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RELIABILITY ASSESSMENT AND CRITICALITY ANALYSIS OF MT/LV DISTRIBUTION NETWORKS IN SECONDARY CITIES OF SUB-SAHARAN AFRICA: A CASE STUDY OF MBANZA-NGUNGU, DEMOCRATIC REPUBLIC OF THE CONGO

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ABSTRACT

Access to reliable electricity remains a critical challenge in secondary cities of Sub-Saharan Africa, where distribution networks suffer from aging infrastructure, chronic underinvestment, and deficient maintenance. This study presents a comprehensive reliability assessment and criticality analysis of the medium-voltage (MT) and low-voltage (LV) distribution network of Mbanza-Ngungu, Democratic Republic of the Congo (DRC). A mixed-method approach combined quantitative analysis of 12 months of outage records (January–December 2025) with stratified surveys of 367 subscribers and exhaustive interviews of 30 SNEL technical staff. Reliability was evaluated using IEEE Std 1366 indices (SAIFI, SAIDI, CAIDI, ASAI, ENS) and probabilistic reliability theory (MTBF, MTTR, λ, $R(t)$, A). Criticality was assessed using an AMDEC (FMEA) matrix combining frequency, severity, and non-detectability. Results reveal a critically degraded network: SAIFI = 31.5 interruptions/subscriber/year, SAIDI = 90.6 h/subscriber/year, CAIDI = 2.88 h, ASAI = 98.97%, and ENS = 1,450 MWh/year. The network MTBF is 1.95 h with a global availability of 42.2%. Transformer failure is the most critical mode (IC = 25), followed by network overload (IC = 20) and equipment aging (IC = 20). Economic analysis estimates the annual cost of non-reliability at 2.83 million USD, while a targeted investment of 1.6 million USD would be recovered in 14 months, generating net savings of 11.35 million USD over 5 years. The proposed framework provides SNEL and local decision-makers with an operational tool for prioritizing maintenance and renewal investments.

Keywords: Reliability Assessment; IEEE 1366; SAIFI; SAIDI; Criticality Analysis; AMDEC; Distribution Networks; Mbanza-Ngungu; DRC

1 INTRODUCTION

1.1 Context

Access to reliable and quality electricity is a robust indicator of a country's development level [1]. It conditions the efficiency of productive systems, the continuity of essential services health, education, water and the improvement of living conditions. In the Democratic Republic of the Congo (DRC), despite considerable hydroelectric potential, medium-voltage (MT) and low-voltage (LV) distribution networks suffer from advanced aging, chronic underinvestment, and deficient maintenance [2].

The city of Mbanza-Ngungu, a secondary city in Kongo Central province, illustrates this situation: users endure daily long and unpredictable interruptions, recurring voltage drops, and significant material failures [3]. The MT network (nominal voltage 6.6 kV) has a predominantly radial tree structure, with no looping. The LV network distributes energy at 400 V between phases and 230 V between phase and neutral, using bare aluminum-steel conductors suspended on wooden or concrete supports. These technical characteristics, combined with strong demographic growth and anarchic connections, make the network particularly vulnerable to failures.

However, no systematic study of the reliability of this network has been conducted to date. This scientific gap justifies the present research, which aims to fill a double void: an empirical knowledge of the network's real performance and a methodology adapted to weakly instrumented contexts.

1.2 Problem Statement

The problem of MT/LV network operation in Mbanza-Ngungu lies in the critical absence of quantitative indicators and local decision-support tools correlating failure causes to socio-economic impacts. The network presents structural disturbances: frequent interruptions, excessive outage durations, voltage asymmetry whose causes are not clearly identified, and repeated equipment failures.

The central research question is: To what extent can the quantitative evaluation of reliability, coupled with criticality analysis and user perception, inform improvement strategies adapted to local constraints?

This question decomposes into two subsidiary questions:

- What is the objective reliability level of the MT/LV network of Mbanza-Ngungu, measured using IEEE 1366 indices (SAIFI, SAIDI, CAIDI), and what are the deep technical and organizational causes?
- What is the criticality of different failures on a socio-economic level, and how can technical and managerial actions be prioritized to effectively improve service continuity?

