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Intelligent Asset Health Evaluation for Electrical Transmission and Distribution Networks

Rashad Mammadov
Department of Electrical Engineering, Azerbaijan Technical University, Baku, Azerbaijan

ABSTRACT

The increasing complexity of electrical transmission and distribution networks has created a critical requirement for intelligent asset health evaluation mechanisms capable of improving reliability, operational efficiency, and lifecycle management. Traditional asset management practices primarily depend on periodic inspection, historical maintenance records, and experience-based decision-making, which are insufficient for modern power systems characterized by large-scale infrastructure, diverse equipment conditions, and rapidly changing operational environments. This research paper proposes an integrated conceptual framework for intelligent asset health evaluation by combining multidimensional asset indicators, lifecycle management principles, knowledge-driven evaluation mechanisms, and machine learning-based predictive maintenance approaches.

The study develops a research framework that considers physical asset condition, operational performance, economic value, environmental influence, and strategic importance as interconnected dimensions of asset health. Based on existing research on power grid physical asset evaluation, asset lifecycle management, and operational indicator knowledge systems, the paper analyzes the relationships among influencing factors affecting asset performance and proposes a structured evaluation approach. Interpretive structural modeling concepts are incorporated to understand hierarchical relationships among asset health determinants, while knowledge graph-based approaches are considered for improving information integration and decision support.

The research highlights that intelligent asset health evaluation should move beyond isolated equipment monitoring toward a comprehensive decision architecture integrating real-time data acquisition, condition assessment, predictive analytics, and strategic asset optimization. Machine learning-based predictive maintenance approaches demonstrate significant potential in identifying abnormal operational patterns, forecasting equipment degradation trends, and reducing unnecessary maintenance activities (Philip, 2025). However, practical implementation requires addressing challenges related to data quality, model interpretability, cybersecurity, and organizational adaptation.

The findings indicate that an intelligent asset health evaluation framework can enhance the sustainability and resilience of transmission and distribution networks by enabling proactive maintenance, improving investment decisions, and supporting lifecycle-oriented management strategies. The proposed framework provides theoretical and practical contributions by establishing a comprehensive perspective for evaluating power infrastructure health and supporting the transition from conventional maintenance models toward intelligent, predictive, and value-oriented asset management.

KEYWORDS

Intelligent asset health evaluation; power transmission and distribution networks; predictive maintenance; machine

learning; asset lifecycle management; power grid physical assets; condition assessment; knowledge graph; smart grid reliability.

1. INTRODUCTION

1.1 Background

The Electrical transmission and distribution networks represent one of the most critical infrastructures supporting modern economic and social development. The reliability of electricity supply depends not only on network planning and operational control but also on the health condition of numerous physical assets, including transformers, circuit breakers, transmission lines, distribution equipment, protection systems, and associated infrastructure. As power networks continue to expand in scale and complexity, conventional asset management methods based praimarily on scheduled maintenance and manual inspection are increasingly unable to satisfy requirements for reliability, cost efficiency, and sustainability.

Power grid enterprises possess extensive physical assets accumulated over decades of development. These assets differ significantly in age, operating environment, technical characteristics, failure probability, and economic importance. Consequently, effective management requires a comprehensive understanding of asset health rather than simple evaluation based on individual technical parameters. Research on power grid physical assets has emphasized the necessity of establishing comprehensive evaluation index systems to analyze asset conditions from multiple perspectives, including technical performance, operational efficiency, and management value (Wei et al., 2020).

The concept of intelligent asset health evaluation has emerged from the integration of advanced sensing technologies, digital information systems, artificial intelligence, and lifecycle management theories. Unlike traditional approaches that identify failures after degradation becomes visible, intelligent evaluation focuses on continuous condition monitoring, early anomaly detection, and predictive decision-making. Such an approach enables utilities to optimize maintenance strategies, reduce operational risks, and extend asset service life.

1.2 Problem Statement

Although power enterprises have developed various asset management systems, several limitations remain. First, existing evaluation methods often concentrate on individual equipment states without adequately considering interactions among multiple influencing factors. Asset health is not determined solely by physical deterioration but also by operational conditions, environmental stress, maintenance history, strategic importance, and economic consequences.

Second, the increasing volume of operational data generated by smart grid technologies creates both opportunities and challenges. Large amounts of monitoring data can support accurate health evaluation; however, ineffective data integration and insufficient analytical capabilities may prevent utilities from transforming information into actionable knowledge. Studies on power grid enterprise operational indicators have demonstrated the importance of structured knowledge systems for improving information organization and decision support (Li et al., 2020).

