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# STRATEGIC FORMULATION OF INDUSTRIAL MAINTENANCE BASED ON EQUIPMENT RELIABILITY IN A SUGAR AND ETHANOL PRODUCTION PLANT

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***ABSTRACT***

Maintenance and management have substantial importance in the search of the company’s competitive advantages. In this direction, a reliability analysis of equipments is very important for the definition of the most suitable maintenance strategy. The main goal of this paper is to assess the reliability-centered maintenance of the industrial reliability curve of a sugar cane department of an industry located in São Paulo State, Brazil. The proposed research method was based on the application of existing statistical modeling for the times between failures (TBF) of all reported equipment failures or the interruption times in the production line. These times were modeled by standard lifetime probability distributions as log-normal and Weibull distributions. The results showed that the company's strategy for preventive maintenance during the off-season is not adequate and the statistical analysis also identified important factors that affect the company's maintenance strategy. These results could be of great interest for the company and for engineering applications in general.

**Keywords**: maintenance, management, reliability, lifetime, sugar-cane

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## 1. INTRODUCTION

Competition between process industrial organizations requires proper maintenance planning to lead to the most high reliability for the industrial equipment's, which significantly could reduce losses during production (RUSCHEL, SANTOS, LOURES, 2017).

For Gandhare, Akarte and Patil (2018), a process industry requires large amounts of investment and continued availability of its facilities, which makes maintenance a critical area of the company, as it is responsible for the equipment performance. The sugar industry considered in this study operates seasonally and the availability of its facility during the sugar-manufacturing period determines its performance (GANDHARE; AKARTE; PATIL, 2018)

For Alsyouf (2009), maintenance activities are becoming more complex, as a conventional manufacturing system does not only consist of traditional mechanical equipment, but it also incorporates in its system, electronic, hydraulic, electromechanical, software and human elements. Inadequately maintained or neglected industrial installations will eventually require costly repairs, as overtime equipment, machinery or installations will wear out (VISHNU; REGIKUMA, 2016).

Also according to Vishnu and Regikuma (2016), the main goal of maintenance in an industrial plant is to achieve minimum downtime and to keep the equipment in operating condition at the lowest possible cost. The European Federation of National Maintenance Societies (EFNMS) defines maintenance as the combination of all technical, administrative and managerial actions used during the life cycle of equipment that are intended to retain or restore it to the state it can satisfactorily perform its required function. Mobley (2002) points out that maintenance could be classified as: corrective maintenance, preventive maintenance, predictive maintenance, total productive maintenance (TPM) and reliability centered maintenance (RCM).

According to Farrerro, Tarrés and Losilla (2002), in order to obtain an efficient maintenance policy, a combination of corrective, preventive and predictive maintenance is necessary, but the type of maintenance utilized and the interval between them is a function of their behavior, failure rate and the overall cost involved in the occurred damage.

Fogliatto and Ribeiro (2008) define RCM (Reliability Centered Maintenance) as a program that combines maintenance engineering techniques with systematic treatment and its objective is to guarantee the original function of the manufacturing equipment (see also, MOUBRAY,1997).

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It is important to point out that the sugar and alcohol production industries have as their main priority the planned corrective maintenance due to the seasonal characteristics of their operation, since there is great availability of time in the period known as off-season (approximately six months). In the food industry, the production line consists of machines interconnected by common transfer mechanisms with different failure modes. In the event of random failure in some equipment, most of the line interrupts the process, where the unfinished product should be discarded because of deterioration or quality problems, that is, the impact of the failure is negative and causes a decrease in reliability and production (TSAROUHAS, 2012).

This study is applied in nature, with a quantitative approach and, as its method, it uses statistical modeling to estimate the reliability through time-to-failure modeling - TBF of the production equipment. Equipment operating out of optimum condition can lead to unrecoverable losses for companies in competitive markets. In general, investment in production equipment is high, which is why one should seek to maximize its utilization and hence increase its financial return for the organization (MENGUE; SELLITTO, 2013; RAPOSO, 2011).

The paper is organized as follows: in sub-section 1.1, the problem and the research questions are introduced; in sub-section 1.2, the research goals are presented; in sub-section 1.3, the methodological aspects are delineated; in section 2, the company characterization is introduced; in section 3, some concepts on reliability models, especially the Weibull and the log-normal distributions are presented; in subsection 3.4, RCM applications for maintenance strategies are discussed; in section 4, the results of the study are presented; finally, in section 5, some discussion on the obtained results, future work and conclusions are presented.

### 1.1. Problem and research questions

Sellitto (2005), considering a qualitative study with several managers, concluded that maintenance strategies are usually elaborated by subjective methods, that is, in critical equipment they are submitted to preventive maintenance; for inactive equipment it is allowed emergency maintenance and for redundant equipment it is recommended corrective maintenance. For Alsyouf (2007), an effective maintenance policy makes a company more competitive in the market, through better use of equipment time.

Maintenance is usually under increasing pressure to improve the plant's industrial performance and short-term cost savings, but in the long term, the effects of improper

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maintenance are negative and those responsible for maintenance must be able to convince senior management that a solid investment and structured maintenance will save the company considerable amounts in the future (WAEYENBERGH; PINTELON, 2009).

RCM is one of the widely known maintenance strategies used to preserve the operational efficiency of industrial plants in a variety of sectors, including critical sectors such as power, military, aviation, rail, oil and naval (CARRETERO et al. 2003).

