



Comparative Reliability, Maintainability and Availability Analysis of Industrial Gas Turbines Using ISO 3977-9

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ABSTRACT

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Reliability $R(t)$, Maintainability $M(t)$, and Availability $A(t)$ are widely recognized as key indicators for assessing and improving maintenance strategies in industrial systems, particularly in high-risk sectors such as the oil and gas industry. In these environments, maintenance activities play a central role not only in ensuring production continuity but for enhancing operational safety and limiting unplanned downtime. Consequently, dependability analysis (R.A.M) has become an essential support for informed maintenance decision-making.

This study illustrates a comparative evaluation of the reliability, maintainability, and availability performance of two industrial gas turbines using actual operational data collected between 2015 and 2021. The analysis is based on the calculation of RAM indicators and associated metrics, in accordance with the international standard ISO 3977-9. The use of this normative framework ensures consistency, transparency, and reproducibility of the results.

The findings highlight obvious differences in operational performance between the two turbo-compressors, reflecting the influence of operating conditions and maintenance practices. The study determines that ISO-based RAM assessment provides practical and robust indicators that can effectively support the maintenance decision-making.

1. INTRODUCTION

Dependability is built on the premise that all equipment is prone to failure. Consequently, it is essential to analyze both the mechanisms that cause these failures and the methods used to eliminate them [1, 2]. In an industrial setting, assessing dependability serves as a strategic tool to optimize maintenance and enhance operational performance by maintaining control over critical parameters.

Dependability is generally measured through three primary indicators: reliability, which tracks a system's ability to function without failing; availability, which estimates the probability that a system is operational at any time; and maintainability, which reflects how easily a system can be restored to its original state after a breakdown. These factors are vital for ensuring that operations remain continuous, safe, and cost-effective. Because maintenance runs alongside production, it

significantly impacts overall performance, influencing production capacity, product quality, and total costs. Indeed, research proposes that maintenance accounts for 15% to 40% of production costs, averaging around 28%, which highlights the necessity of a continuous improvement mindset [3].

Two key maintenance strategies are typically used: preventive maintenance (PM), based on schedules or sensor monitoring, and corrective maintenance (CM), performed after a failure [4]. These approaches complement each other and should be part of a policy suited to a company's technical and economic needs [6-7]. Specifically, PM aims to lower failure rates and improve system health [8]. Over time, several specialized PM strategies have developed. These include Time-Based Maintenance (TBM) [9-10], Condition-Based Maintenance (CBM) [11-13], Reliability-Centered Maintenance (RCM) [14-15], and Risk-Based Maintenance (RBM) [16-17].

This study focuses specifically on evaluating the dependability of industrial turbo-compressors within the oil and gas sector. These are critical assets where unplanned downtime can lead to production losses, safety hazards, and environmental damage. To evaluate the RAM (or dependability analysis) of such systems, two main pathways exist: probabilistic models, such as the Weibull distribution, and normative methods, such as the ISO 3977-9 standard. While the Weibull distribution can statistically predict failure times, it requires extensive historical data and complex parameter estimation. In contrast, ISO 3977-9 offers a straightforward, repeatable methodology based directly on operational data such as service hours, planned and unplanned outages, and failure counts. This makes it highly effective for maintenance planning and decision-making, especially in environments with fluctuating operating conditions.

By applying the ISO 3977-9 standard, one can directly calculate key metrics like reliability, MTBF (Mean Time Between Failures), MTTR (Mean Time To Repair), availability, MTBM (Mean Time Between Maintenance), and the service factor. These provide concrete, actionable data for comparing equipment performance.

It is worth noting that even technically identical equipment's can show different RAM performance due to variations in workloads, maintenance practices, and shutdown scheduling. Therefore, a comparative analysis based on ISO 3977-9 is required to identify performance gaps and refine maintenance strategies.

Accordingly, the objectives of this study are: (i) To compare the RAM indicators of two technically identical units using the ISO 3977-9 standard. (ii) To evaluate secondary performance metrics, including MTBF, MTTR, MTBM, and service factor. And (iii) To identify the operational factors that influence performance and propose strategies for maintenance optimization.

2. METHODOLOGY

This section describes in detail the comparative methodology implemented to evaluate and compare the performance of two technically identical industrial turbochargers in terms of reliability, maintainability, and availability, based on real operational failure and repair time data. The approach is aligned with the recommendations of the international standard ISO 3977-9 and structured to meet the requirements of risk management, operational safety, and loss prevention.