Third, predictive maintenance technologies require further integration into asset management frameworks. Machine learning approaches provide opportunities for forecasting equipment failures and identifying degradation patterns, but their effectiveness depends on data availability, model reliability, and practical deployment mechanisms. Predictive maintenance research has demonstrated that machine learning can improve electric power system maintenance decisions by enabling earlier identification of abnormal conditions and reducing unexpected failures (Philip, 2025).

Therefore, there is a need for a comprehensive intelligent asset health evaluation framework that combines technical assessment, information integration, predictive analysis, and lifecycle optimization.

1.3 Research Relevance

The importance of intelligent asset health evaluation is closely associated with the transformation of power systems toward digitalization and intelligent operation. Traditional asset management emphasizes maintaining equipment functionality, whereas modern approaches focus on maximizing asset value throughout the entire lifecycle. Lifecycle-oriented evaluation considers acquisition, operation, maintenance, renewal, and retirement decisions as interconnected processes rather than independent activities.

Research on asset lifecycle management evaluation systems has highlighted that effective asset management requires systematic indicators covering different stages of asset existence and utilization (Tang, 2017). This perspective provides a foundation for developing intelligent evaluation models capable of supporting long-term infrastructure planning.

Furthermore, strategic evaluation of power grid enterprises requires understanding how asset health influences organizational objectives, investment efficiency, and service reliability. Studies analyzing strategic objective structures of provincial power grid companies have indicated that operational goals and asset capabilities are closely connected through complex influencing mechanisms (Ma et al., 2019). Intelligent asset evaluation therefore contributes not only to equipment management but also to broader enterprise-level decision-making.

1.4 Research Objectives

This research aims to develop a conceptual and analytical framework for intelligent asset health evaluation in electrical transmission and distribution networks. The specific objectives are:

First, to analyze the theoretical foundations of intelligent asset health evaluation by integrating asset lifecycle management, physical asset assessment, and predictive maintenance concepts.

Second, to establish a multidimensional evaluation framework incorporating equipment condition, operational performance, economic factors, environmental impacts, and strategic importance.

Third, to examine the role of advanced analytical approaches, including knowledge-based systems and machine learning techniques, in improving asset condition assessment and maintenance decision-making.

Fourth, to identify implementation challenges and limitations associated with intelligent asset evaluation systems and propose future development directions.

1.5 Scope and Significance

The scope of this research focuses on transmission and distribution network assets and their intelligent health evaluation mechanisms. The study does not examine individual equipment design improvements but concentrates on system-level evaluation and management approaches.

The significance of this research lies in supporting the transition from reactive maintenance models toward proactive and predictive asset management. By integrating multiple information sources and analytical methods, intelligent evaluation can improve reliability, reduce maintenance costs, and enhance infrastructure sustainability.

The proposed framework also contributes academically by synthesizing existing research on asset evaluation indicators, knowledge-driven management systems, and predictive maintenance technologies into a unified perspective. Practically, it provides guidance for power utilities seeking to implement intelligent asset management strategies under increasingly complex operational conditions.

2. LITERATURE REVIEW

2.1 Development of Power Grid Asset Health Evaluation Research

The evaluation of power grid assets has gradually evolved from traditional equipment reliability assessment toward integrated asset health management. Earlier approaches mainly focused on individual equipment parameters, failure records, and maintenance schedules. However, the increasing scale and complexity of electrical networks have demonstrated that equipment health cannot be accurately represented through isolated technical indicators. Modern asset evaluation requires consideration of multiple dimensions, including physical condition, operational contribution, economic value, and strategic significance.

Fu and He (2019) analyzed influencing factors affecting the benefits of physical assets in substation equipment through an interpretive structural model. Their research emphasized that asset performance is influenced by interconnected factors rather than independent variables. The study demonstrated that hierarchical analysis methods can identify relationships among influencing factors and reveal underlying drivers affecting asset value. This perspective provides theoretical support for intelligent asset health evaluation because intelligent systems must not only measure asset conditions but also understand causal relationships among different factors.

Similarly, Wei et al. (2020) proposed a comprehensive evaluation index system for analyzing power grid physical assets. Their research highlighted the necessity of establishing multidimensional indicators to evaluate asset conditions systematically. The evaluation framework considered various aspects of physical assets and provided a foundation for integrating technical and management-oriented measurements. However, the study mainly focused on constructing evaluation indicators, while intelligent analysis and predictive capabilities require further development.

