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# Optimization of Preventive Maintenance of a Motor-Pump Unit Based on FMEA Coupled With Reliability Models: Application at the REGIDESO N'Djili plant (DRC)

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***Abstract***— *The continuity of potable water production and distribution services is a major challenge for water utility companies. At the REGIDESO N'Djili water treatment plant in the Democratic Republic of Congo, motor-pump units are critical assets whose failures can lead to service interruptions, increased maintenance costs, and reduced operational availability. This study proposes an optimization approach for preventive maintenance based on the integration of Failure Modes, Effects and Criticality Analysis (FMECA) and reliability models. The methodology consists of identifying critical components of the motor-pump unit, analyzing failure modes and their effects, evaluating criticality levels, and estimating reliability parameters using statistical reliability models, particularly the Weibull distribution. The approach enables the determination of optimal maintenance intervals based on the actual degradation behavior of equipment components. The results indicate that bearings, mechanical seals, lubrication systems, and electric motors are the most critical elements of the motor-pump unit. Reliability analysis reveals that most failures are associated with equipment aging and wear-out mechanisms. By coupling FMECA with reliability modeling, an optimized preventive maintenance plan was developed, leading to a reduction in unexpected breakdowns, an increase in Mean Time Between Failures (MTBF), improved equipment availability, and lower maintenance costs. The study demonstrates that the integration of FMECA and reliability analysis provides an effective decision-support tool for maintenance management in water production facilities. This approach contributes to enhancing operational performance, improving service continuity, and optimizing maintenance resources. Future work may focus on the integration of condition-based monitoring systems and artificial intelligence techniques for predictive maintenance of critical pumping equipment.*

***Keywords***— *Preventive Maintenance, FMECA, Reliability Analysis, Weibull Distribution, Motor-Pump Unit, MTBF, Availability, Water Production System, REGIDESO N'Djili.*

## I. Introduction

In drinking water production and distribution companies, the availability of pumping equipment directly impacts the continuity of service provided to consumers. In the Democratic Republic of Congo, REGIDESO operates several water intake, treatment, and distribution stations whose performance largely depends on the proper functioning of their pump units.

However, industrial equipment is subject to wear, aging, and various mechanical stresses that promote the occurrence of failures. The resulting unplanned downtime affects productivity, increases maintenance costs, and compromises service quality. Faced with these challenges, industrial companies are increasingly turning to reliability-based maintenance strategies to anticipate failures and optimize interventions.

Among the most widely used decision-support tools are Failure Mode, Effects, and Criticality Analysis (FMECA) and probabilistic reliability models. FMECA helps identify critical components, while reliability models estimate their behavior over time. Combining these two approaches provides an effective framework for optimizing preventive maintenance.

The objective of this study is to develop an integrated FMEA-Reliability approach applied to a motor pump group at the REGIDESO N'Djili plant in order to improve its operational availability and reduce costs related to failures.

## II. Materials and methods

### *2.1 Presentation of the system studied*

The motor-pump unit under study consists primarily of:

a) of an electric motor;
b) of a mating;
c) of a drive shaft;
d) of a centrifugal pump;
e) bearings;
f) of a lubrication system;
g) of a mechanical seal.

This system ensures the transfer of water from the intake structures to the treatment and distribution facilities.

### *2.2 FMEA Method*

The FMEA was applied according to the following steps:

a) Functional breakdown of the motor-pump unit;
b) identification of failure modes;



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c) analysis of causes and effects;
d) severity assessment (G);
e) evaluation of occurrence (O);
f) detectability assessment (D);
g) calculation of the criticality index.

The criticality index is determined by:

[C = G \times O \times D] (2.1)

Components with the highest criticality values are considered a priority in the maintenance program.

*3. Mechanical Reliability*

*3.1. Introduction*

In what follows, we will present some distribution laws that come into play in the analysis of product life data used in a reliability study.

We will mention the main properties of these laws (density, reliability function and failure rate).

*3.1.1. Objectives and benefits of mechanical reliability*

Reliability analysis is an essential phase in any dependability study.

