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Failure Mode Analysis and Reliability Assessment of HFO Centrifugal Separators in a Thermal Power Plant: A Case Study of the Ouaga East (Kossodo) Power Plant, Burkina Faso

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Abstract

This paper presents an in-depth failure mode analysis and a quantitative reliability assessment of heavy fuel oil (HFO) centrifugal separators operating at the Ouaga East Kossodo thermal power plant. In this study, historical operational and maintenance logs collected from September 8, 2021, to August 19, 2024, are leveraged to identify critical failures, compute key reliability indicators (Mean Time Between Failures, Mean Time To Repair, and operational availability), and perform survival function estimation using Kaplan-Meier curves. The Ishikawa cause-and-effect diagram identifies equipment-related issues as the primary failure source, accounting for 33% of causes, while methodological factors and workforce contributions each represent 20%. Additionally, the Failure Modes, Effects, and Criticality Analysis (FMECA) reveals that sludge discharge system failures, bearing and seal degradation, and separation disc malfunctions are responsible for 27%, 26%, and 30% of unplanned shutdowns, respectively. The aggregate MTBF across the three separators is calculated at 86.28 hours, yielding a failure frequency of approximately one event per 86 operational hours, alongside an overall operational availability of 69.72%. The Kaplan-Meier reliability curves distinctly highlight an accelerated wear-out phase manifesting after 1500 cumulative operating hours. These notably poor reliability indicators are potentially attributable to external aggravating factors, such as elevated ambient temperatures, inconsistent HFO physicochemical quality, suboptimal maintenance scheduling, and the procurement of unsuitable spare parts. Collectively, the outcomes of this investigation constitute an indispensable baseline reference state, which is paramount prior to the deployment of any condition-based maintenance strategy aimed at enhancing system longevity and operational continuity.

Keywords

Thermal Power Plant, Centrifugal Separator, HFO, Failure Mode, Reliability

1. Introduction

In Sahelian countries, thermal power plants account for more than half of primary electricity needs. In Burkina Faso, their share was estimated at over 80% in 2018 [1]. These power plants, such as the Kossodo plant in Burkina Faso, largely rely on heavy fuel oil (HFO) for their operation. HFO contains various impurities (water, salts, solid particles, etc.) that must be removed before injection into the engines. Centrifugal separators are the key equipment for this purification process. Their failure leads to premature engine deterioration, production outages, and increased maintenance costs.

The Kossodo (Ouaga East) thermal power plant has a total installed capacity of 112.7 MW and uses three (03) GEA centrifugal separators. These separators experience recurrent failures, particularly during periods of high heat, which correspond to peak production (March to June), as well as during variations in HFO quality. No systematic reliability analysis has been conducted to date. Moreover, one of the three separators was in corrective maintenance when the data were collected. Corrective maintenance is the prevailing practice, with interventions often performed in an ad hoc manner.

The overall objective of this work is to analyze the failure modes and assess the reliability of the three (03) HFO centrifugal separators used in the Ouaga East thermal power plant located in Kossodo. Specifically, we aim to identify and classify the failure modes of these separators, determine the operational reliability indicators (MTBF, MTTR, availability), and establish a baseline reference for the introduction of reliability-centered maintenance (RCM).

Research work focused on the reliability of centrifugal separators in thermal power plants is scarce. Such studies most often concern separators on marine vessels (tankers or gas carriers), or those used in the dairy or petrochemical industry [2]-[5]. In the context of power plants, several advanced techniques such as Failure Mode and Effects Analysis (FMEA), Reliability Block Diagram (RBD), Reliability-Centered Maintenance (RCM), Monte Carlo Simulation (MCS), Markov Analysis (MA), Bayesian Networks (BN), fuzzy logic, etc., have been developed or combined by researchers to identify, evaluate, and prioritize potential equipment failures in order to mitigate the risks associated with the failure of such systems [4] [6]-[17]. All these studies pay very little attention to HFO centrifugal separators in thermal power plants. The MTBF indicator values reported for similar separators range from 2000 to 3000 hours [18]. Our aim is therefore to contribute to filling this gap, particularly in a tropical environment with limited resources.