Tang (2017) examined evaluation indicators for asset lifecycle management systems and emphasized that asset health should be considered throughout the entire service process. Lifecycle management changes the traditional perspective of managing equipment only during operation and instead evaluates asset value from planning, acquisition, operation, maintenance, and retirement stages. This approach is particularly relevant for transmission and distribution networks because many critical assets have long service periods and require continuous optimization throughout their operational lifespan.

2.2 Knowledge-Based Evaluation and Information Integration

The development of digital power systems has generated significant amounts of operational, maintenance, and equipment data. Effective utilization of this information requires structured approaches capable of transforming distributed data into meaningful knowledge. Li et al. (2020) investigated the construction and application of knowledge graphs for power grid enterprise operation indicators. Their study demonstrated that knowledge graph technology can improve the organization, association, and application of complex operational information.

Knowledge-based evaluation approaches provide important support for intelligent asset health assessment because asset condition is influenced by diverse information sources. Equipment monitoring data, maintenance records, environmental conditions, and operational history must be integrated before accurate health evaluation can be achieved. A knowledge graph-based framework can establish relationships among equipment characteristics, operational events, and performance indicators, enabling more comprehensive analysis.

However, information integration alone does not guarantee intelligent decision-making. The challenge lies in converting interconnected information into predictive and actionable insights. Therefore, knowledge representation approaches need to be combined with analytical models capable of identifying patterns and forecasting future asset conditions.

The reviewed studies provide important foundations for intelligent asset health evaluation; however, several research gaps remain.

First, existing evaluation studies mainly focus on indicator construction and factor analysis. While these approaches establish measurement frameworks, they provide limited capability for continuous monitoring and future condition prediction.

Second, knowledge-based approaches improve information organization but require stronger analytical mechanisms to transform knowledge relationships into operational decisions.

Third, predictive maintenance research demonstrates the value of machine learning; however, predictive models need integration with broader asset management strategies to ensure that predictions support practical maintenance and investment decisions.

Fourth, current studies often examine technical, operational, or strategic perspectives separately. A comprehensive framework combining these dimensions remains insufficiently developed.

Based on these gaps, this research positions intelligent asset health evaluation as an integrated management framework combining multidimensional assessment, knowledge integration, predictive analytics, and lifecycle optimization. The theoretical foundation is derived from the interaction between asset management theory, intelligent decision systems, and data-driven maintenance approaches.

3. METHODOLOGY

3.1 Research Design

This study adopts a conceptual framework development methodology based on systematic synthesis of existing asset management theories and intelligent evaluation approaches. The objective is not to develop a single equipment-level diagnostic algorithm but to establish an integrated evaluation architecture applicable to electrical transmission and distribution networks.

The methodology combines four analytical perspectives:

1. Multidimensional asset health evaluation.

2. Hierarchical influencing factor analysis.

3. Knowledge-driven information integration.

4. Predictive maintenance-oriented intelligence.

The framework considers asset health as a dynamic state influenced by technical, operational, economic, environmental, and strategic factors.

3.2 Intelligent Asset Health Evaluation Framework

The proposed framework consists of five interconnected layers:

Layer 1: Data Acquisition Layer

The first layer collects information from multiple sources, including equipment monitoring systems, operational databases, maintenance records, environmental monitoring systems, and enterprise management platforms.

The purpose of this layer is to establish a comprehensive information foundation. Unlike conventional assessment methods relying on limited inspection data, intelligent evaluation requires continuous information acquisition to capture changing asset conditions.

Layer 2: Data Processing and Knowledge Integration Layer

Raw data collected from different systems often contains inconsistencies, missing information, and different structural formats. Therefore, data processing and knowledge integration are necessary.

A knowledge graph approach can be applied to establish relationships among assets, indicators, events, and operational states. According to Li et al. (2020), knowledge-based organization of power grid indicators improves information association and supports more effective analysis.

In the proposed framework, each asset is represented through interconnected attributes, including:

- Technical characteristics.
- Operating history.
- Maintenance records.
- Failure information.
- Environmental exposure.
- Strategic importance.

This structure enables comprehensive representation of asset conditions.

3.3 Multidimensional Health Evaluation Model

Asset health is evaluated through multiple dimensions rather than a single indicator.