Originally, reliability concerned high-tech systems (nuclear power plants, aerospace). Today, reliability has become a key parameter for quality and decision-making in the study of most "consumer" components, products, and processes: transportation, energy, buildings, electronic components, mechanical components, etc.

Many manufacturers are working to evaluate and improve the reliability of their products throughout their development cycle, from design to commissioning (design, manufacturing and operation) in order to develop their knowledge of the Cost/Reliability ratio and control the sources of failure.

Reliability analysis in the field of mechanics is a very important tool for characterizing product behavior in different life phases, measuring the impact of design changes on product integrity, qualifying a new product and improving its performance throughout its mission.

In mechanics, reliability analysis provides answers to several questions:

a) What components cause the mechanical system to fail?
b) What are the influences of uncertainties on the data, particularly on product performance?
c) What level of quality control must be met?
d) What parameters are involved in the dimensioning of the structure for a given precision?
e) How to optimize the use of equipment? etc.

*3.1.2. Key characteristics of reliability*

This paragraph is a collection of key probabilistic elements used to measure reliability.

*1° Reliability function or survival function*

The reliability of a device after a time t corresponds to the probability that this device will not fail between 0 and time t. Denoting by T the random variable characterizing the time of failure of the device, reliability is expressed by the function R(t) – from the English "Reliability" – such that: R(t) = Probability (that an entity E is not faulty over the duration [0; t], assuming that it is not faulty at time t = 0)

$$R(t) = P(T \geq t) = 1 - F(t) \qquad (3.1)$$

*F(t)* is the distribution function of the variable T.

Note that the variable "time" must be considered as a unit of use. Indeed, in the case of certain specific devices, it will be necessary to consider: a distance traveled (kilometers), number of revolutions, number of activations, etc.

The reliability function generally has the following form (figure 3.1):

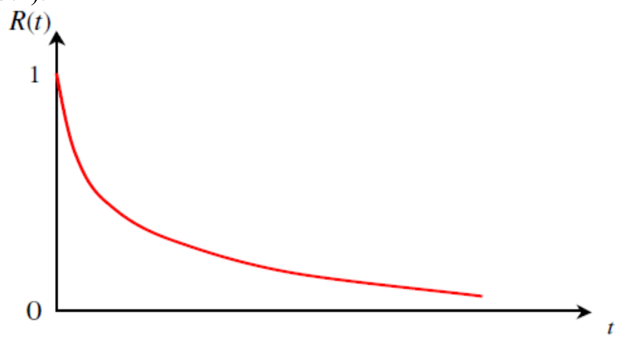


Figure 3.1: Reliability function

The opposite characteristic of reliability is called unreliability or probability of system failure. It is the complement of reliability to 1.

In the specific case where the study concerns equipment that operates under stress (starter, airbag, switch, ammunition), the reliability measurement is considered equivalent to the probability that the equipment will function when stressed. In practice, the probability of failure under stress, denoted p = 1 - R, is more commonly measured.

An estimate of this probability for a test of N materials is defined by the ratio of the number of failures to the stress and the total number of stresses.

$$p = \frac{k}{N} \qquad (3.2)$$

With ;

*N*: number of items tested;

*k*: number of devices that did not function when requested;

*p*: probability of failure under stress.

Failure to change state when requested: on-off, open-close, ignition, etc.

A reliability estimator is given by:

$$\check{R} = 1 - p = 1 - \frac{k}{N} \qquad (3.3)$$

*3.1.3. Instantaneous failure rate*

The mathematical expression for the failure rate at time t, denoted λ(t), is as follows:

$$\lambda(t) = \lim_{\Delta t \to 0} \left( \frac{1}{\Delta t} . \frac{R_{(t)} - R_{(t+\Delta t)}}{R_{(t)}} \right) \qquad (3.4)$$

Physically, the term λ(t)Δt measures the probability that a device failure will occur in the time interval [t, t+Δt] given that the device has functioned correctly up to time t.