2. Theory and Formula

2.1. FMECA Analysis

The Ishikawa diagram, also known as the cause-and-effect diagram, is a quality management tool developed by Kaoru Ishikawa in the 1950s [19] [20]. We will use this tool upstream to comprehensively identify the causes of a critical failure of an HFO separator, and then perform the FMECA analysis in accordance with IEC 60812 [21]. For each failure mode, we will assign:

- ✓ severity (S): from 1 (minor: production stoppage of less than 15 minutes) to 10 (critical: power plant shutdown of 2 hours or more);
- ✓ occurrence (O): from 1 (rare failure) to 10 (very frequent failure: at least once per week);
- ✓ detection (D): from 1 (certain detection, obvious signs) to 10 (impossible to detect, no signs);
- ✓ criticality (C): $C = S \times O \times D$.

2.2. Computation of Reliability Metrics

- ❖ MTBF (Mean Time Between Failures): Mean time between two successive failures.
  - ➢ For each separator $\text{MTBF} = \dfrac{\text{Operating time} - \sum \text{Failure hours}}{\text{Total failure count}}$ (1)
- ❖ MTTR (Mean Time To Repair): mean repair time (hours).
- ❖ Operational availability: $D = \dfrac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$ (2)
- ❖ Failure rate: $\lambda = \dfrac{1}{\text{MTBF}}$ (3)

2.3. Reliability Curve (Kaplan-Meier)

The reliability function $R(t)$ was estimated using the Kaplan-Meier method [22], with right-censoring applied, since, as stated in the introduction, one of the three separators was undergoing corrective maintenance while the other two were still in perfect working order; their future failure times are therefore unknown. This corresponds to a multiple-failure scenario with renewal, as the separators fail and are subsequently repaired. Accordingly, we consider inter-failure times rather than absolute age. In this context, right-censoring applies to the last interval of each separator:

- S1 has its last interval censored (as it was under maintenance);
- S2 and S3 have their last intervals complete (since they failed before the end of the study).

The Kaplan-Meier estimator is the standard reference tool in reliability analysis and provides a more accurate estimate of the survival probability of the equipment or the system.

$$R(t)=\prod_{i:t_i\le t}\left(1-\frac{d_i}{n_i}\right) \quad (4)$$

where t_i are the observed failure times, d_i is the number of failures at time t_i, n_i is the number of subjects "at risk" just before t_i.

2.4. Algorithm and Software Used

We summarize the process for calculating reliability indicators and analyzing the results in the algorithm shown in Figure 1 below. A computation code was developed using Matlab version R2020a for data input, execution of algorithm commands, and curve plotting.