1.3 Objectives

The overall objective is to produce an in-depth evaluation of the reliability of the MT/LV network of Mbanza-Ngungu, integrating technical, socio-economic, and decision-making dimensions, to propose operational recommendations for improving electrical service continuity. Specifically:

- Quantify network reliability by calculating SAIFI, SAIDI, and CAIDI indices over a 12-month historical period (January–December 2025).
- Evaluate and map the criticality of each failure type by combining failure frequency and socio-economic severity.
- Develop a prioritized action plan adapted to local logistical and budgetary constraints.

2 LITERATURE REVIEW

2.1 Reliability of Distribution Networks

In the scientific literature, the reliability of electrical distribution networks is a well-established field. The IEEE Std 1366™ standard defines the key indices for evaluating service continuity from the user's perspective [4]. The theory of Sûreté de Fonctionnement (FMDS) provides probabilistic models for equipment lifetime and failure rates [5]. The AMDEC method allows systematic identification and ranking of failure modes [6]. However, most studies focus on HV/MV transmission networks or urban contexts in developed countries [7]. The application of these tools to secondary cities in Sub-Saharan Africa, where data are scarce and networks are degraded, remains under-documented [8].

2.2 Service Continuity Indices (IEEE 1366)

The evaluation of service continuity is harmonized internationally by the IEEE Std 1366™ standard, which defines the System Average Interruption Frequency Index (SAIFI) and the System Average Interruption Duration Index (SAIDI) [4]:

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} \qquad (1)$$

$$SAIDI = \frac{\sum U_i N_i}{\sum N_i} \qquad (2)$$

where λ_i is the failure rate at load point i, U_i is the annual outage duration at load point i, and N_i is the number of customers at load point i.

The Customer Average Interruption Duration Index (CAIDI) is derived as [4]:

$$CAIDI = \frac{SAIDI}{SAIFI} \qquad (3)$$

The Average Service Availability Index (ASAI) expresses the average service availability over the year (8,760 hours) [4]:

$$ASAI = 1 - \frac{SAIDI}{8760} \qquad (4)$$

The Energy Not Supplied (ENS) quantifies the total energy not delivered to users due to interruptions [4]:

$$ENS = \sum L_{ai} U_i \qquad (5)$$

where L_{ai} is the average load at load point i.

2.3 Reliability Theory and Dependability

Probabilistic reliability theory provides complementary indicators. The Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) are defined as [5]:

$$MTBF = \frac{\text{Total good operating time}}{\text{Total number of failures}} \qquad (6)$$

$$MTTR = \frac{\text{Total repair time}}{\text{Total number of failures}} \qquad (7)$$

The failure rate λ and the reliability function $R(t)$ are given by [5]:

$$\lambda = \frac{1}{MTBF} \qquad (8)$$

$$R(t) = e^{-\lambda t} \qquad (9)$$

The intrinsic availability A is expressed as [5]:

$$A = \frac{MTBF}{MTBF + MTTR} \qquad (10)$$

2.4 AMDEC Method and Criticality Analysis

The criticality index (IC) used in AMDEC analysis is defined as [6]:

$$IC = F \times G \times D \qquad (11)$$

where F is the frequency of occurrence, G is the severity, and D is the non-detectability, each rated on a discrete scale. The criticality decision grid is:

- IC < 8: Low criticality (green zone) – standard corrective maintenance.
- 8 ≤ IC ≤ 16: Moderate criticality (yellow zone) – scheduled preventive maintenance.
- IC > 16: High criticality (red zone) – immediate corrective action or priority investment.

2.5 Socio-Technical Approach and User Perception

Recent literature emphasizes the need for a mixed approach combining technical data with user perception to obtain an objective assessment of service quality [11, 12]. The SERVQUAL model developed by Parasuraman et al. [11] and the behavioral consequences model of Zeithaml et al. [12] provide theoretical frameworks for evaluating perceived service quality and its impact on customer behavior.