Technical Condition Dimension

This dimension evaluates physical performance and degradation status. Parameters may include equipment age, insulation condition, failure frequency, abnormal operating signals, and maintenance history.

Technical condition represents the direct physical health of assets but cannot independently determine overall asset value.

Operational Performance Dimension

Operational performance evaluates how effectively an asset performs its intended function within the network. Factors include loading level, reliability contribution, operational efficiency, and service continuity.

An asset may have moderate physical degradation but remain strategically essential due to its network position. Therefore, operational contribution must be included.

Economic Value Dimension

Economic evaluation considers investment value, maintenance cost, replacement cost, and lifecycle benefits. Tang (2017) emphasized that lifecycle evaluation is essential for understanding long-term asset management value.

Environmental and External Influence Dimension

External conditions such as climate exposure, operating environment, and sustainability requirements influence asset degradation patterns. Incorporating these factors improves evaluation accuracy.

Strategic Importance Dimension

Strategic importance reflects the consequences of asset failure. Assets supplying critical areas or forming important network connections require higher evaluation priority.

3.4 Hierarchical Influence Analysis Model

A major challenge in intelligent asset health evaluation is understanding the complex relationships among different influencing factors. Asset degradation and performance changes are rarely caused by a single variable; instead, they result from interactions among technical, operational, environmental, and management-related factors.

This research adopts the principle of interpretive structural modeling (ISM) to analyze hierarchical relationships among asset health determinants. ISM provides a systematic approach for converting complex relationships into structured models by identifying direct and indirect influences among factors. Previous research on substation physical asset benefit analysis demonstrated that ISM can reveal important relationships among influencing factors and distinguish fundamental drivers from dependent factors (Fu & He, 2019).

Within the proposed framework, influencing factors are classified into three levels:

The first level consists of fundamental driving factors, including asset design characteristics, environmental exposure, investment strategy, and technological conditions. These factors determine long-term asset behavior and degradation patterns.

The second level includes intermediate operational factors, such as maintenance effectiveness, loading conditions, operational stress, and monitoring quality. These factors directly affect asset condition evolution.

The third level includes observable health outcomes, including failure probability, remaining useful life, reliability level, and maintenance requirements.

The hierarchical model allows asset managers to understand not only the current health status but also the reasons behind asset deterioration. This improves decision transparency and enables targeted intervention strategies.

3.5 Machine Learning-Based Predictive Evaluation Mechanism

The integration of machine learning represents a significant advancement in intelligent asset health evaluation. Traditional assessment methods generally identify current conditions, whereas predictive models aim to estimate future degradation trends.

The proposed methodology incorporates machine learning as a predictive layer that processes historical and real-time operational data. The primary functions include:

First, anomaly detection. Machine learning models can identify deviations from normal operating patterns by analyzing large volumes of sensor and operational data.

Second, condition prediction. Predictive models can estimate future equipment health based on historical degradation patterns and current operating conditions.

Third, maintenance optimization. Prediction results can support decisions regarding inspection timing, repair strategies, and asset replacement planning.

Philip (2025) highlighted that machine learning-based predictive maintenance approaches provide opportunities for improving reliability and reducing unexpected failures in electric power systems. However, this research recognizes that predictive accuracy alone is insufficient. Practical asset management requires integration between prediction outputs and engineering decision processes.

Therefore, the proposed framework considers machine learning as a supporting decision technology rather than a replacement for expert knowledge. Human expertise remains essential for validating predictions, interpreting abnormal conditions, and determining appropriate maintenance actions.

Consider a high-voltage transformer operating in a regional transmission network. Traditional management may evaluate the transformer based on scheduled inspection results and operational history. However, the intelligent framework continuously collects temperature variations, loading patterns, insulation monitoring data, maintenance records, and environmental information.

The knowledge integration layer establishes relationships among these factors and identifies abnormal trends. The predictive model detects increasing degradation probability due to combined thermal stress and aging effects. The health index calculation categorizes the transformer as an attention-level asset.

Based on this assessment, the utility schedules targeted inspection rather than immediate replacement. This approach avoids unnecessary expenditure while reducing unexpected failure risks.

Such an example demonstrates that intelligent asset evaluation improves decision quality by connecting technical analysis with economic and operational considerations.

4. RESULTS

The analysis of the proposed intelligent asset health evaluation framework reveals several significant findings.

First, asset health evaluation requires a multidimensional assessment structure rather than a single technical measurement. The reviewed literature indicates that physical asset performance is influenced by interconnected technical, operational, economic, and strategic factors (Wei et al., 2020; Fu & He, 2019). Therefore, comprehensive evaluation improves the accuracy of understanding asset conditions.