The failure rate of a device at time t is therefore defined by:

$$\lambda(t) = -\frac{dR_{(t)}}{dt} . \frac{1}{R_{(t)}} = \frac{dF_{(t)}}{dt} . \frac{1}{R_{(t)}} = \frac{f_{(t)}}{R_{(t)}} \qquad (3.5)$$

This knowledge is sufficient to determine reliability, using the following formula:



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$$R_{(t)} = exp\left\{-\int_0^t \lambda_{(t)}.dt\right\} \quad (3.6)$$

*3.1.4. Average operating time*

The mean time to failure (MTTF) corresponds to the expected lifespan T, it is denoted MTTF (Mean Time To Failure):

$$MTTF = E[T] = \int_0^{-\infty} t.f_{(t)}\,dt \quad (3.7)$$

By definition, MTTF is the average lifespan of the system.

### *3.2. Main Probability Laws Used in Reliability*

In this section, we will present some life distributions that most frequently appear in the analysis of life data and that are common to several disciplines. We will discuss continuous distributions in particular.

We will state the main properties of these laws (probability density, reliability functions and failure rate) as well as their application in reliability engineering. There are also other reliability laws specific to a particular domain; we will discuss the Birnbaum-Saunders law, which characterizes failures due to fatigue crack propagation.

*3.2.1. The exponential law*

This law has numerous applications in several fields. It is a simple law, widely used in reliability engineering, where the failure rate is constant. It describes the lifespan of equipment that experiences sudden failures.

The probability density function of an exponential distribution with parameter λ is written as:

$$f_{(t)} = \lambda\,.\,e^{-\lambda t} \quad (3.8)$$

The reliability function:

$$R_{(t)} = e^{-\lambda t} \quad (3.9)$$

The failure rate is constant over time:

$$\lambda(t) = \lambda \quad (3.10)$$

*1° Memoryless properties of the exponential law*

A key property of the exponential law is that it is memoryless.

"property" in English:

$$P(T\ t{+}\Delta t/T\ t) = \geq\geq \frac{e^{-\lambda(t+\Delta t)t}}{e^{-\lambda t}} e^{-\lambda.\Delta t} = = P(T \geq \Delta t)\ or\ t>0,\ \Delta t>0$$
3.11)

As shown in Figure (3.2), this result shows that the conditional law of the lifetime of a device that has operated without failing up to time t is identical to the law of the lifetime of a new device.

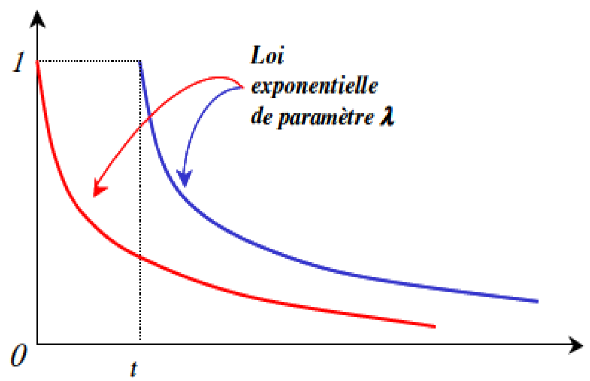

Figure 3.2: Memoryless property of the exponential law

This means that at time t, the device is considered as new (or "as good as new" in English), with an exponential lifespan of parameter λ.

*2° Scope of application of the exponential law.*

The bathtub curve, representing the lifespan of a system, reveals a more or less long period of maturity during which the system's failure rate remains relatively constant. This is the scope of the exponential law, which is based on the assumption (λ = constant), therefore (MTBF =). Electronic equipment lends itself well to the application of the exponential law when the components are known. $\frac{1}{\lambda}$

*3.2.2. The normal (Laplace-Gauss) distribution*

The normal distribution is very common among probability distributions because it applies to many phenomena. In reliability engineering, the normal distribution is used to represent the distribution of lifespans of devices nearing the end of their life (wear) because the failure rate is always increasing. It is only used if the mean lifespan is greater than three times the standard deviation. This is because the t-value is always positive, while the normal variable is defined from -∞ to +∞; the imposed restriction reduces the theoretical probability of finding a negative lifespan to approximately 0.1%.