In a study by Vishnu and Regikumar (2016), in the sugarcane processing industry in India, it was found that RCM in general had not been implemented due to the lack of adequate methodologies and tools. The policy of maintaining a sugar cane processing plant, like in this study, is historically divided into two periods known as harvest and off-season. During the harvest period, from the beginning of April to the end of November, the plant operates fully and steadily, with 6-hour periodic monthly shutdowns reconciled with a planned daily maintenance routine. In this period, also there is the planning of the maintenance for the off-season period, since the data and demands collected in this phase are the basis for future maintenance.

In the off-season period, ranging from the beginning of December to the end of March, the operation of the industry is totally stopped, due to the end of the sugarcane harvest. Therefore, the industry is available in this period for maintenance according to the planning and budget previously established during the harvest period.

Mengue and Sellito (2013) define the maintenance strategy (preventive, predictive, corrective or emergency) most suitable for a centrifugal pump of an oil plant based on the concepts of reliability theory. The times obtained in the study were modeled by standard existing probability distributions and from the obtained inference results it was estimated the Reliability R(t), Maintainability M(t) and Pump Availability functions (MENGUE; SELLITO, 2013).

In a related study, Komninakis (2017) evaluated the coherence of the maintenance strategy of a food industry through statistical modeling applied to the repair times (TTR) and to the times between failures (TBF) of a production line consisting of six packaging machines modeled by Log-normal and Weibull probability distributions. Based on what it was exposed above by many authors, the main goal of this study is to evaluate through the proposed studies of Sellitto (2005), Mengue and Sellitto (2013) and Komninakis (2017) whether the current

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strategy of the maintenance of the company object of study is best suited for the maintenance management of the sugar cane plant.

### 1.2. Research goals

The main goal of this study is to evaluate through Reliability Centered Maintenance (RCM) whether the current strategy of the equipment maintenance of a sugar, ethanol and electric power plant is adequate. Besides the main goal, the study also has as some specific goals, the analysis of the repair times (TTR), to estimate the availability of the equipment's, to position the equipment's in the life cycle curve (bathtub curve), to discover specific factors that can significantly affect the repair times and the times between failures and, according to the obtained results to suggest to the company managers the best maintenance strategy to be used in future.

### 1.3. Methodological aspects

The research used in this paper is descriptive because it aims to develop a statistical model that describes the faults that occur in the equipment of an industry and to develop a profile with its characteristics. This analysis is performed through the information contained and stored in a company's own database. Data collection is obtained by extracting historical data of change of rotation and grinding stops available in the management system and the database of the company under study. The approach is quantitative and the method used will be the statistical modeling with the estimation of the equipment reliability by modeling the times between failures (TBF), repair times (TTR) and the survival times of the industrial equipment of a sugar and ethanol producing industry (RAUSAND, 1998; LAFRAIA, 2001).

## 2. COMPANY CHARACTERIZATION

The studied company operates in the sugar and ethanol industry sector with the production of sugar, ethanol and electricity generation. The plant was founded in 1953 in the countryside of São Paulo State, Brazil, together with a colony that houses employees working in the agricultural and industrial sectors. In the 1990's, the company was incorporated by a large group of mills and now it is currently part of a joint venture between a domestic and a foreign company.

Over the years, it has undergone numerous renovations and extensions. Its industrial park has a daily sugarcane crushing capacity of 7,300 tons, producing 20,000 bags of sugar and generating 4.4 MW of electricity. The industry has about 120 employees, 30 of which who are dedicated exclusively to the maintenance of the industrial plant that operates 24 hours a day, 7

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days a week. The industry, as it is the tradition and history of the sector, operates seasonally two periods of the year known as harvest and off-season periods.

The maintenance policy of the company under study is divided into these two periods. The first one is the off-season period between the months of December and the end of March, during which the industry's operation is completely paralyzed and available for maintenance according to the previously established planning and budget.

The off-season period is particularly warm with rainy climate conducive to sugarcane germination and growth, and at this time the harvesting of sugarcane is not recommended, as the excess of soil moisture facilitates the removal of roots during cutting and makes heavy machinery traffic difficult, damaging sugarcane fields and compromising future sprouts.

The second period known as the crop period, occurs in the remainder of the year (April to November), when the plant operates fully and steadily, similar to a consumer goods company. The company has as maintenance policy a monthly shutdown either lasting six hours or when rain occurs, which prevents sugarcane cutting as it was already mentioned; in the latter case, the duration is indefinite and may reach days depending on the amount of rain. In this case, the return of industrial activity occurs only after the resumption of agricultural activity of cutting, loading and transporting sugarcane to the industry.

The data collected for the statistical analysis consists of 1209 company fault records from May 1, 2012 to October 15, 2017. These records contain the times between failures and repair times related to different equipment.

## 3. USE OF RELIABILITY MODELS

The reliability function is one of the main probabilistic functions used to describe survival studies and is defined as the probability of an observation not failing until a certain time t, that is, it is possible to determine the probability of non-failure successes over a given time (see, for example, GIOLO; COLOSIMO, 2006). That is, the reliability function is defined by $R(t) = P(T > t)$, $t > 0$. As a consequence, the cumulative failure distribution function is defined by $F(t) = P(T \leq t) = 1 - R(t)$. The failure probability density function denoted by f(t) allows the probability of failures to be determined over a period of time (see, for example, LAWLESS, 1982; ELSAYED, 1995).