2.1 General framework and justification

In the hydrocarbon industry, gas turbines are critical components of installations: their unexpected downtime can compromise entire processes and generate major incidents in terms of safety, the environment, and production. A rigorous comparative evaluation of reliability (R), maintainability (M), and availability (A) parameters not only quantifies equipment performance but also identifies areas for improvement to enhance process safety and prevent losses.

The approach follows the normative framework of ISO 3977-9, which provides standardized definitions and appropriate formulas for calculating Dependability

parameters in the context of gas turbines and their subsystems (including compressors), thus facilitating comparability and reproducibility of results.

2.2 Operational data and definitions of indicators

For each of the turbochargers (U380KT and U390KT), the following quantities are extracted from the operational database: (PH): Period Hours, (SH): Service Hours, (FOH): Forced Outage Hours, (POH): Planned Outage Hours, (F): total number of forced stops; (P): total number of planned stops.

These quantities form the basis for quantifying RAM performance according to ISO 3977-9 [18].

2.3 Reliability Indicators

2.3.1 Operational reliability

Reliability $R(t)$ is defined as the probability that an equipment is not in forced shutdown at a given time. According to ISO 3977-9:

$$R(\%) = \frac{PH - FOH}{PH} \times 100 \quad (1)$$

This calculation directly expresses the fraction of time the equipment operates without unplanned interruption.

2.3.2 Mean Time Between Failures (MTBF)

MTBF is a standard reliability indicator that measures the average operating time between two consecutive failures:

$$MTBF = \frac{SH}{F} \quad (2)$$

A high MTBF is often associated with a reduction in the risk of unexpected shutdowns and improved operational safety.

2.4 Maintainability Indicators

2.4.1 Mean Time to Repair (MTTR)

Maintainability $M(t)$ is assessed through MTTR, representing the average time required to return the equipment to service after a forced shutdown:

$$MTTR = \frac{FOH}{F} \quad (3)$$

A low MTTR is associated with an ability to quickly restore operation, thus limiting the windows of vulnerability of industrial processes.

2.4.2 Maintainability function

Assuming an exponential law for repair times, the maintainability function is:

$$M(t) = 1 - e^{-\frac{t}{MTTR}} \quad (4)$$

A low MTTR is associated with an ability to quickly restore operation, thus limiting the openings of vulnerability of industrial processes.

2.5 Availability indicators

2.5.1 Operational availability

Availability expresses the probability that the unit will be operational (neither forced nor planned shutdown):

$$A(\%) = \frac{PH - (FOH + POH)}{PH} \times 100 \quad (5)$$

This indicator provides a synthetic measure of the overall performance of equipment in a real operational context.

2.5.2 Mean Time Between Maintenance Operations (MTBM)

MTBM expresses the average period between two maintenance operations, whether planned or not:

$$MTBM = \frac{SH}{F + P} \quad (6)$$

2.5.3 Service Factor (SF)

The service factor describes the intensity of equipment use during the analyzed period:

$$SF(\%) = \frac{SH}{PH} \times 100 \quad (7)$$

2.6 Comparative Approach

The originality of this study lies in the systematic comparison of dependability performance between two identical gas turbines (U380KT) and (U390KT), although they are technically similar but operated in potentially different contexts. The comparative approach unfolds in three stages:

(1) Calculation of RAM indicators (R, MTBF, MTTR, A, MTBM, SF) for each turbocharger independently, according to equations (1) to (7).

(2) Comparative quantitative analysis of indicators to identify performance gaps between (U380KT) and (U390KT).

(3) Interpretation of observed discrepancies in relation to operational factors (loads, operating profiles, maintenance practices), which allows for the highlighting of practical recommendations for loss prevention and process safety improvement.

This comparative analysis provides significant scientific and industrial value, by identifying not only performance differences, but potential causes based on actual operating and maintenance practices.

3. Results and Discussion

3.1 Case study

The BRN field is an oil deposit jointly operated by an Algerian -Italian joint venture (Sonatrach/ENI). Production began in 1995, initially reaching no more than 40,000 barrels per day. Subsequently, other fields and

satellite fields were discovered, coming into production between 2000 and 2005. This expansion led to the extension of the oil production center (CTH) through the addition of a second and third production train. This initiative resulted in an increase in production to 120,000 barrels per day. The installation of the associated gas reinjection unit (U-370) within the oil production center (CTH) aims to optimize oil production at the wellhead. This unit consists of two identical, redundant compression subsystems, namely U380KT and U390KT (see **Figure 1**). The U380 and U390 gas turbines in this unit are MS 5002C models. They are used to drive BCL-type multistage centrifugal