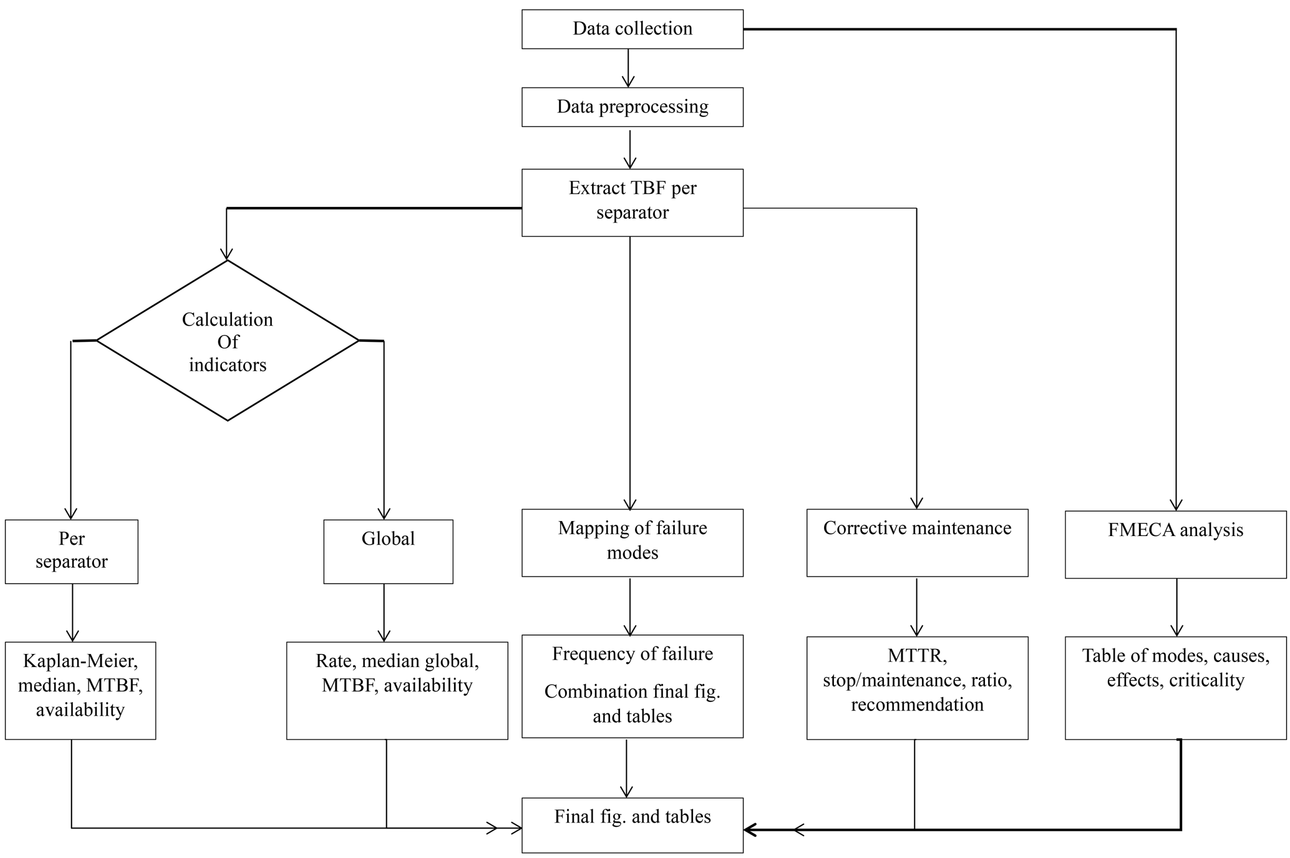

Figure 1. Calculation algorithm.

3. Experimental Setup

3.1. Equipment Studied

➢ **Power plant characteristics**

The thermal power plant is located in the industrial zone of the Kossodo district, north of the city of Ouagadougou. It consists of eight (08) generator sets, one

(01) of which has been out of service since the beginning of 2019. These generator sets comprise diesel engines and alternators mechanically coupled for the conversion of mechanical energy into electrical energy. Since 2021, the installed capacity has been approximately 112.7 MW, and its production covers 73.86% of the Ouagadougou Regional Consumption Center (CRCO). Table 1 summarizes the characteristics of the power plant's machinery.

Table 1. Characteristics of the generator sets and construction stages of the Kossodo power plant.

Stage	Group batch	Concerned group (s)	Brand	Power (MW)	Commissioning date
1	1	G1	MAN B & W	3.8	15 march 2000
2	2	G2 G3	DEUTZ	6.25	17 july 2000
3	1	G4	DEUTZ	6.25	20 may 2003
4	1	G5	DEUTZ	6.25	24 november 2004
5	2	G6 G7	WARTSILA	7	14 february 2006
6	1	G8	MAN B & W	18.9	14 november 2006
7	3	G9 G10 G11	MAN B & W	18.9	1er september 2021
Total		8 Groups	-	112.7	-

Ouaga East comprises the last three generator sets (G9, G10, and G11), whose separators are the subject of this study.

➢ **Centrifugal separator characteristics**

Three GEA centrifugal separators are studied in this work. They are arranged in parallel and are not operated simultaneously except during periods of high electricity production during hot weather (March to June). Figure 2 shows a view of the HFO unloading area (Figure 2(a)) and an image of one of the installation's separators (Figure 2(b)).

The separation process in a centrifugal separator relies on the density difference between heavy fuel oil and impurities (water, solid particles, etc.). The heavy fuel oil is introduced into the separator through the inlet piping. The mixture of fuel and impurities is directed toward the rotating bowl. This rotation generates a centrifugal force that projects the impurities toward the bowl walls. The fuel, being less dense, remains closer to the center of the bowl. The separated impurities are discharged via the sludge discharge system. This process ensures that only clean, impurity-free fuel is used in the engines or boilers.

(a) (b)

Figure 2. (a) External view of the unloading area at the Ouaga East thermal power plant; (b) HFO separator of the Ouaga East thermal power plant.

