aggregate study characteristics [2]	Supports the specification of failure frequency and related reliability indicators	Individual-site records are required for site-specific scores
Energy efficiency	Measurement-informed energy models and deployment scenarios [1]	Supports energy-intensity assessment and scenario-based comparison	Energy observations are not linked to the reliability sample
Maintenance performance	Required indicators can be specified methodologically	Defines the variables needed to assess intervention frequency, repair duration, and maintenance burden	A comparable site-level maintenance dataset has not been established

Integrated prioritization	Proposed multi-criteria decision framework	Defines how the three dimensions can be combined consistently	Empirical site rankings require harmonized observations across all dimensions

Table 1 demonstrates that the evidence is sufficient to specify the proposed decision framework but insufficient to establish an empirically validated ranking of individual sites. Combining findings from separate studies does not create a common dataset when their observational units, periods, and measurement boundaries differ.

4.2. Quantitative Analysis of Energy Efficiency

Golard et al. [1] reported a reference energy intensity of 0.15 kWh/GB for a fourth-generation-only scenario in Belgium in 2025. Their analysis also described fifth-generation energy intensity as approximately three to five times lower than the reference under the specified comparison, with improvements of approximately eight to twelve times in scenarios incorporating sleep mode.

These relative improvements can be used to calculate illustrative energy-intensity ranges. Let the reference energy intensity be EI_ref, and let *r* represent the reported relative improvement factor. The derived scenario intensity is calculated as:

$$EI_{scenario} = EI_{ref} / r$$

For the reference value of 0.15 kWh/GB, an improvement factor between three and five yields a derived range of 0.030–0.050 kWh/GB. For an improvement factor between eight and twelve, the corresponding range is 0.0125–0.01875 kWh/GB.

Table 2. Published reference and scenario-derived energy-intensity values

Scenario	Reference or improvement factor	Derived energy intensity (kWh/GB)	Evidence classification
Fourth-generation reference scenario	0.15 kWh/GB	0.150	Value reported by [1]
Fifth-generation comparison	3–5 times lower	0.030–0.050	Calculated from the published reference and relative improvement
Fifth-generation comparison incorporating sleep mode	8–12 times lower	0.0125–0.01875	Calculated from the published reference and relative improvement

Note: The ranges in Table 2 are derived calculations, not independent field measurements. They depend on the reference value and relative improvement factors reported for the specified scenarios.

The calculations illustrate the potential magnitude of differences in energy intensity under the scenarios described in the source study. They do not demonstrate that every fifth-generation site will achieve the calculated values. Actual performance depends on network configuration, equipment characteristics, traffic demand, operating conditions, and the implementation of energy-saving functions.

The results also highlight the distinction between energy intensity and absolute electricity consumption. Energy intensity measures electricity use relative to traffic volume, whereas absolute consumption represents the total electricity required during the observation period. An improvement in energy intensity does not necessarily imply a reduction in total electricity demand if traffic volume increases or multiple generations of equipment operate simultaneously.

For the proposed decision framework, energy intensity is an appropriate comparative indicator when energy and traffic measurements use consistent periods and boundaries. Absolute electricity consumption should be retained as a complementary indicator rather than replaced by energy intensity alone.

4.3. Reliability Evidence and Failure Concentration

The reliability evidence reported by Wu et al. [2] consists of 7,725 base stations and 4,615 failure events observed over eight months. Dividing the total number of reported events by the number of stations gives an aggregate event-to-station ratio:

$$R_{aggregate} = 4615 / 7725 \approx 0.597$$

This calculation produces approximately 0.597 reported failure events per station over the study period. It is an aggregate ratio derived from the published totals, not an estimated site-specific failure rate. It does not reveal

how failures were distributed among stations, whether individual stations experienced repeated events, or how event severity varied.

Table 3. Aggregate reliability evidence reported in the base-station failure study

Indicator	Value	Interpretation
Number of base stations	7,725	Size of the reported station population
Number of failure events	4,615	Aggregate number of recorded events
Observation period	8 months	Period covered by the study
Aggregate event-to-station ratio	Approximately 0.597	Total events divided by total stations
Site-specific failure frequency	Not established from aggregate totals alone	Requires station-level event records and exposure periods

Source: Wu et al. [2] for the reported study characteristics; the aggregate ratio is calculated from those published totals.