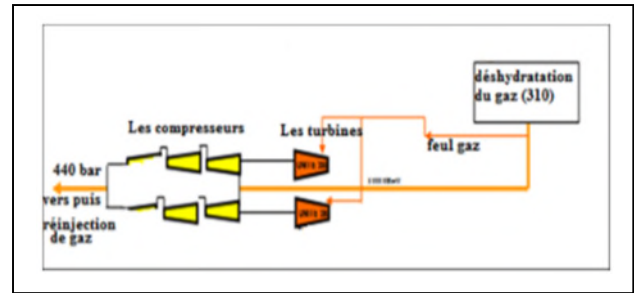


Figure 1 Turbine and compressor configuration at CTH

3.2 Data treatment

Historical data from the system under review of gas turbines (U380KT and U390KT), provided by the company for the period from 2015 to 2021, were compiled for each month and year. This data was organized into tables containing the calculation variables specified by the formulas outlined in the methodology section for the U380KT and U390KT turbines. **Table 1** containing the data collected for 2015 are provided as an illustration.

Table 1. Data collected for the U380KT gas turbines (year 2015)

U380KT								
	Period Hrs	Operating Hrs.	Serv. Factor	Fiabilité	Disponibilité	MTBF	MTTR	MTBM
	hrs (PH)	hrs (SH)	% (SF)	% (R)	%(A)	Hrs	hrs	hrs
20	744	741	99,6	99	99	148,2	2,1	148,2
15	672	664	98,81	100	99	N/A	N/A	664
1	744	742	99,73	100	100	247,33	0,75	247,33
3	720	714,5	99,24	100	100	357,25	1,37	357,25
4	744	740	99,46	99	99	246,66	1,33	246,66
5	720	682,1	94,74	99	98	170,52	1,20	97,44
6	744	721,4	96,96	100	100	721,4	0	360,7
7	744	744	100	100	100	N/A	N/A	N/A
8	720	719,90	99,99	100	100	N/A	N/A	N/A
9	744	740,40	99,52	100	100	370,2	1,75	370,2
10	720	392,7	54,54	100	58	32,725	0,29	24,54
11	744	743,0	99,87	100	100	743	0,5	743
12								

The data from the years 2015 to 2021 presented in **Tables 1** (presented as example of operational data used in this study), processed by the formulas mentioned in Section II, allowed us to obtain the results mentioned in **Table 2** and **Table 3**.

Table 2. Results of U390KT data processing

U380KT	PH	SH	FOH	POH	F	P
2015	8760	4152	175	210	2	3
2016	8760	5790	310	175	5	2
2017	8760	3778	205	260	3	4
2018	8760	6585,9	295	210	5	3
2019	8760	6701	170	180	2	2
2020	8760	6789	263	260	4	4
2021	8760	8345	195	115	3	1

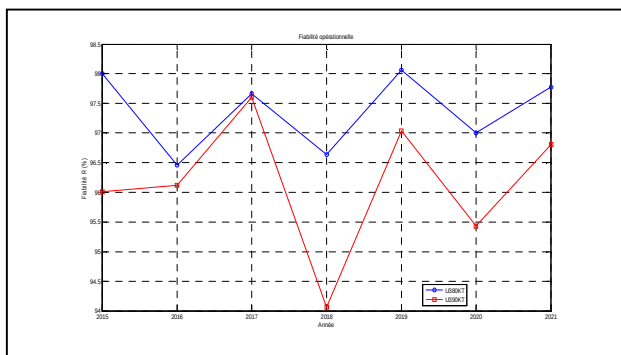
Table 3: Results of U390KT data processing

U390KT	PH	SH	FOH	POH	F	P
2015	8760	4778	350	260	2	4
2016	8760	2482	340	115	4	1
2017	8760	4914,5	210	175	3	2
2018	8760	2016	520	210	6	3
2019	8760	1283,9	260	110	3	1
2020	8760	6071,6	400	175	2	2
2021	8760	6981,1	280	260	3	4

3.3 Representations of the dependability parameters of the two studied configuration branches

The Dependability parameters of the two configurations studied are presented in the form of curves in order to better understand their evolution during the observed period (2015-2021) (see **Figures 2, 3 and 4**).