Assuming that the reliability function is derivable and continuous with respect to the failure times, the cumulative failure distribution function is also derivable. Under this hypothesis, the cumulative failure distribution function F(t) can be derived to obtain the failure

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probability density function f(t). The risk rate or failure rate function denoted by h(t) is the probability of failure occurring within a time interval $[t_1, t_2]$, since it did not occur until $t_1$, in other words, representing the proportions of failures occurring per unit of time. The probability of failures in the interval $[t_1, t_2]$ can be expressed in terms of the reliability function as $R(t_1) - R(t_2)$. Thus, the failure rate in the interval $[t_1, t_2]$ is expressed by,

$$[R(t_1) - R(t_2)]/(t_2-t_1)R(t_1) \quad [1]$$

In general, one can represent the interval $[t_1, t_2]$ by $(t, t + \Delta t)$, that is, $t_2 = t + \Delta t$; thus the rate function is given by $h(t) = [R(t) – R(t + \Delta t)]/[\Delta t R(t)]$. Assuming a very small value for $\Delta t$, h (t) represents the instantaneous failure rate, or risk rate, at time t conditional on survival up to time t, that is, it describes how the instantaneous failure rate changes over time (see, for example, LAWLESS, 1982).

Thus, one can find from expression (1), when $\Delta t \rightarrow 0$, a very useful formula for the risk function h (t) given by $h(t) = f(t)/R(t)$. The mean time denoted by MTTF (mean time to failure) measures the time of an item, component, or system surviving before failure, that is, the average lifetime MTTF is obtained by the area under the reliability function, that is,

$$MTTF = \int_0^\infty R(t)dt \quad [2]$$

### 3.1. Reliability Models

In survival analysis or reliability analysis, there are two types of models: non-parametric models and parametric models. The use of non-parametric methods allows us to gain perspective on the nature of the data distribution from which it was designed without, however, selecting a specific probability distribution (LEWIS, 1994). For Giolo and Colosimo (2006), the use of parametric techniques has been more frequent in the industrial area than in the medical area. Although there is a wide variety of probabilistic models used in the survival analysis, some models gain a prominent position, as they have proven adequacy in different situations. In this case, we have the exponential model, Weibull and the lognormal models (GIOLO; COLOSIMO, 2006).

### 3.2. Weibull Distribution

The Weibull distribution, widely used in reliability because of its flexibility in accommodating different forms of risk function, is perhaps the most widely used distribution model for lifetime analysis. For a random variable T with Weibull distribution, the probability density function is given by,

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$$f(t) = \frac{\gamma}{\theta^{\gamma}} t^{\gamma-1} \exp\{-(\frac{t}{\theta})^{\gamma}\}, \quad [3]$$

for t > 0 where t is the time to failure, γ is the shape parameter and θ is the scale parameter, all positive. For the Weibull distribution (3), the survival or reliability function R(t) is given by $R(t) = \exp\{-(t/\theta)^{\gamma}\}$ and has a failure rate (hazard function) given by,

$$h(t) = \frac{\gamma}{\theta^{\gamma}} t^{\gamma-1} \quad [4]$$

for $t > 0$, $\gamma > 0$ e $\theta > 0$.

The shape of the survival curve is related to the parameter γ. With γ > 1, the failure rate is increasing; with γ = 1, there is a constant failure rate (exponential distribution); with γ <1, the failure rate is decreasing. The mean life time E(T) and variance Var(T) of the Weibull model are given respectively, by,

$$E(T) = \theta\, \Gamma[1 + (1/\gamma)]$$

and

$$Var(T) = \theta^2\{\Gamma[1 + (2/\gamma)] - \Gamma[1 + (1/\gamma)]^2\}, \quad [5]$$

where the gamma function, Γ(k), is defined by $\Gamma(k) = \int_0^{\infty} x^{k-1} \exp\{-x\}dx$.

Sellitto (2005) relates the phases of the bathtub curve life cycle to the values of the Weibull shape parameter γ, which represents the behavior of the equipment fault curve, listing the most common types of faults found in each phase, namely:

- In the infant mortality phase, where γ < 1, the failure rate is high but decreasing over time; thus, failures are premature, usually caused by deficiencies in the manufacturing process, improper installation, or out-of-specification materials;
- In the maturity phase, where γ = 1, the failure rate fluctuates around a constant average, the failures are haphazard and due to less controllable factors such as equipment misuse, resistance overrun or unpredictable natural phenomena.
- In the senile mortality or wear phase, where γ > 1, the failure rate is increasing. Thus, failures are caused by aging, mechanical, electrical or chemical degradation, fatigue, corrosion, or very short design life. It is the end of equipment life.

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### 3.3. Log-normal distribution

A random variable T defined for positive values has a lognormal distribution if the logarithm of T , that is, ln(T) is normally distributed with mean and standard deviation given respectively by μ and $\sigma^2$. The probability density function for T is given by:

$$f(t) = \frac{1}{\sigma t\sqrt{2\pi}} \exp\left(-\frac{(lnt - \mu^2)}{2\sigma^2}\right) \quad [6]$$

The mean and variance of T are given respectively by,

$$\mu_T = \exp\left(E(lnT) + \frac{Var(lnT))}{2}\right) \quad [7]$$

$$Var(T) = \exp\left(2E(lnT) + Var(lnT)(e^{-Var(lnT)} - 1)\right)$$

### 3.4. RCM applications for maintenance strategies

The choice of a company's maintenance strategy should be driven by the use of quantitative methods where in recent years several approaches of this type have been studied and applied to maintenance in companies of various segments such as the Reliability-Centered Maintenance (RCM) identifying the risks and impacts of failure modes and thus proposing the best type of maintenance to be performed to minimize damage (SELLITTO, 2007).