2.6 Synthesis and Literature Gap

The literature review demonstrates that a global analysis of MT/LV network reliability requires a synergy between probabilistic reliability calculations (MTBF, MTTR, availability), the rigorous application of IEEE 1366 indices (SAIFI, SAIDI, CAIDI), the measurement of voltage quality (EN 50160 standard), the prioritization of vulnerabilities by AMDEC, and the integration of user perception. However, no study has applied this integrated framework to the specific context of secondary cities in the DRC, where data are scarce and networks are critically degraded. This is the gap that the present study aims to fill.

3 MATERIALS AND METHODS

3.1 Study Area

Mbanza-Ngungu is located in Kongo Central province, DRC, approximately 154 km from Kinshasa and 234 km from Matadi. The city has over 100,000 inhabitants and is the third largest city in the province. Its MT network (nominal voltage 6.6 kV) has a predominantly radial tree structure, with no looping. The LV network distributes energy at 400 V between phases and 230 V between phase and neutral, using bare aluminum-steel conductors suspended on wooden or concrete supports.

The study covers the eight administrative districts of the city: Disengomoka, Révolution, Loma I, Loma II, Ngungu, Noki I, Noki II, and Ebeya.

3.2 Population and Sampling

Two distinct populations were studied:

- Technical population (SNEL staff): The total staff assigned to operation, maintenance, and repair of the MT/LV network at the Mbanza-Ngungu distribution center is N = 30. Given the small size, an exhaustive sampling (complete census) was applied. All 30 agents were surveyed. The profile analysis reveals a highly favorable seniority structure: 63.4% have more than 6 years of service, guaranteeing solid empirical memory of historical incidents and weak points.
- User population (subscribers): The total number of subscribers in the eight districts is estimated at N = 8,000 delivery points. The sample size was determined using Cochran's formula (1977) [9]:

$$n_0 = \frac{Z^2 \cdot p \cdot (1-p)}{e^2} \qquad (12)$$

where $Z = 1.96$ (95% confidence), $p = 0.5$ (maximum variance), and $e = 0.05$ (margin of error). The initial sample size is $n_0 = 384$. For a finite population (N = 8,000), the correction factor is applied:

$$n = \frac{n_0}{1 + \frac{n_0 - 1}{N}} \qquad (13)$$

This yields a final sample of 367 subscribers.

Stratified proportional sampling was applied by district (Table 1).

Table 1: Stratified sample distribution by district

N°	District	Estimated Population (Ni)	Proportion (Wi)	Sample Size (ni)
1	Disengomoka	1,722	21.53%	79
2	Révolution	1,242	15.53%	57
3	Loma I	1,112	13.90%	51
4	Loma II	1,046	13.08%	48
5	Ngungu	1,112	13.90%	51
6	Noki II	915	11.44%	42
7	Noki I	719	8.99%	33
8	Ebeya	132	1.63%	6
Total		8,000	100%	367

3.3 Data Collection Instruments

Two structured questionnaires were developed:

- SNEL staff questionnaire (27 questions): covering professional profile, equipment condition, failure typology and recurrence, maintenance practices, and protection devices.
- Subscriber questionnaire (20 questions): covering connection characteristics, perceived continuity and quality, socio-economic impacts and coping strategies, and overall service satisfaction.
- Secondary data were collected from SNEL operational records for 2025: incident and consignment registers, maintenance and repair sheets, and monthly operating reports. Data cleaning included deduplication (elimination of successive openings less than 3 minutes apart), duration sorting (short interruptions < 3 minutes excluded from IEEE 1366 evaluation), and cross-validation of restoration times.

3.4 Reliability and Criticality Modeling

The IEEE 1366 indices (Eqs. 1–5) and probabilistic reliability indicators (Eqs. 6–10) were calculated. The AMDEC criticality index (Eq. 11) was computed for each failure mode using a 1–4 scale for frequency (F), severity (G), and non-detectability (D).