Second, intelligent evaluation enhances the transition from condition assessment toward predictive decision-making. Traditional methods mainly identify existing problems, whereas machine learning-based approaches enable forecasting of future equipment behavior. Predictive maintenance research demonstrates that data-driven methods can support earlier fault identification and improve maintenance efficiency (Philip, 2025).

Third, knowledge integration is essential for intelligent asset management. Power enterprises operate multiple information systems containing equipment records, operational indicators, and maintenance data. Knowledge graph approaches provide mechanisms for connecting fragmented information and improving decision support capability (Li et al., 2020).

Fourth, lifecycle-oriented evaluation provides a more effective management perspective compared with short-term maintenance analysis. Considering asset acquisition, operation, maintenance, and replacement decisions together enables utilities to maximize long-term value. This finding supports lifecycle management research emphasizing comprehensive asset evaluation systems (Tang, 2017).

Fifth, intelligent evaluation frameworks must balance technological capability with practical usability. Although advanced algorithms can improve prediction accuracy, implementation challenges remain regarding data quality, model transparency, and integration with existing organizational processes.

Overall, the findings indicate that intelligent asset health evaluation should be considered a strategic management approach rather than only a technical monitoring system. Its effectiveness depends on combining data intelligence, engineering knowledge, and lifecycle decision principles.

5. DISCUSSION

The proposed framework demonstrates that intelligent asset health evaluation represents a significant advancement in power infrastructure management. By integrating physical condition assessment, knowledge representation, predictive analytics, and strategic evaluation, utilities can achieve more proactive and efficient asset management.

A key theoretical implication is the transition from isolated equipment evaluation toward interconnected system analysis. Previous studies have established evaluation indicators and influencing factors; however, intelligent management requires understanding relationships among these factors. The integration of hierarchical analysis methods provides a pathway for identifying root causes behind asset deterioration.

From a practical perspective, intelligent evaluation can improve maintenance efficiency by allowing utilities to prioritize high-risk assets. Instead of applying identical maintenance strategies to all equipment, resources can be allocated according to actual health conditions and operational importance.

However, several limitations must be considered. First, intelligent evaluation systems depend heavily on data availability and quality. Incomplete historical records or inconsistent monitoring data may reduce model reliability. Second, machine learning models may create interpretability challenges because operational engineers require understandable explanations before accepting automated recommendations (Philip, 2025). Third, implementation requires organizational transformation, including improved data management capabilities and cooperation between technical and managerial departments.

The framework also presents trade-offs. Increasing evaluation complexity may improve analytical accuracy but may increase implementation costs. Similarly, highly automated systems can improve efficiency but require appropriate human supervision to prevent incorrect decisions.

Compared with existing research, this study extends previous indicator-based evaluation approaches by incorporating predictive intelligence and knowledge integration. Research on strategic objectives of power grid enterprises demonstrates that asset capability is closely related to organizational performance (Ma et al., 2019). Therefore, intelligent asset health evaluation should support both equipment reliability and enterprise-level strategic objectives.

Future development should focus on improving explainable artificial intelligence techniques, enhancing real-time evaluation capability, and integrating sustainability considerations into asset health models. These improvements can further support resilient and sustainable electrical infrastructure management.

6. CONCLUSION

Intelligent asset health evaluation provides a comprehensive approach for improving the reliability, efficiency, and sustainability of electrical transmission and distribution networks. This research developed an integrated framework combining multidimensional assessment, lifecycle management, knowledge integration, hierarchical influence analysis, and machine learning-based predictive maintenance.

The study demonstrates that asset health is a complex condition influenced by multiple interconnected factors. Effective evaluation requires consideration of technical status, operational contribution, economic value, environmental influence, and strategic importance. The proposed framework addresses limitations of conventional maintenance approaches by enabling continuous monitoring, predictive analysis, and informed decision-making.

The research contributes theoretically by integrating concepts from asset management, intelligent systems, and predictive maintenance into a unified evaluation perspective. Practically, it provides guidance for power enterprises seeking to improve maintenance strategies and optimize infrastructure investment.

Future research should investigate large-scale implementation using real operational datasets, develop more transparent predictive models, and establish standardized intelligent evaluation procedures across different categories of power assets. With continued advancement in digital technologies, intelligent asset health evaluation will become an essential component of future smart grid management.

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