To formulate an industrial maintenance policy in the metalworking sector, Sellitto (2005) reviewed the concepts related to random process variables as a way to define the basis of reliability and modeling applied to maintenance management through the modeling of the techniques from time to failure and until repair was established the maintenance policies in factories of this sector (SELLITO, 2005).

Mengue and Sellito (2013) defined the maintenance strategy (preventive, predictive, corrective or emergency) most suitable for a centrifugal pump of an oil plant based on the concepts of reliability. The times obtained in the study were modeled by probability distributions and, from the obtained results, the estimated reliability functions R(t), Maintainability M(t) and Pump Availability (MENGUE; SELLITO, 2013) were estimated. Komninakis (2017) evaluated the coherence of the maintenance strategy of a food industry through statistical modeling applied to the repair time (TTR) and time between failures (TBF) of a production line consisting of six packaging machines modeled by Log-normal and Weibull probability distributions (see, KOMNINAKIS; PIRATELLI; ACHCAR, 2018).

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Chopra, Sachdeva and Bhardwaj (2016) studied the relationship between MCC implementation factors and increased productivity in the Indian process industries of the textile, fertilizer, pharmaceutical, food and beverage industries. For this purpose, a questionnaire was prepared containing questions to be answered on the four-point Likert scale (1- nominal gain, 2- reasonable gain, 3- high gain and extremely high 4-gain) and delivered to 100 small, medium and large companies with 64 responding companies. The questionnaire was divided into two sections: the first dealt with RCM implementation factors and the second dealt with manufacturing parameters, that is, productivity. The obtained result showed that companies with higher level of MCC implementation have higher productivity compared to companies with lower level of implementation.

Gandhare, Akarte and Patil (2018) conducted an empirical investigation of maintenance performance management practices in the sugar processing industry in India. Through the collected data, statistical methods such as correlation, multiple regression and cluster analysis were used to achieve the objective of the study which was to understand the used maintenance practices and the differences in maintenance performance among the industries analyzed in the survey.

To verify the best decision-making process for maintenance on equipment in power plants with gas turbines (GTPP), steam turbines (STPP) and combined cycle (CCPP), Sabouhi Abbaspour, Fotuhi-Firuzabad and Dehghania (2016) reported the use of reliability theory to quantify the criticality and importance of each individual component in the reliability performance of a power generation system. For this purpose it was necessary to identify the series and parallel arrangements of the components and later to elaborate an analysis of the overall system reliability indexes such as the repair rate, average system cycle time (SCT), average system downtime (TMI), mean time to premature failure (MTTF1) and mean time to failure (MTTF). This approach helped operators and managers understand the importance of each component in the overall plant performance and to show that the STPP system is more reliable, followed by the GTPP and CCPP ones.

Vishnu and Regikuma (2016) developed a general RCM model that is suitable for all types of process plants with interconnected complex subsystems and critical components. For this purpose, a framework was developed following the methodology based on the Analytical Hierarchy Process (AHP) to develop a database system that monitors maintenance actions and

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equipment information to define cost-effective ways to increase industry availability and profitability.

Heo, Kim and Lyu (2014) presented a Reliability Centered Maintenance (RCM) model to analyze the power sector maintenance strategy to maintain reliability also studying potential failures in substation transmission system components. The goal of the study was to find an optimal maintenance strategy and to compare MCC with the current adopted strategies, that is, the Time Based Maintenance and the Condition Based Maintenance. The obtained results showed that MCC has a best cost-benefit ratio than the others.

## 4. RESULTS

The data collected for the statistical analysis consist of 1209 company fault records from May 1, 2012 to October 15, 2017, divided into 6 crop years. These records contain the times between failures (TBF) and repair times (TTR) related to different equipment that may interfere with the industry shutdown, that is, at the time the milling process is interrupted and the milling is stopped. In this study, only the results of the statistical analysis for the TBF data denoted here by MTBF are presented.

Initially, an ANOVA (analysis of variance model) model is considered in the data analysis to compare the TBF means in different years. In this case, the data are considered in the logarithmic scale since the transformed data presents better normality compared to the data in the original scale. This is observed in the normal probability plots given in Figure 1 for the 1209 observations considered in the study; similarly, good normality is also observed if we analyze each year separately, that is, the normality is better when using log-scale data.

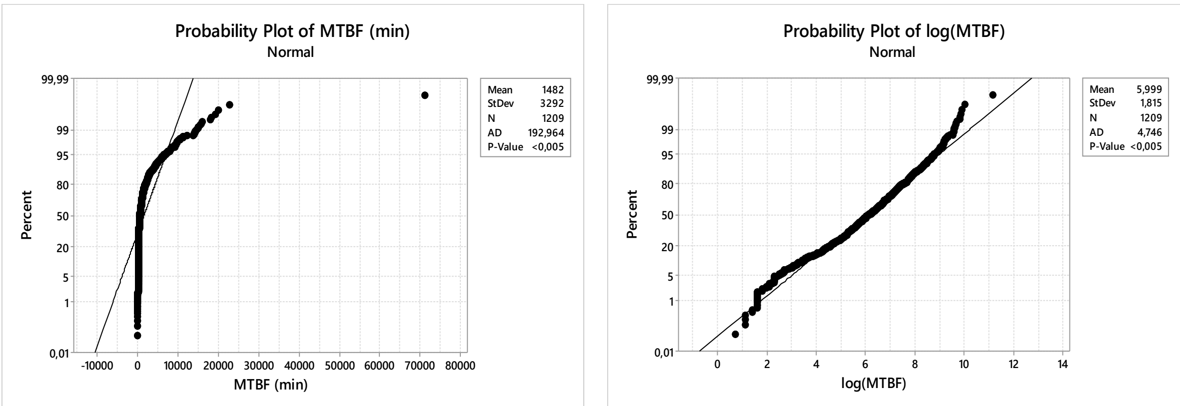


Figure 1: Normality plots for the original and logarithmic scale data.
Source: The authors