The aggregate ratio is useful for describing the scale of the reported evidence, but it should not be interpreted as the probability that an individual station will fail. Such an interpretation would require a clearly defined statistical model and appropriate information about observation exposure, repeated events, and station-level heterogeneity.

For modernization prioritization, this limitation reinforces the need to calculate failure frequency and downtime for each eligible site rather than assigning the aggregate ratio to every station. The proposed framework can accommodate these indicators when the underlying records are available, but the published aggregate figures alone cannot support a site-level reliability ranking.

4.4. Implications for Integrated Modernization Prioritization

The findings support the methodological integration of reliability, energy efficiency, and maintenance performance, while also identifying the data requirements for operational implementation. The framework combines normalized dimension-specific scores through the following expression:

$$P_i = w_R \times D_{iR} + w_E \times D_{iE} + w_M \times D_{iM}$$

where P_i denotes the modernization priority score for site *i*, D_{iR} is its reliability score, D_{iE} is its energy-efficiency score, D_{iM} is its maintenance-performance score, and the three weights sum to one.

Because a common site-level dataset has not been established, numerical values for P_i cannot be calculated for actual stations from the evidence presented in this study. Instead, Table 4 identifies the types of operational profiles the framework is designed to distinguish. These profiles are conceptual examples, not classifications of observed sites.

Table 4. Conceptual operational profiles for integrated modernization assessment

Operational profile	Reliability dimension	Energy dimension	Maintenance dimension	Implication for screening
Reliability-constrained site	Frequent failures or substantial downtime	May be efficient or inefficient	May involve low or high maintenance burden	Requires reliability-focused technical assessment; critical thresholds should be considered separately
Energy-intensive site	May have acceptable reliability	High energy consumption or energy intensity relative to comparable sites	May have low or high maintenance burden	Requires examination of equipment configuration, traffic, and potential energy-saving interventions
Maintenance-intensive site	May experience recurring failures	May have acceptable or poor energy performance	Frequent interventions or long repair durations	Requires comparison of continued maintenance with component replacement or broader modernization
Multi-dimensional concern	Poor performance across several dimensions	High energy-related concern	High maintenance burden	May receive a high composite score, subject to data quality, weighting, and reliability safeguards

Insufficient-data site	Reliability evidence incomplete	Energy or traffic measurements incomplete	Maintenance records incomplete	Should not receive an artificially favorable score; additional data or a documented exclusion rule is required

Table 4 illustrates why the three dimensions should be assessed together but remain separately visible. Two sites may obtain similar composite scores for different reasons: one may be constrained primarily by reliability, while another may have high energy intensity and recurring maintenance interventions. The appropriate intervention may differ substantially even if their overall scores are similar.

The framework therefore supports two complementary outputs: a composite priority score for relative screening and a dimension-specific profile explaining the principal contributors to that score. A separate reliability safeguard can identify sites requiring technical review even when their composite scores are not among the highest.

The operational usefulness of these outputs depends on the quality and comparability of the input data. The weighting procedure, normalization population, observation periods, and missing-data rules must be documented before scores can be interpreted as a defensible ranking.

4.5. Summary of Results

The evidence reviewed in this study supports three conclusions. First, published base-station failure records provide a basis for defining reliability indicators, but aggregate failure totals are insufficient to establish site-specific reliability performance. Second, published energy scenarios can support transparent calculations of illustrative energy-intensity ranges, provided that derived values are clearly distinguished from direct measurements. Third, the integration of reliability, energy efficiency, and maintenance performance requires linked site-level records that are not established by the separate studies examined here.

Accordingly, the results demonstrate the methodological feasibility of the proposed framework but do not constitute an empirical validation of its rankings. No actual site priority scores, maintenance improvements, investment returns, or causal effects of modernization are claimed. Those outcomes require a harmonized dataset and a subsequent empirical evaluation.

5- Discussion

5.1. Interpretation of the Evidence

The proposed framework addresses a central challenge in telecommunication site modernization: operational decisions must account for several performance dimensions that are related but not interchangeable. Reliability, energy efficiency, and maintenance performance describe different aspects of site operation. Assessing them independently may produce conflicting investment priorities, whereas combining them without an explicit methodology can obscure the reasons behind a decision.