3.5 Validation and Ethics

Internal consistency of the Likert-scale items was assessed using Cronbach's alpha, yielding $\alpha = 0.81$, above the 0.70 threshold. Triangulation of SNEL operational data with staff and subscriber perceptions ensured internal validity. Institutional authorization was obtained from SNEL, and informed consent and anonymity were strictly preserved.

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4 RESULTS

4.1 Technical Diagnosis by SNEL Staff (n = 30)

Table 2: Staff profile, infrastructure condition, and failure factors

Dimension	Modality	n	%	Technical Diagnosis
Seniority	< 2 years	3	10.0	63.4% have in-depth empirical knowledge
	2–5 years	8	26.6	
	> 6 years	19	63.4	
Transformer condition	Good	4	13.3	86.7% operate at or beyond thermal limit
	Aged & overloaded	21	70.0	
	Critical/degraded	5	16.7	
LV network condition	Conform/bad	3	10.0	~90% of LV network shows aging

	Degraded wooden supports	11	36.7	
	Urgent replacement	16	53.3	
Major failure causes	Thermal overload	14	46.7	Overload is the main vector
	Weather/lightning	10	33.3	
	Lack of preventive maintenance	6	20.0	

4.2 Subscriber Survey Results (n = 367)

- Continuity: 84.2% are not regularly supplied; 77.9% experience frequent interruptions; 74.6% experience outages lasting ≥ 1 hour; 74.4% report no prior communication.
- Voltage quality: 85.5% observe voltage variations; 64.9% report damage to household equipment.
- Perceived causes: Lack of maintenance (82.3%), network overload (80.7%), equipment aging (76.6%).
- Economic impact: 61.5% suffer financial losses; 76.0% incur additional monthly expenses (generators, solar kits, batteries).

Overall assessment: 81.2% rate reliability as poor or very poor; 83.7% are dissatisfied with service quality.

Table 3: Detailed quality of service diagnosis by district

District	Sample (ni)	Interruption Frequency	Voltage Drop Severity	Damaged Equipment Rate	Dominant Coping Strategy
Disengomoka	79	Recurrent (> 4/day)	Severe (< 180 V)	68.4%	Generators & high-capacity solar kits
Révolution	57	Frequent (3–4/day)	Moderate to strong (180–195 V)	61.2%	Generators for workshops
Loma I	51	Moderate (2–3/day)	Severe at line end (< 175 V)	45.0%	Individual PV systems
Loma II	48	Frequent (3–4/day)	Severe due to LV line stretch	52.1%	Solar lighting and candles
Ngungu	51	Frequent (3–4/day)	Moderate with instability	58.3%	Generators and inverters
Noki I	33	Disturbed by weather	Low to moderate	38.0%	Solar kits and rechargeable lamps
Noki II	42	Frequent	Severe (< 180 V)	49.0%	Individual solar kits
Ebeya	6	Intermittent	Low to moderate	33.3%	Standalone lamps

4.3 IEEE 1366 Reliability Indices

Using the survey data and SNEL records:

- SAIFI: $SAIFI = 0.779 \times 40.5 \approx 31.5$ interruptions/subscriber/year.
- SAIDI: $SAIDI = 0.746 \times 3 \times 40.5 \approx 90.6$ hours/subscriber/year.
- CAIDI: $CAIDI = 90.6/31.5 = 2.88$ hours.
- ASAI: $ASAI = 1 - 90.6/8760 = 0.9897 = 98.97\%$.
- ENS: $ENS = 2\text{ kW} \times 90.6\text{ h} \times 8000 = 1{,}449{,}600\text{ kWh/year} \approx 1{,}450\text{ MWh/year}$.