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### 4.1. Use of an analysis of variance model (ANOVA) to compare the MTBF means in different years

To verify statistically whether there are significant differences among the MTBF means for the different years, this section considers the use of a one-way analysis of variance model. The analysis of variance technique (ANOVA) is a statistical methodology to test if a given factor has a significant effect on the dependent variable denoted by Y (MONTGOMERY; RUNGER, 2010).

The ANOVA results with one classification were obtained using Minitab® software to compare the MTBF means on the logarithmic scale. Since the obtained p-value is smaller than 0.001, that is, much lower than 0.05 (the usual significance level), there is significative statistical difference among the means of MTBF in different years.

The needed assumptions to validate the inferences in the ANOVA model were verified from residual graphs (normality and constant variance of residuals). From the plots of Figure 2 (95% confidence intervals for the means), significant differences among the means for the different years are also confirmed (95% confidence intervals for the means are not overlapping).

### 4.2. Use of reliability models to estimate the MTBF means on the original scale for each year

In this section, the TBF data are analyzed by reliability models assuming the original scale data to verify the maintenance performance between years. From Weibull and log-normal probability graphs obtained from the models fitted by the maximum likelihood estimator (MLE) methods and the Minitab® software, it is observed that the Weibull distribution is better fitted by the data (points closest to the line in the Weibull probability graph when compared to the normal probability graph) as observed in Figure 3.

Thus, the Weibull distribution is assumed in order to obtain the reliability curves estimated by the maximum likelihood method for the MTBF times in the different years reported in the database. The failure rates, reliability functions and MLE estimators of the shape and scale parameters are presented in Figure 4.

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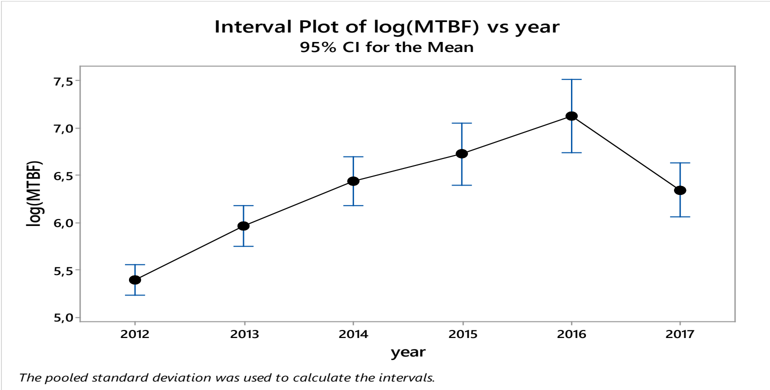


Figure 2: 95% confidence intervals for log averages (MTBF) in different years.
Source:The authors (2019)

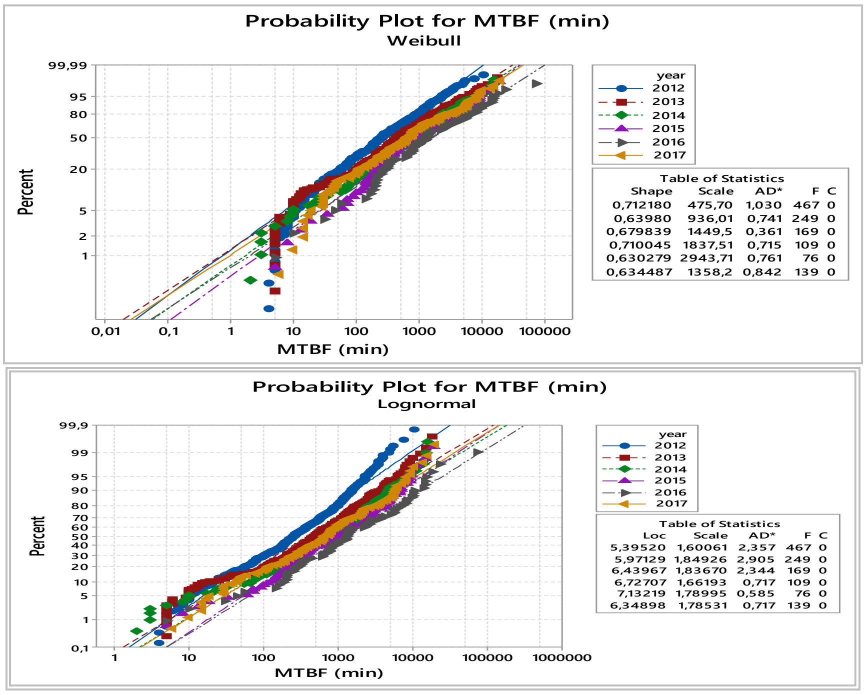


Figure 3: Weibull and Lognormal probability graphs.
Source: The authors (2019)

In Figure 5 (extracted values of Figure 4) the shape parameter estimators ($\gamma$) for the Weibull fit are presented for the MTBF data in each year. From these values, it is observed that for all cases there are always values $\gamma < 1$, which does not present a pattern that can relate to a possible improvement, that is, with a trend $\gamma \cong 1$, phase of maturity in the life cycle.