The reliability evidence discussed by Wu et al. [2] demonstrates the relevance of analyzing base-station failure events at the network level. Their study provides a basis for considering the occurrence and distribution of failures rather than relying exclusively on aggregate network availability. However, published network-level failure counts do not establish the failure rate of every individual station. A site-specific assessment requires records linking each event to its location, observation period, and operational consequences.

Energy assessment presents a related interpretive challenge. Golard et al. [1] examined the energy footprints of fourth- and fifth-generation radio access networks through measurement-informed modeling and alternative deployment scenarios. This type of evidence supports the use of energy intensity and configuration-sensitive indicators in modernization assessment. Nevertheless, energy consumption per unit of traffic and absolute electricity consumption answer different questions. A site may exhibit relatively low energy intensity while consuming substantial total electricity because it carries a large traffic volume. Conversely, a site with low absolute consumption may perform inefficiently relative to the traffic it supports.

The broader review by Williams et al. [3] also highlights the importance of distinguishing operational energy from embodied energy and indirect energy effects when evaluating fifth-generation networks. Consequently, the proposed framework focuses on operational indicators within a defined measurement boundary. It does not claim to represent the complete environmental footprint of equipment replacement or network modernization.

Maintenance performance adds a further dimension. Repeated interventions, long repair durations, and recurring failures may indicate that continued maintenance is becoming operationally burdensome. However, these indicators do not independently establish that replacement is the most appropriate intervention. The condition of the equipment, the severity of failures, the availability of spare parts, and the technical feasibility of upgrading individual components also influence the decision.

Taken together, these considerations support an integrated assessment structure but do not establish a universally optimal weighting scheme. The relative importance of each dimension depends on network objectives, service requirements, and investment constraints. The principal contribution of the proposed model is therefore its transparent decision structure rather than a claim that one particular weighting configuration is empirically superior.

5.2. Implications for Modernization Investment Decisions

The framework has several implications for operators responsible for allocating modernization budgets across geographically distributed telecommunication sites.

First, investment screening should distinguish between the identification of a performance problem and the selection of an intervention. A high reliability-need score may justify a technical investigation, but the appropriate response could involve replacing a defective component, improving power-system resilience, modifying maintenance procedures, or upgrading the entire site. The composite priority score should identify candidates for further assessment rather than automatically prescribe full replacement.

Second, energy efficiency should be evaluated alongside service demand and operational requirements. Energy-intensity indicators are useful for comparing sites with compatible measurement boundaries, but they should not replace absolute electricity-consumption measurements. Investment decisions should consider whether the proposed modernization is expected to reduce total energy use, improve energy use relative to traffic, or achieve both outcomes.

Third, maintenance records should be integrated into investment screening whenever comparable data are available. Repeated repairs may increase the operational burden of retaining existing equipment, but maintenance expenditure alone is insufficient to establish the financial superiority of replacement. A defensible economic comparison requires estimates of acquisition and installation costs, maintenance costs, expected energy savings, service-interruption consequences, equipment lifetime, and other relevant lifecycle cash flows.

Fourth, reliability safeguards should be applied separately from the composite score when service requirements impose non-negotiable performance conditions. Under an unrestricted additive model, favorable performance in one dimension can offset unfavorable performance in another. Such compensation may be inappropriate when a site fails a critical reliability requirement. A separately defined engineering threshold can identify sites requiring immediate technical review regardless of their overall score.

Finally, decision-makers should examine ranking stability before allocating capital based on the model's output. If a site's priority changes substantially when reasonable alternative weights are applied, the decision is sensitive to stakeholder preferences and should be reviewed accordingly. Sites that remain highly ranked across multiple plausible configurations may provide more robust candidates for detailed technical and financial appraisal. This interpretation remains conditional on the availability and quality of the underlying observations.

5.3. Methodological Contribution

The methodological contribution of this study is the specification of a transparent, multi-criteria framework that integrates reliability, energy efficiency, and maintenance performance within a common decision structure.

The framework offers three principal advantages. First, normalization enables indicators measured in different units to be incorporated into a dimensionless assessment. Second, hierarchical weighting preserves the distinction between the importance of each primary dimension and the contribution of individual indicators within that dimension. Third, sensitivity analysis makes the influence of decision preferences on the resulting ranking explicit.