The probability density function of a normal distribution with mean μ and standard deviation σ is written:

$$f_{(t)} = \frac{1}{\delta\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\delta}\right)^2} \quad (3.12)$$

The distribution function is written as:

$$F_{(t)} = \frac{1}{\delta\sqrt{2\pi}} \int_{-\infty}^{t} e^{-\frac{(x-\mu)}{2\delta^2}} dx \quad (3.13)$$

The reliability provided by:

$$R_{(t)} = 1 - \Phi(1-\mu)/\sigma \quad (3.14)$$

Where Φ is the cumulative distribution function of the standard normal distribution (σ=1):

$$\Phi_{(t)} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t} e^{\frac{-u^2}{2}} du \quad (3.15)$$

*3.2.3. The Log-normal (or Galton) law*

A continuous and positive random variable T is distributed according to a log-normal distribution if its natural logarithm is normally distributed. This distribution is widely used to model real-world data, particularly fatigue failures in mechanics.

The probability density function of a log-normal distribution with positive parameters μ and σ is:

$$f_{(t)} = \frac{1}{\sigma.\sqrt{2\pi}} e^{-1/2\left(\frac{t-\mu}{\sigma}\right)^2}, t > 0 \quad (3.16)$$

The reliability function:

$$R_{(t)} = \frac{1}{\sigma.\sqrt{2\pi}} \int_0^t e^{-1/2\left(\frac{t-\mu}{\sigma}\right)^2}.dt \quad (3.17)$$

The distribution function:

$$F_{(t)} = \frac{1}{\sigma.\sqrt{2\pi}} \int_0^t e^{-1/2\left(\frac{t-\mu}{\sigma}\right)^2}.dt \quad (3.18)$$

Since the domain of definition is never negative, there is no limitation to the use of the log-normal distribution in reliability.

The failure rate is increasing in the early stages of life and then decreasing, tending towards zero, and the distribution is very asymmetrical.

*3.2.4. Weibull's Law*


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This is the most popular law, used in several fields (electronics, mechanics, etc.). It allows, in particular, the modeling of many situations involving equipment wear.

It characterizes the system's behavior in the three phases of its life: early life, useful life, and wear or aging. In its most general form, the Weibull distribution depends on the following three parameters: β, η, and γ. The probability density function of a Weibull distribution is expressed as:

$$f_{(t)} = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}, \quad t \geq \gamma \qquad (3.19)$$

Or :

- $\beta$: is the shape parameter (β >0)
- η: is the scaling parameter (η > 0)
- γ: is the position parameter (γ ≥ 0)

The reliability function is written as:

$$R_{(t)} = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \qquad (3.20)$$

The failure rate is given by:

$$\lambda_{(t)} = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \qquad (3.21)$$

Depending on the values of β, the failure rate is either decreasing (β < 1), constant (β = 1), or increasing (β > 1). The Weibull distribution thus allows us to represent the three life cycles of a device described by the bathtub curve (Figure 3.3).

The case γ > 0 corresponds to devices whose probability of failure is zero up to a certain age γ

- *Area of use:*

The three-parameter Weibull distribution is very flexible, allowing it to be adapted to a large number of samples taken throughout the lifetime of a piece of equipment. It covers the case of variable failure rates, whether decreasing (early years) or increasing (old years). This distribution is widely used in reliability engineering, particularly in the mechanical field. Its application provides:

- An estimate of the "MTBF" of the population.
- The equations of R(t) and λ(t), as well as their variations in graphical form.
- The shape parameter β which can guide a diagnosis, its value being characteristic of certain failure modes.