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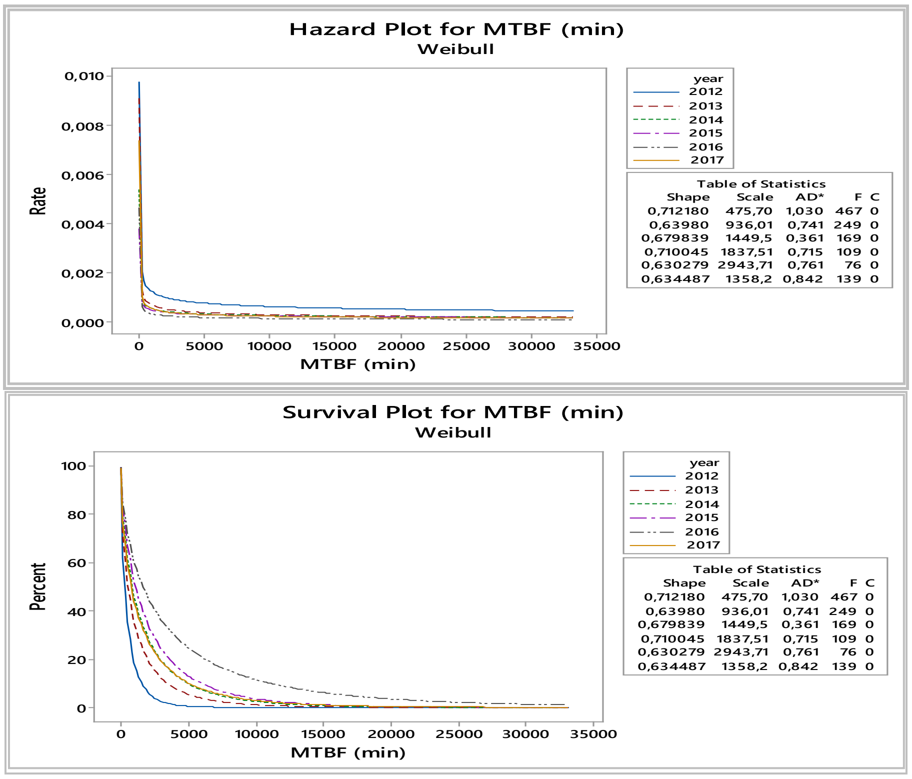


Figure 4: Failure rate and reliability graphs assuming a Weibull distribution
Source: The authors (2019)

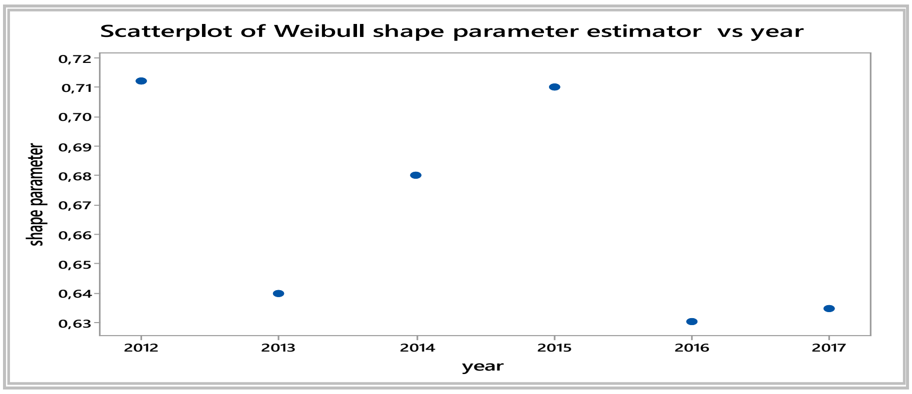


Figure 5: Weibull shape parameter estimator versus year
Source: The authors (2019)

## 4.3. Use of an analysis of variance model (ANOVA) to compare the MTBF means in different months

In this section, it is compared the MTBF means for the different months, using a one-way analysis of variance model using the Minitab® software with the data in the logarithmic scale. Since the obtained p-value is smaller than 0.001, there is statistical difference among the means of MTBF in different months.

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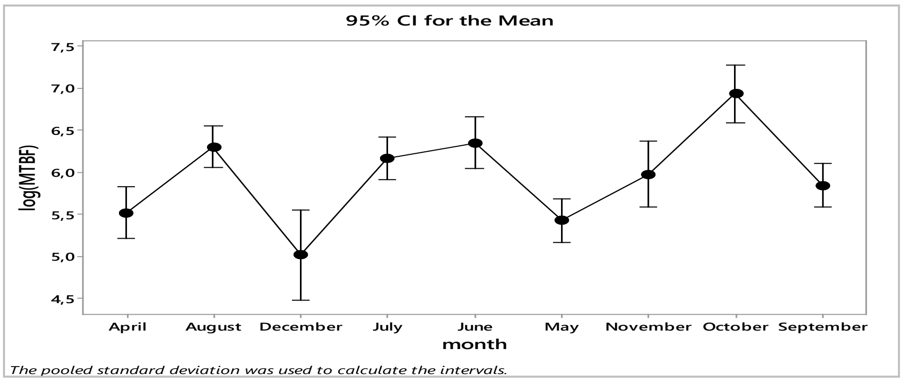


Figure 6: 95% confidence intervals for the mean of MTBF in each month
Source: The authors (2019)

Normality and constant variance of residuals also were verified by standard residual plots. From the plots of Figure 6 (95% confidence intervals for the means), significant differences among the means for the different months also are confirmed (95% confidence intervals for means are not overlapping).