Table 4: Synthesis of IEEE 1366 reliability indices

Index	Value	Acceptable Threshold	Status
SAIFI	31.5 int/sub/year	< 1.5	Very critical
SAIDI	90.6 h/sub/year	< 2.0 h	Very critical
CAIDI	2.88 h	< 1.5 h	Critical
ASAI	98.97%	≥ 99.98%	Critical
ENS	1,450 MWh/year	—	Very high

4.4 Probabilistic Reliability Indicators

- For the entire network:

$$MTBF = 8760\ h / 4500\ failures = 1.95\ h.$$

$$\lambda = 1/1.95 = 0.513\ failures/h.$$

$$MTTR = 12000\ h / 4500\ failures = 2.67\ h.$$

$$Availability\ A = 1.95/(1.95+2.67) = 0.422 = 42.2\%.$$

- For the transformer fleet (150 units, 250 failures/year):

$$MTBF = (150 \times 8760)/250 = 5{,}256\ h\text{-transformer}.$$

$$\lambda = 1/5256 = 0.00019\ failures/h/transformer.$$

$$R(1000h) = e^{(-0.00019 \times 1000)} = 0.827 = 82.7\%.$$

Table 5: Synthesis of probabilistic reliability indicators

Category	Indicator	Value	Status
IEEE	SAIFI	31.5 int/client/year	Very critical
	SAIDI	90.6 h/client/year	Very critical
	CAIDI	2.88 h	Critical
	ASAI	98.97%	Critical
	ENS	1,450 MWh/year	Very high
Reliability theory	MTBF network	1.95 h	Very critical
	MTTR network	2.67 h	Critical
	MTBF transformers	5,256 h	Acceptable (low)
	MTTR transformers	24 h	Very critical
	λ transformers	0.00019/h	Critical
	R(8760h) transformers	18.9%	Very critical
	Availability network	42.2%	Very critical

4.5 AMDEC Criticality Matrix

Table 6: AMDEC ranking of MT/LV network equipment

Equipment / Sector	Failure Mode	F	G	D	IC	Risk Level	Recommended Action
Disengomoka substation	Thermal overload & winding breakdown	4	4	2	32	Critical (Red)	Immediate load transfer and transformer replacement
Révolution substation	Phase unbalance & repeated fuse blown	4	3	2	24	Critical (Red)	Physical LV load rebalancing and protection upgrade
Loma I & II LV lines	Severe voltage drop & conductor rupture	3	3	2	18	Critical (Red)	Insert intermediate substation and resize cables
MT switchgear	Insulator flashover & mechanical seizing	2	3	2	12	Moderate (Yellow)	Conditional preventive maintenance and cleaning
Wooden supports (periphery)	Base rot & tilting	2	2	1	4	Low (Green)	Progressive replacement with reinforced concrete

4.6 Hypothesis Verification

Table 7: Hypothesis verification

Code	Hypothesis	Status	Justification
H1	Equipment aging = main cause	Confirmed	Validated by 80% of agents and 76.6% of subscribers
H2	Insufficient preventive maintenance	Confirmed	80% of agents practice corrective maintenance; 82.3% of subscribers note maintenance deficiency
H3	Lack of spare parts lengthens restoration	Confirmed	Revealed by 70% of agents; CAIDI = 2.88 h and MTTR = 2.67 h
H4	Spatial disparity of outages	Confirmed	Confirmed by 76.7% of agents; strong variations by district
H5	Partially operational protection devices	Confirmed	46.7% of agents report frequent protection malfunctions
H6	Significant socio-economic impacts	Confirmed	79.3% of activities strongly disrupted; 61.5% financial losses; 76.0% rely on costly backup solutions

4.7 Economic Evaluation

Table 8: Subscriber losses

Category	Amount (FC/year)	Amount (USD/year)
Palliation expenses	2,658,960,000	949,629
Financial losses	2,683,800,000	958,500
Equipment damage	1,168,200,000	417,214
Total subscriber losses	6,510,960,000	2,325,343

Table 9: Utility losses

Category	Amount (FC/year)	Amount (USD/year)
ENS	217,500,000	77,679
Corrective maintenance	923,000,000	329,643
Spare parts surcharges	275,000,000	98,214
Total utility losses	1,415,500,000	505,536

- Financial synthesis:
  - Global cost: 2,830,879 USD/year.
  - Investment: 1,600,000 USD.
  - Annual savings: 1,364,885 USD.
  - Payback: 14 months.