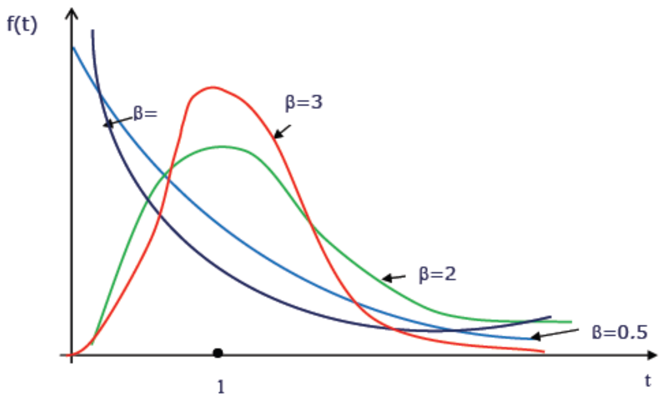


Figure 3.3: Influence of the shape factor β on the probability density curve

*1° Distribution function (γ=0, η=1)*

These graphs show the polymorphism of the "Weibull" law under the influence of the shape parameter (β))[33].

*2° Representative curves of R(t), λ(t) (γ=0, η=1)*

The reliability R(t) for a Weibull distribution is represented by different curves depending on the value of the form factor β. (Figures 3.4 and 3.5)

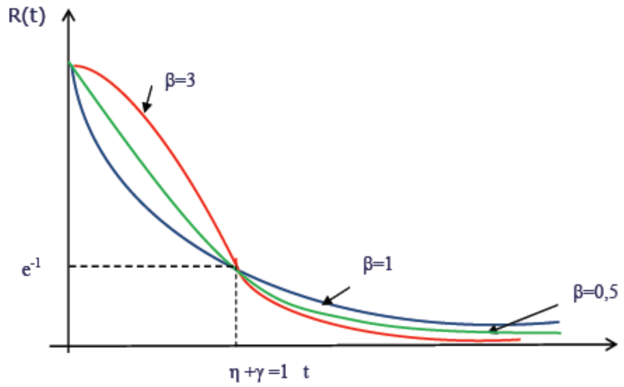


Figure 3.4. Influence of the form factor β on the reliability curve

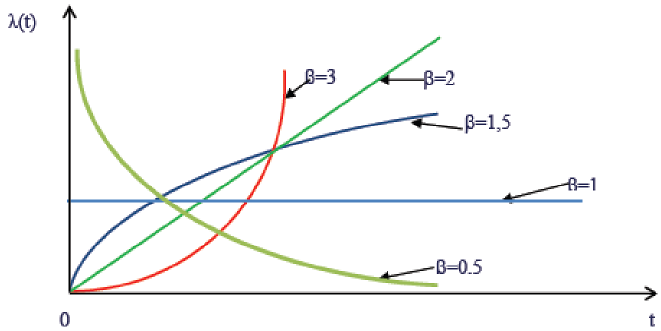


Figure 3.5. Influence of the shape factor β on the failure rate curve

*3° Meaning of the "Weibull" reliability parameters*

- β: called shape parameter (β>0), often it is equal to, less than or greater than 1. The "Weibull" law corresponds to an instantaneous failure rate, constant, decreasing or increasing.
- η: is called the scale parameter (η>0) sometimes named "life characteristic" it is a simple time parameter.
- γ: is called position parameter (-∞<γ<+∞) it defines a change of origin in the time scale.

For example (γ > 0); there is total survival (no failure between 0 and γ). (Figure 3.6)

*4. Study of the failure rate:*

a) If 0 < β < 1, the failure rate is decreasing. To improve reliability, pre-aging (run-in) is carried out.

b) If β = 1, λ(t)=1/ η, this is the case of the exponential law of MTBF = η.

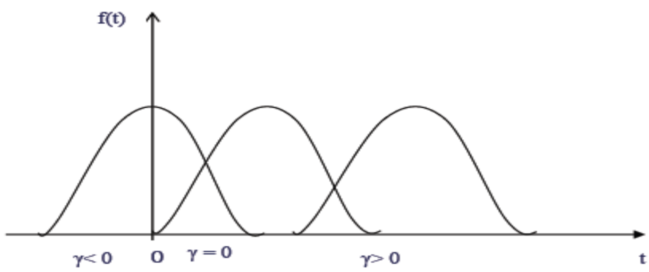


Figure 3.6. Density curve as a function of the position parameter (γ)



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c) If β > 1, the failure rate is increasing. To improve reliability, design improvements are made or a more rigorous preventive maintenance policy is implemented.
d) If 1 < β < 2, the failure rate is high at the beginning and low afterwards.
e) If β > 2 the failure rate increases slightly at the start but more strongly at the end.
f) If β = 2 the failure rate is linear.