From the obtained results, it is observed that the mean of MTBF is larger for October when compared to the other months. In the same way, a smaller estimate for the mean of MTBF for December is observed.

### 4.4. Use of reliability models in the estimation of the MTBF means for each month

In this section the TBF data are analyzed by reliability models assuming the original scale data in order to verify the maintenance performance among different months. From Weibull and log-normal probability graphs obtained from the models fitted by the maximum likelihood estimator (MLE) methods and the Minitab® software, it is observed that the Lognormal distribution is better fitted by the data (points closest to the line in the Normal probability graph when compared to the Weibull probability graph) as observed in Figure 7.

Thus, the Lognormal distribution is assumed to obtain the reliability curves estimated by the maximum likelihood method for the MTBF times in the different months reported in the database. The failure rates, reliability functions and MLE estimators of the shape and scale parameters are presented in Figure 8.

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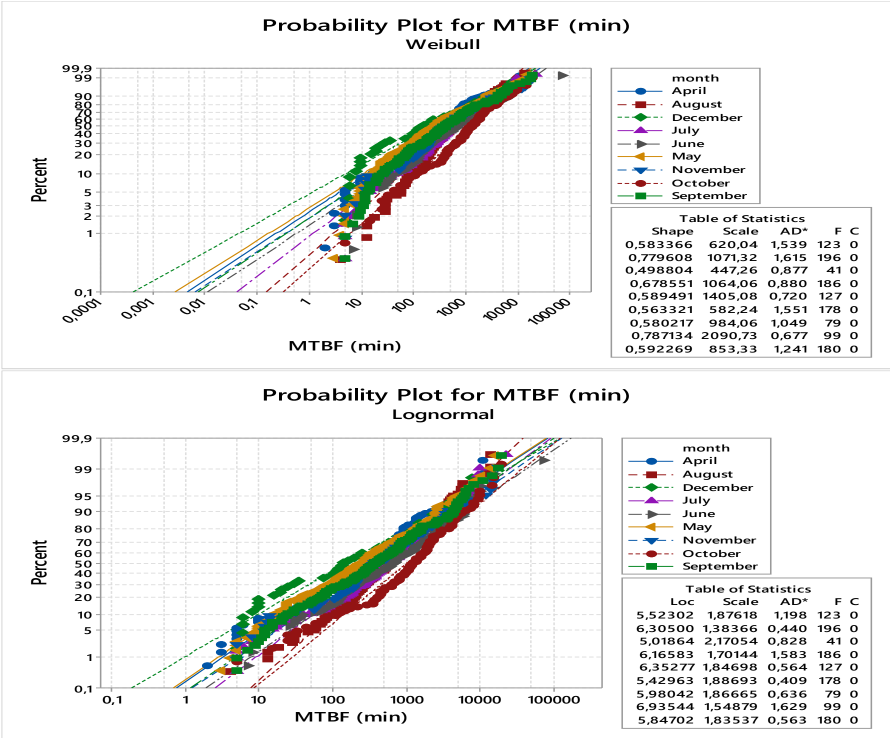


Figure 7: Weibull and Lognormal probability graphs.
Source: The authors (2019)

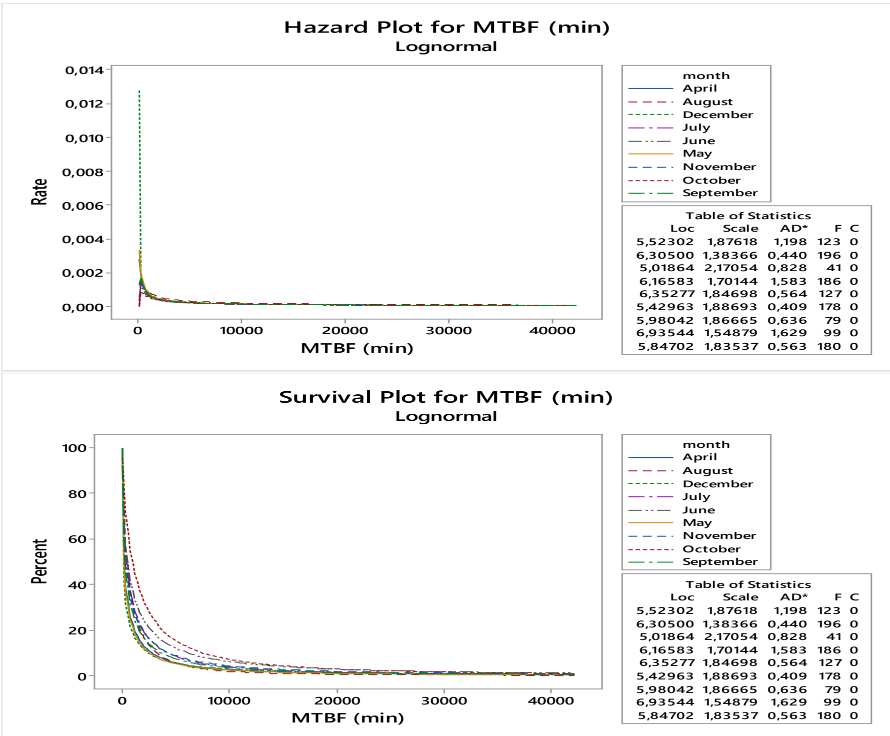


Figure 8: Failure rate and reliability graphs assuming a Lognormal distribution
Source: The authors (2019)

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### 4.5. Use of an analysis of variance models (ANOVA) to compare the MTBF means assuming different causes of failure

To verify statistically if there is significant differences between the MTBF means for the different causes of failure, this section considers the use of a one-way analysis of variance model using Minitab® software to compare the MTBF means on the logarithmic scale. Since the obtained p-value is smaller than 0.001, there is statistical difference among the means of MTBF in different causes of failure. Normality and constant variance of residuals also were verified by standard residual plots. From the plots of Figure 9 and Table 1 (95% confidence intervals for the means), significant differences between the means for the different causes are also confirmed (95% confidence intervals for means are not overlapping).