3.3.1 Reliability

**Figure 2** Reliability behavior of the two configuration branches (U380KT and U390KT)

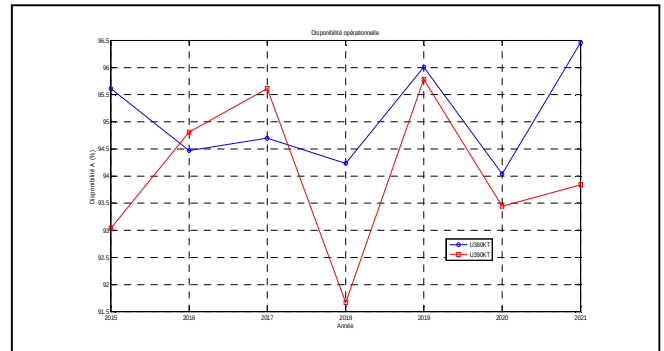
Reliability $R(t)$, calculated according to ISO 3977-9 as the percentage of time without forced downtime, shows the following trends:

- (1) U380KT: Reliability remains generally stable between 95% and 99% depending on the year, with a slight dip in 2017 where the duration of forced stops was greater.
- (2) U390KT: Reliability is more variable, with values fluctuating between approximately 85% and 97%. The

years 2016 and 2018 show lower reliability due to more frequent or longer failures.

The U380KT appears more reliable and consistent, while the U390KT is more prone to failures. This suggests that even technically identical machines can exhibit different dependability behaviors depending on operating conditions and maintenance practices.

3.3.2 Availability

**Figure 3** Availability behavior of both configuration branches (U380KT and U390KT)

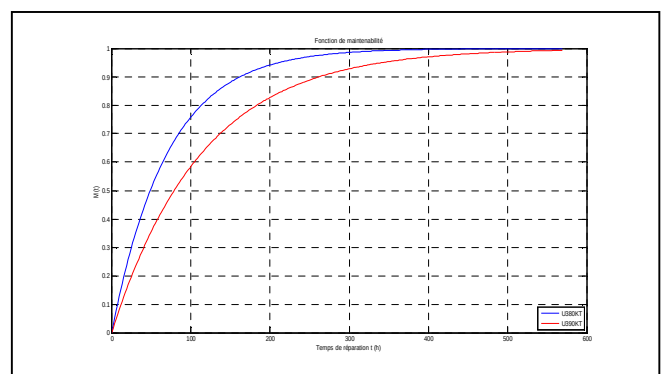
Availability combines forced and planned shutdowns:

- (3) U380KT: Availability remains high ($\approx 88-95\%$), close to reliability since planned shutdowns are moderate.

- (4) U390KT: Availability is more fluctuating, sometimes well below 90%, particularly in 2016 and 2018 where cumulative FOH and POH are significant.

The discrepancies between availability and reliability reflect the impact of planned downtime. Even if a machine is operating without failure, planned maintenance can reduce its actual availability. This underscores the importance of optimizing maintenance planning to minimize operational losses.

3.3.3 Maintainability

**Figure 4** Maintainability behavior of the two configuration branches (U380KT and U390KT)

The maintainability function, here based on the average MTTR:

- (4) U380KT: The maintainability function grows rapidly over time, indicating that repairs are generally quick and the machine returns to its operational state in a short time.

(5) U390KT: The progression of $M(t)$ is slower, reflecting longer and less regular average repair times.

The U380KT is easier to maintain and repairs are more predictable, contributing to better overall availability. The U390KT has longer or more irregular repair times, which may explain the observed variations in availability and reliability.

3.3.4 Others indicator's

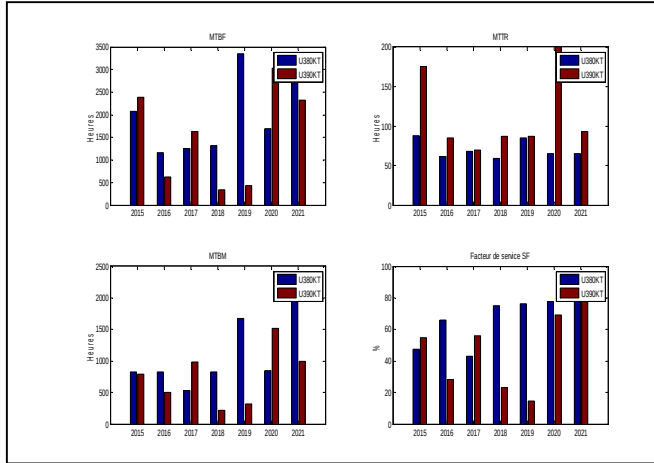


Figure 5 MTBF, MTTR, MTBM, and SF of the two configuration branches (U380KT and U390KT)

The **Table 4** shows the interpretation of the obtained results from the analysis results presented in the Figure 5.