## III. Optimizing Preventive Maintenance Through FMEA And Reliability Models

### *4.1 Introduction*

The analyses conducted in the previous chapter highlighted several recurring failures affecting the pump unit at the REGIDESO N'Djili plant. These failures lead to unplanned shutdowns, reduced equipment availability, and increased maintenance costs. To improve system performance, a structured approach is needed to anticipate failures and define appropriate preventive actions.

According to Moubray (1997), modern maintenance should be geared towards controlling the risk of failure by identifying critical equipment and analyzing its behavior over time. From this perspective, this chapter proposes an approach combining Failure Mode, Effects, and Criticality Analysis (FMECA) and reliability models to optimize the preventive maintenance program for the pump unit.

### *4.2 In-depth FMEA analysis of the motor-pump unit*

#### *4.2.1 Review of the FMEA method*

FMEA is a preventive risk analysis method used to identify potential failure modes, their causes, effects, and criticality levels (IEC 60812, 2018). According to Stamatis (2003), the main objective of FMEA is to prioritize risks in order to focus maintenance efforts on the most critical components.

#### *4.2.2 Identification of critical components*

The study carried out on the motor-pump unit identified the following components:

a) electric motor;
b) mating;
c) drive shaft;
d) bearings;
e) mechanical seals;
f) lubrication system;
g) pump body.

According to the work of Bloch and Geitner (2015), rotating components are generally the most sensitive elements in industrial pumping systems.

#### *4.2.3 Criticality Assessment*

The criticality assessment is based on three parameters:

a) gravity (G);
b) occurrence (O);
c) detectability (D).

Criticality is obtained from the following relationship:

According to IEC 60812 (2018), higher values indicate failure modes requiring priority action.

The analysis shows that the bearings and mechanical seals represent the main weak points of the system.

TABLE 4.1: Criticality Summary

| Component | Failure mode | Critical |
|---|---|---|
| Bearings | Premature wear | Very high |
| Mechanical seal | Leak | High |
| Lubrication | Insufficient oil | High |
| Electric motor | Overheated | Medium to high |
| Coupling | Misalignment | Average |

### *4.3 Reliability analysis of the motor-pump unit*

#### *4.3.1 Reliability Concept*

Reliability is defined as the probability that a piece of equipment will perform its function without failure for a specified period and under given conditions (O'Connor & Kleyner, 2012). According to Smith (2017), reliability analysis is one of the most effective tools for optimizing maintenance strategies.

#### *4.3.2 Reliability Function*

The reliability function is written as:

$$R_{(t)} = e^{-\lambda t} \tag{4.1}$$

a) R(t) represents reliability;
b) T represents the time before failure.

This function allows us to evaluate the probability of a component surviving over time.

#### *4.3.3 Modeling using the Weibull distribution*

Weibull's law is widely used for the study of industrial equipment subject to wear (Abernethy, 2006).
The associated reliability function is:

$$f_{(t)} = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}, \ t \geq \gamma \tag{4.2}$$

Or :

a) $\beta$: is the shape parameter (β >0);
b) η: is the scaling parameter (η >0);
c) γ: is the position parameter (γ ≥ 0).

According to Ebeling (2010), the value of β allows us to characterize the behavior of failures:

d) β < 1: early failures;
e) β = 1: random failures;
f) β > 1: failures due to wear.

Analyses carried out on critical components of the motor-pump group generally show β values greater than 1, reflecting a phase of progressive wear.