HFO: the properties are measured using an Anton Paar DMA 4200 M apparatus, which offers a precision of 0.0001 g/cm^3 and an operating temperature of up to 150˚C. The values of the constants measured by the operators are presented in Table 2.

Table 2. Physical Properties of the HFO (Sample 178_SPTN-0169F703/6294F703(1)_178).

Kinematic viscosity at 50˚C (mm^2/s)	Density (g/cm^3)	Dynamic viscosity (mPa.s)	Average water content (%)	Nominal flow rate (L/s)
163.11	0.94557	2669.9	1.2	70

3.2. Data Collection

- Commissioning date of the Ouaga East power plant: September 1, 2021.
- **Observation period**: September 8, 2021 to August 19, 2024.
- **Sources:** maintenance logs, logbooks, intervention reports, fault sheets.
- **Data collection:** The data extracted from the aforementioned sources form the monitoring dashboard used to track the operation of the separators. For each separator, an Excel spreadsheet logs the date and duration of each interruption, service hours, operating time, failed components (including both individual and simultaneous failures), failure type, corrective actions, as well as parts and labor costs. We subsequently propose a stepwise algorithm to process these data.

4. Results and Discussions

4.1. Analysis of Failure Causes

We applied the Ishikawa diagram to the data collected on the HFO separators during the observation period. This allowed us to determine the origin of the failures. Figure 3 summarizes the results obtained.

From the analysis of this diagram, it appears that equipment is the main source of failures, accounting for 33% of the causes. Method and labor each represent 20% of the causes, material 14%, and environment 13%. We will therefore primarily focus our failure mode, effects, and criticality analysis on the centrifugal separators themselves.

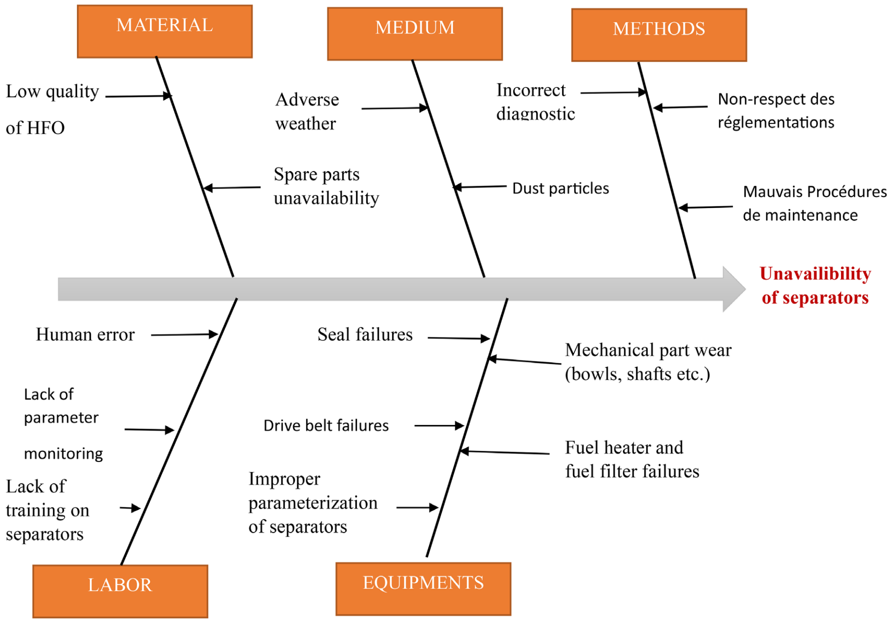

Figure 3. Ishikawa diagram of the HFO separators.

4.2. Failure Modes and Criticality (FMECA)

We now apply the FMECA to all three HFO centrifugal separators. The results are presented in Table 3 below.

Table 3. FMECA results for all three separators.

Component	Failure mode	G	O	D	C	%
Bearings	Vibration, overheating, seizing	6	5	5	**150**	**14.39**
Separation discs	Clogging, deformation	9	7	5	**315**	**30.23**
Seals	HFO leakage, water ingress	7	5	3	**105**	**10.08**
Vibration sensors	Drift, false alarm	5	4	4	**80**	**7.68**
Drive motor	Thermal relay tripping, winding short circuit, overheating	7	4	4	**112**	**10.75**
Sludge discharge system	Blockage, non-opening	8	7	5	**280**	**26.87**

4.3. Separator-Specific Reliability Indicators

Based on the elementary individual and simultaneous data gathered on the operating behavior of the three separators (S1, S2, and S3) over the observation period, and applying formulas (1) through (3), the resulting reliability indicator values are compiled in Table 4 below.