Table 4: Interpretation of obtained MTBF, MTTR, MTBM, and SF of the two configuration branches (U380KT and U390KT)

	U380KT	U390KT	Interpretation
MTBF	Higher and relatively stable MTBF (≈ 830 – 2890 h), which confirms a lower failure frequency.	MTBF lower and highly variable (≈ 500 – 2390 h), reflecting more frequent failures or failures concentrated in certain years.	A high MTBF for U380KT indicates fewer unplanned downtimes and better service continuity. Significant variations in MTBF for U390KT indicate a more demanding operating environment or conditions for this machine.
MTTR	Moderate average MTTR (≈ 35 – 70 h), with few peaks,	MTTR is more variable, sometimes reaching high values	The U380KT offers superior maintainability, minimizing production downtime. The

	which promotes a rapid return to service.	(e.g., 260 h), indicating that some repairs are long or complex.	U390KT sometimes requires lengthy interventions, reducing its availability and potentially impacting production.
MTBM	Stable MTBM, indicating good planning and appropriate maintenance frequency.	MTBM is more variable, reflecting more irregular corrective or planned maintenance.	The regularity of MTBM for U380KT reflects a consistent maintenance policy, while the variations for U390KT suggest less optimized practices or different operational constraints.
Service factor	High and stable SF (≈ 48 – 95%), which shows regular and intensive use.	SF more variable (≈ 15 – 95%), reflecting more frequent interruptions and less continuous use.	U380KT benefits from more optimal and continuous use, while U390KT experiences prolonged periods of downtime which reduce operational efficiency.

The results obtained (see **Figures 2, 3, 4, and 5**) highlight discrepancies in the three dependability parameters, even though both turbochargers are of the same brand and operated and maintained under identical conditions. Consequently, it is strongly recommended to adjust maintenance planning based on these operational results rather than systematically following the manufacturer's maintenance program. This approach purposes to reduce downtime, improve performance, and minimize the costs associated with corrective maintenance. Indeed, adherence to the systematic maintenance program currently followed by the company's maintenance department has led to a series of downtimes followed by corrective maintenance interventions.

4. CONCLUSIONS

This study analyzes and compares the dependability performance of two industrial gas turbines, units U380KT and U390KT, based on real-world operational data straddling the period 2015–2021. The evaluation follows the indicators established by the international standard

ISO 3977-9 supplemented by standard metrics such as MTBF, MTTR, MTBM, and service factor. This framework provided a clear and consistent long-term view of the operational behavior of each unit.

The findings highlight that the U380KT gas turbines generally exhibits more stable and robust performance. This unit is characterized by higher reliability and availability levels, alongside more controlled repair times. Such results suggest a more effective management of forced outages and a better capacity for restoring equipment to service following a failure. In contrast, the U390KT unit appears more vulnerable to unplanned interruptions and experiences longer repair durations, which directly impacts its overall operational availability.

Nevertheless, it is important to note that while differences exist between the two gas turbines, their individual performances remain within the operational requirements of the oil and gas industry. This observation validates the use of redundant architectures in critical installations, as they mitigate the impact of failures and ensure operational continuity within demanding industrial contexts.

One of the key findings of this study lies in the effectiveness of the normative approach adopted. The use of ISO 3977-9 makes it possible to generate reliable, consistent, and easily comparable indicators directly from field data. Its ease of implementation and its suitability to real-world situations make it a particularly well-suited tool for maintenance decision-making, especially in environments with variable operating conditions where availability is critical.

Finally, these results provide a solid foundation for refining the maintenance strategy of the systems studied. They offer concrete evidence to guide intervention planning, specifically toward condition-based or opportunistic maintenance strategies that target the equipment most detrimental to availability. Future work could build upon these findings by integrating probabilistic models, thereby enhancing predictive analysis while maintaining the rigor and traceability provided by the ISO 3977-9 framework.

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disponibilité, maintenance et sécurité.

NOMENCLATURE

PH	Period Hours,
SH	Service Hours,
FOH	Forced Outage Hours,
POH	Planned Outage Hours,
F	total number of forced stops;
P	total number of planned stops.
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MTBM	Mean Time Between Maintenance
R(t)	Reliability
M(t)	Maintainability
A(t)	Availability
PM	Preventive maintenance
CM	Corrective maintenance
TBM	Time-Based Maintenance
CBM	Condition-Based Maintenance
RCM	Reliability-Centered Maintenance
RBM	Risk-Based Maintenance