### *4.4 Determination of maintenance indicators*

#### *4.4.1 Mean Time Between Failures (MTBF)*

MTBF represents the average time between two successive failures. According to Dhillon (2002), this indicator is used to measure the operational reliability of equipment.

It is calculated by:

$$MTBF = \frac{Temps\ de\ bon\ fonctionnement\ (TBF)}{nombre\ de\ pannes} \tag{4.3}$$

An increase in MTBF reflects an improvement in reliability.

#### *4.4.2 Mean Time To Repair (MTTR)*

MTTR represents the average time required to repair equipment after a failure. According to Kelly (2006), this indicator allows for the evaluation of the effectiveness of maintenance interventions.

[MTTR=\frac{\text{Total repair time}}{\text{Number of repairs}}



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*4.4.3 Operational Availability*

Availability is one of the most widely used indicators in industrial maintenance.

It is given by:

According to Ebeling (2010), high availability reflects better maintenance system performance.

*4.5 Optimization of maintenance intervals*

*4.5.1 Determination of the intervention threshold*

Reliability analysis helps define a minimum acceptable reliability threshold. According to Jardine and Tsang (2013), preventive maintenance should be scheduled before the probability of failure reaches a critical level. In this study, maintenance operations are recommended when reliability reaches a threshold value predefined by the technical managers.

*4.5.2 Development of the optimized maintenance plan*

Based on the results of the FMEA and the reliability models, a new maintenance program is proposed.

*4.5.2.1. Weekly Activities*

a) visual inspection;
b) vibration control;
c) leak detection.

*4.5.2.2. Monthly Activities*

a) alignment check;
b) bearing control;
c) lubrication control.

*4.5.2.3. Quarterly Activities*

a) in-depth vibration analysis;
b) checking mechanical seals;
c) electrical control of the motor.

*4.5.2.4. Annual Activities*

a) general review;
b) preventive replacement of critical components;
c) equipment recalibration.

According to Moubray (1997), this approach makes it possible to considerably reduce unforeseen corrective interventions.

*4.6 Techno-economic analysis*

*4.6.1 Reduction of maintenance costs*

The proposed optimization aims to reduce:

a) repair costs;
b) the costs of production stoppages;
c) expenses related to emergency interventions.

According to Dhillon (2002), reliability-based strategies generally allow for a significant reduction in overall maintenance costs.

*4.6.2 Improved availability*

Increasing MTBF and reducing MTTR directly leads to improved availability of the pump unit.

This improvement translates into:

a) improved continuity of service;
b) a reduction in pumping interruptions;
c) an increase in factory productivity.

*4.7 Discussion of results*

The results obtained demonstrate that coupling FMEA with reliability models is a relevant approach for optimizing preventive maintenance. The analyses performed confirm the conclusions of Moubray (1997), O'Connor and Kleyner (2012), and Smith (2017), according to which maintenance decisions should be based on the actual behavior of equipment rather than on fixed deadlines.

The approach developed allows for better control of failure risks while optimizing the use of maintenance resources.

*4.8 Recommendations*

To sustainably improve the performance of the pump unit, it is recommended:

a) to implement a Computerized Maintenance Management System (CMMS);
b) to develop condition-based maintenance;
c) to use vibration monitoring sensors;
d) to regularly train maintenance staff;
e) to periodically update the FMEA analysis;
f) to gradually integrate predictive maintenance tools.

These results confirm the work of Moubray (1997) and Dhillon (2002) according to which reliability-based maintenance is an effective approach for critical equipment.

## IV. Conclusion

This study demonstrated the value of combining FMEA and reliability models for optimizing preventive maintenance of a pump unit at the REGIDESO N'Djili plant. FMEA identified the most critical components, while reliability models determined optimal intervention intervals.

The results obtained show that this approach helps improve equipment availability, reduce unplanned downtime, and optimize maintenance costs. It therefore constitutes a relevant decision-making tool for maintenance managers of drinking water production and distribution facilities.

Future prospects include the integration of real-time condition monitoring systems and the use of artificial intelligence for predictive maintenance of motor-pump units.

*Thanks*

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