Availability values are identical, since they depend on the overall cumulative figures (i.e., the same proportion of downtime).

Table 4. Reliability indicator values by separator.

Séparators	Number of lifetimes	Observed failures	Censoring counts	Médian (h)	MTBF (h)	Availlability
S1	39	39	0	272.7	658.1	0.697
S2	11	10	1	1292.3	2222.0	0.697
S3	7	6	1	1811.5	3706.7	0.697

4.4. Mapping of Failure Modes

Based on the recorded data pertaining to simultaneous failures across the separators, the histogram of combinations illustrated in Figure 4 is established.

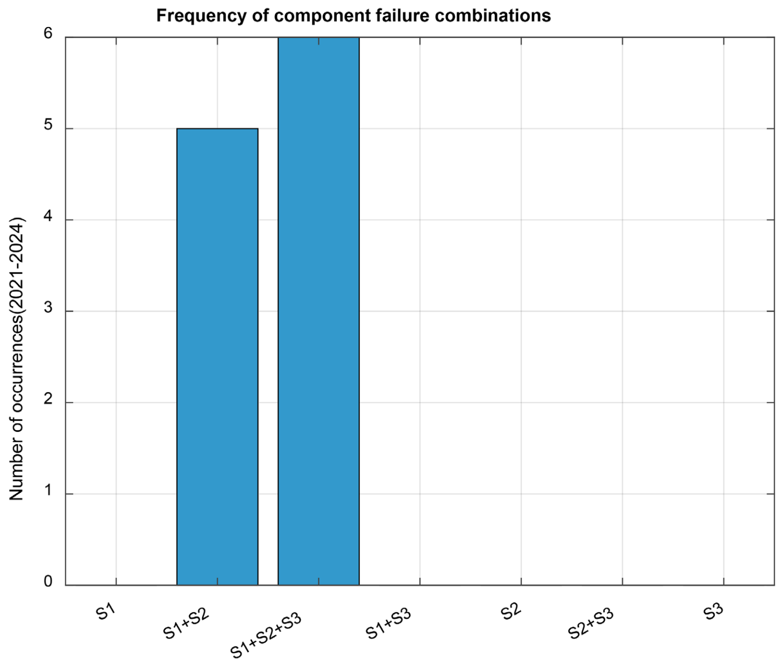

Figure 4. Combination histogram of the three HFO separators.

Concurrent failures of two separators (S1 + S2) or three separators (S1 + S2 + S3) are observed to be frequent (approximately 11 occurrences over a 4-year period). This points to underlying external factors:

- Ambient temperatures are extremely high from March to June. The collected data indicate a higher number of interventions during this period.
- HFO quality (viscosity, water content, impurities) can affect all separators operating in parallel.

The influence of these factors is indeed demonstrated in [14] and [15].

4.5. Overall Indicators

Table 5 shows the aggregated data derived from the collection over the observation period for the three HFO centrifugal separators at the Ouaga Est (Kossodo) power plant.

Table 5. Aggregated data across the three centrifugal separators (pooled).

Year	Service Hours (h)	TBF (h)	Unplanned downtime (h)	Maintenance (h)	Total failures
2021	774	627.8	103.4	42.3	14
2022	2322	1537.7	754.3	30.0	14
2023	2322	1727.8	552.9	41.4	18
2024	1548	851.9	650.0	46.1	9
Total	**6966**	**4745.2**	**2060.62**	**159.8**	**55**

The pooled global indicators for the three separators are thus:

- ✓ Overall failure rate: $\lambda = 0.01159$ failures/hours. This corresponds to one failure every 86 hours.
- ✓ Overall MTBF: $1/\lambda = 86.28$ hours. *i.e.*, 3.6 days.
- ✓ Overall availability (maintenance excluded): $D = 69.72\%$.
- ✓ Unplanned stoppage rate: $1 - D = 30.28\%$. Corresponding to 30.3% of the operating time spent in failure.
- ✓ Global median time to failure: 548.3 hours.