The model also distinguishes the composite score from a critical reliability safeguard. This distinction addresses an important limitation of purely additive decision models: compensation across criteria may produce an apparently acceptable overall score even when a site has a serious operational deficiency.

Nevertheless, min–max normalization and weighted aggregation involve assumptions that must be recognized. Min–max normalization depends on the sites included in the assessment population, while weighted aggregation assumes that the contribution of each criterion can be represented through the selected weights.

The additive model also assumes that trade-offs among the dimensions are acceptable except where separate constraints are imposed.

These characteristics mean that the framework should not be interpreted as a universal optimization model. Its performance depends on the relevance of the indicators, the consistency of the data, the defensibility of the weights, and the appropriateness of the decision constraints. Alternative normalization and aggregation methods could be examined in subsequent research to determine whether they produce materially different priorities.

The framework also does not independently estimate financial returns, carbon reductions, or the causal effect of modernization on network performance. Such outcomes require additional data and suitable evaluation designs. Its immediate purpose is to structure the screening process and make the rationale behind modernization priorities more transparent and reproducible.

5.4. Limitations and Directions for Future Research

The principal limitation is the absence of a verified, harmonized dataset linking reliability events, electricity consumption, traffic volume, and maintenance records for the same telecommunication sites over consistent observation periods. The published evidence supports the relevance of the selected dimensions, but it does not establish that the proposed model has been empirically validated using a common site-level sample.

A second limitation concerns the weighting procedure. Equal weights provide a transparent baseline but do not necessarily reflect the priorities of a particular network operator. Future empirical studies could compare equal weighting with weights derived from documented expert judgments, operational requirements, or observed decision outcomes. The resulting alternatives should be evaluated for their influence on ranking stability rather than assuming that a more complex weighting method is automatically superior.

A third limitation concerns the temporal dimension. Site performance may change as traffic demand, equipment condition, energy prices, and maintenance practices evolve. A ranking based on a single observation period may therefore become outdated. Longitudinal assessments could evaluate how frequently modernization priorities change and whether the proposed framework identifies sites before major reliability or maintenance problems emerge.

Future research should also extend the model to lifecycle and financial evaluation. Such an extension would require verified information on investment costs, maintenance expenditure, energy prices, expected equipment lifetime, and the operational consequences of service interruptions. It could then distinguish between a site's operational need for modernization and the economic attractiveness of a particular intervention.

Finally, empirical validation should compare model-generated priorities with subsequent operational outcomes. Researchers could examine whether sites assigned higher priority subsequently experience greater improvements in reliability, energy performance, or maintenance burden after comparable interventions. This would require an appropriate comparison design and sufficient longitudinal data to distinguish modernization effects from changes caused by traffic demand, network configuration, or other operating conditions.

6- Conclusion

This study developed a multi-criteria decision framework for prioritizing telecommunication site modernization through the integration of reliability, energy efficiency, and maintenance performance. The framework addresses the limitations of evaluating these dimensions independently by providing a common structure for indicator selection, normalization, weighting, composite scoring, and sensitivity analysis.

Reliability assessment incorporates failure frequency, service interruption duration, availability, and recurring failures where suitable records are available. Energy assessment distinguishes absolute electricity consumption from traffic-normalized energy intensity. Maintenance assessment considers intervention frequency, repair duration, recurring faults, and maintenance expenditure when comparable records exist. These indicators are normalized and combined into dimension-specific scores, which are subsequently integrated into a composite modernization priority score.

The methodology also incorporates sensitivity analysis and a separate reliability safeguard to address the possibility that an additive score may conceal critical operational deficiencies. These features improve the transparency of the decision process and clarify how modernization priorities depend on the selected indicators, weighting assumptions, and engineering constraints.

The principal limitation is the absence of a verified dataset that jointly links all three performance dimensions at the individual-site level. Published reliability and energy studies provide a basis for developing the framework, but they do not establish an empirical ranking of sites when the necessary linked observations are unavailable. Accordingly, the proposed model should be regarded as a methodological decision-support framework rather than an empirically validated prediction or optimization system.

Further research should implement the framework using longitudinal, site-level operational data, evaluate alternative weighting and normalization procedures, and connect modernization priorities with lifecycle costs and subsequent performance outcomes. Such validation would establish whether the proposed integrated assessment improves investment screening and supports more defensible allocation of limited modernization resources.

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