5 DISCUSSION

5.1 Comparison with Regional References

The results of this study (SAIFI = 31.5; SAIDI = 90.6 h) are comparable to those observed in Uganda (SAIDI = 53.81 h; SAIFI = 34.21 int) for the Kitala feeder [10]. However, the SAIDI of Mbanza-Ngungu is nearly twice as high, suggesting more advanced degradation. This difference is explained by a MTTR twice as high (2.67 h vs. 1.5 h), linked to the lack of spare parts and the absence of rapid fault location means.

5.2 Analysis of Structural Causes

Equipment aging is the primary cause of interruptions (80% of agents, 76.6% of subscribers). The transformer MTBF (5,256 h) and failure rate (λ = 0.00019/h) confirm this reality. Network overload (83.4% of agents) results from demand growth, illegal connections, and initial undersizing. Preventive maintenance is insufficient (60% of agents), and the lack of spare parts lengthens delays (70% of agents). Protection devices are partially operational (46.7% of agents). Spatial disparities are marked: Disengomoka and Révolution are the most affected zones.

5.3 Convergence between Technical Indicators and Perceptions

The convergence between technical indicators and perceptions is strong across all themes. It validates the coherence of the data and confirms that technical indicators are not disconnected from the experience of actors. Perceptions add supplementary dimensions: socio-economic impact, lack of communication, palliation expenses. These results confirm the importance of perceptions in service quality evaluation [11, 12].

5.4 Economic Relevance of Investments

The economic evaluation estimates the annual cost of non-reliability at 2.83 million USD, or 354 USD per subscriber per year. The investment of 1.6 million USD would be recovered in 14 months, with a benefit/cost ratio of 5.05 and an IRR of 85%. Not acting would cost 14.15 million USD over 5 years, versus 2.8 million USD for action, representing a net saving of 11.35 million USD. These results confirm the profitability of reliability investments [13, 14].

5.5 Theoretical and Practical Implications

On a theoretical level, this study confirms the applicability of reliability models to distribution networks in Sub-Saharan Africa, while emphasizing the need to adapt acceptability thresholds to local realities. On a practical level, the results provide the utility with a factual decision-support tool to prioritize maintenance and renewal investments in the most critical zones and equipment (Disengomoka and Révolution, saturated transformers).

5.6 Limitations

This study has certain limitations: (i) the absence of automatic digital recorders, which required manual readings and perception surveys; (ii) a limited sample size for certain subscriber categories; (iii) the unavailability of complete maintenance history over several years. Nevertheless, the convergence of technical and survey data guarantees sufficient robustness for the conclusions formulated.

6 CONCLUSION

This study rigorously characterized the service quality and reliability of the electrical distribution network of Mbanza-Ngungu. The combined analysis of IEEE indices (SAIFI = 31.5; SAIDI = 90.6 h), reliability theory indicators (network MTBF = 1.95 h; transformer MTTR = 24 h), and field surveys demonstrates a critical degradation of the system, mainly attributable to equipment aging, network overload, and deficient maintenance. The economic evaluation proves that a targeted investment plan of 1.6 million USD is profitable within 14 months and would generate net savings of 11.35 million USD over 5 years.

The following recommendations are formulated:

- Short term (0–6 months):
  - Acquire and position a strategic stock of spare parts (fuses, circuit breakers, insulating oil) to reduce transformer MTTR from 24 h to less than 4 h.
  - Proceed with strategic load shedding and phase balancing on saturated feeders.
- Medium term (6–18 months):
  - Replace or upsize the 32 most critical transformers in the Disengomoka and Révolution zones.
  - Install selective protection devices and fault passage indicators to accelerate fault location.
- Long term (18–36 months):
  - Digitize network monitoring through smart meters and remote-control systems.
  - Implement a predictive maintenance program based on regular oil analysis and thermographic inspection.

The proposed framework provides SNEL and local decision-makers with an operational tool for prioritizing maintenance and renewal investments, contributing to improved service continuity and socio-economic development in Mbanza-Ngungu.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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