From these results, it emerges that the Ouaga Est (Kossodo) thermal power plant has low availability ($D \prec 70\%$), with unplanned downtime reaching a very high level (2060 hours out of 4745 operating hours). Corrective maintenance is the predominant maintenance strategy.

4.6. Reliability Analyses

Based on the actual individual and combined data from the separators, and by applying Equation (4) above, the Matlab computation yields the curves shown in Figure 5 and Figure 6. Figure 5 presents the estimated survival function for each of the three separators. The median survival time for separator S1 is 281 h; for S2 it is 1362 h; and for S3 it is 2400 h. The differences among S1, S2, and S3 can be explained by uneven usage during the observation period. S1 was used much more frequently, hence experienced more failures and a lower median. S3 was subjected to little demand, resulting in fewer failures. Figure 6 shows the estimated survival function for all three separators combined, with a 95% confidence interval. A rapid decrease in the reliability function is observed after 209.5 hours of continuous operation, with a probability of proper functioning of 0.6. This probability drops to 0.25 after 1460 hours, *i.e.*, 60 days of operation. At this point, a slope break appears, suggesting premature wear of bearings and seals. This result was predicted by the FMECA analysis performed earlier and is confirmed by the findings reported in [14] [23]-[25]. At 6000 hours, a decrease in the failure frequency is observed, marked by a horizontal plateau. The system enters a wear-out phase before 15,000 hours of operation. The overall median lifetime is 548.3 hours.

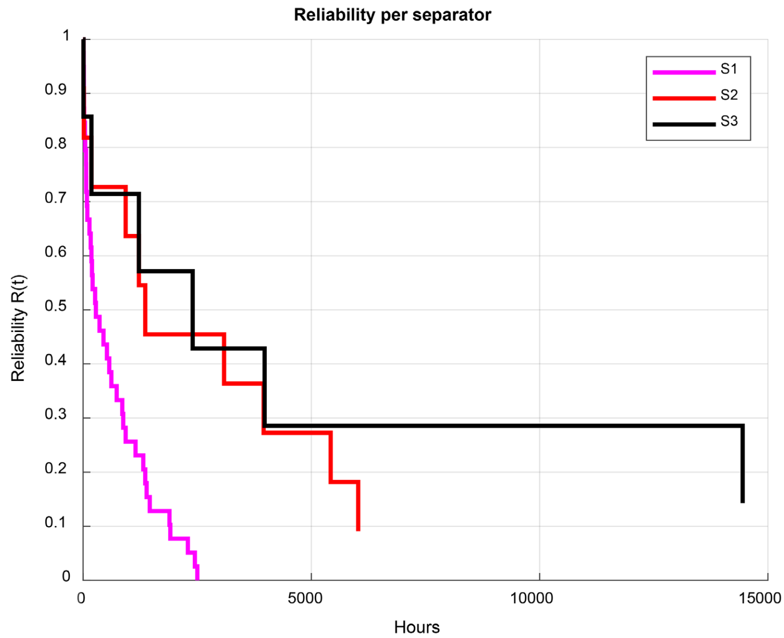

Figure 5. Survival curves by individual separator.

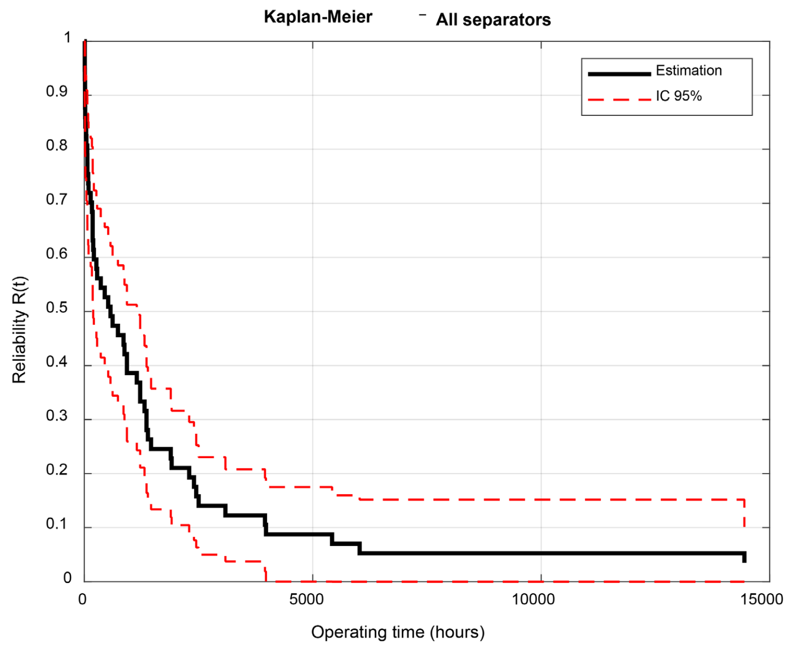

Figure 6. Global reliability curve with 95% confidence bounds.

4.7. Cost Analysis

The mean cost of a single corrective intervention is 700,000 CFA francs (approximately 1200 USD), including spare parts and labor. With a total of 55 failures recorded, the average cumulative repair cost over the observation period reaches 38,500,000 CFA francs (i.e., 64,200 USD). Considering the cost per ungenerated kWh, the production loss attributable to unscheduled downtime is estimated at 87,000 USD.

4.8. Discussions

The low MTBF (86.28 h) compared to standard values can be attributed to several external and context-specific factors related to the city of Ouagadougou:

- High ambient temperature: during hot periods (March to June) in Ouagadougou, peak temperatures sometimes reach 43˚C. Above 40˚C, the viscosity of HFO decreases, which alters the hydraulic load on the discs and accelerates bearing wear.
- Variable HFO quality: water content occasionally exceeding 1.2%, together with the presence of fine sand (not captured by coarse filters), accelerates clogging.
- Predominantly corrective maintenance: lack of continuous vibration and thermal monitoring. Indeed, the Mean Time To Repair (MTTR) is 37.47 h (1.56 days), with an unplanned downtime-to-maintenance ratio of 12.90.
- Non-certified spare parts: use of bearings of questionable origin and lower quality.

This study has several limitations, which relate to:

✓ Manual data recording: certain maintenance interventions were incompletely documented (under-reporting).

✓ Undifferentiated failure modes: no distinction was made between independent failures and induced failures (e.g., clogging can cause bearing overheating).

✓ Absence of on-site vibration data: no measurements of *in-situ* vibratory stresses were available.

In light of the results presented above, we propose the following recommendations for industrial operators:

➢ Enhance preventive maintenance through regular disc cleaning, HFO quality control, and vibration monitoring.

➢ Mitigate concurrent failures by implementing preheating or HFO conditioning (upstream separator, clarification centrifuge).

➢ Pay particular attention to high-temperature periods (March to June).

➢ Provide operator training for early fault detection (e.g., abnormal noise or temperature) and for minimizing setting errors.

➢ Employ only certified replacement parts (SKF, FAG).

➢ Monitor repair durations to identify process bottlenecks.

5. Conclusions

In this paper, we analyzed the failure modes and assessed the reliability of the three HFO centrifugal separators (S1, S2, S3) at the Ouaga Est thermal power plant in Kossodo. Based on field data collected from November 8, 2021, to August 19, 2024, the main findings are as follows:

❖ The major issue is the low availability of the three separators as a whole (D = 69.7%) combined with a very short MTBF (86.28 hours), resulting from frequent failures and lengthy repairs.

❖ Separator S1 is the most critical: its median lifetime is 281 hours, with 39 failures.

❖ The critical failure modes are wear/clogging, vibration, overheating, seizing, and simultaneous failures. These failures are mainly related to HFO quality and high ambient temperatures.

❖ Maintenance is almost exclusively corrective. Hence, there is a need to transition to condition-based maintenance.

For a more in-depth study enabling the implementation of an effective and efficient operational policy, the results of this work could be complemented by predictive modeling and maintenance optimization. This would, for example, improve the MTBF while reducing repair costs.

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CRediT Authorship Contribution Statement

Hassime Guengane: Writing—review & editing, Data curation, Conceptualization;

Abdoul Aziz Toure: Writing—original draft, Supervision, Data curation, Conceptualization;

Inoussa Tougri: Writing—review & editing, Investigation, Formal analysis;

Thierry Sikoudouin Maurice Ky: Software, Formal analysis;

Sié Kam: Supervision, Project administration;

Dieudonné Joseph Bathiébo: Validation, Supervision, Resources, Funding acquisition.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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