From the obtained results, it is observed that the mean of MTBF is larger for civil maintenance (7.534), although there is only two observations, when compared to the other causes.

Table 1: Estimated means for MTBF and 95% confidence intervals for the mean of MTBF in each different cause

| Cause | N | Mean | 95% CI |
|---|---|---|---|
| Excess Capacity Milling | 1 | 5.704 | (2.261; 9.146) |
| Maintenance Industrial Automation | 9 | 6.242 | (5.095; 7.390) |
| Civil Maintenance | 2 | 7.534 | (5.100; 9.969) |
| Maintenance Instrumentation | 15 | 6.178 | (5.289; 7.067) |
| Mechanical Maintenance | 290 | 6.0876 | (5.8855; 6.2898) |
| Operating - Sugar Factory | 258 | 6.2799 | (6.0656; 6.4942) |
| Operating - Power Generation | 5 | 6.429 | (4.890; 7.969) |
| Operating - Steam Generation | 135 | 4.924 | (4.628; 5.220) |
| Operating - Preparation / Grinding | 276 | 6.477 | (6.269; 6.684) |
| Electrical Maintenance | 218 | 5.564 | (5.330; 5.797) |

Source: The authors (2019)

## 5. GENERAL CONCLUSIONS AND FUTURE WORK

The main goal of the study was to verify if the maintenance strategy adopted by the company is the most appropriate to manage its maintenance. Related to four different factors, we have some conclusions and interpretations:

- Regarding to the year factor, it was possible to identify that, in the bathtub curve, the sector is in the infant mortality phase ($\gamma < 1$) and, therefore, should use the most appropriate maintenance strategy for this phase. Table 2 shows a comparison between the recommended maintenance practices for infant mortality according to Sellitto (2005) and that practiced by the company. In the region of infant mortality, premature failures occur due to errors in manufacturing processes, installation or application of equipment materials (MENGUE; SELLITTO, 2013). According to Table 2, the

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recommended maintenance strategies were corrective and emergency, as they would seek the root cause of possible defects and eliminate them from operation. However, the sugar and alcohol industry sector, as well as the analyzed company, has the practice of supporting its decisions in the employees' experiences and in the history of breakages and, thus, makes intensive use of preventive maintenance during the off-season, through the massive replacement of static and rotating items (electrical and mechanical) without a well-defined criterion by inspections and technical reports. Thus, the company was mistaken in the strategy, because, as mentioned in Table 2, the practice of preventive maintenance perpetuates and even aggravates mortality, as it replaces the survivors of the previous crop, instead of preventing the breakdown as expected.

Table 2: Life cycle maintenance strategy of the infant mortality and company mortality lifecycle practiced by the company (infant mortality, failures in origin)

| Estrategy | Consequence | Recommended | Company |
|---|---|---|---|
| Emergency | Delays or even prevents the end of child mortality by not reinforcing items that have broken or not removing causes of origin failures | Yes | Yes |
| Corrective | Anticipates the end of child mortality by reinforcing items that have broken or removed the causes of origin failures | Yes | Yes |
| Preditive | Monitors failures in progress that can result in breakage, but these are very few at this stage, as breaks give more for low resistance | No | No |
| Preventive | Perpetuates or even aggravates child mortality by accurately exchanging survivors, strong items that have no source flaws | No | Yes |

Source: The authors (2019)

- Still regarding the year factor, the highest MTBF average was observed for the year 2016. It was also observed that the MTBF average increases during the period from 2012 to 2016, but in 2017 there is a decrease in the MTBF average. This drop is due to the continuity of the wrong maintenance practices, which initially showed favorable results, but were not sustainable for long periods.

- Regarding the month factor, from the obtained results, it was observed that the MTBF average is higher for October, when compared to the other months. Similarly, a lower estimate for the MTBF average is observed for December. This is explained when the data are analyzed chronologically, between the beginning (April and May) and end of harvest (November and December) which are more subject to disturbances that lead to the interruption of the industrial operation. The start months are susceptible to process variations and adjustments and the end months to sharp wear and tear of equipment throughout the crop year resulting in equipment breakdown. The remaining months (mid-season) have historically been stable due to few variations and continuous operation of the industrial plant.

- Regarding The cause of failure factor, from the obtained results, it was observed that the MTBF average is higher for civil maintenance (7.534) when compared to the other causes. This fact is the result of the total demobilization of the civil maintenance sector of the industrial plant, through the strategic definition of the company. Thus, in the occurrence of any event, the emergency hiring of external labor is necessary, which makes any type of repair of this order too slow.

As future research work, we could point out that,

- With all that is discussed in this study, it is hoped that the results may contribute to future research and encourage the improvement of reliability techniques. As a continuation proposal of this work, it is suggested to extend the proposed methodology to the TTR (time to repair) statistical modeling.
- Another approach to be considered in a future study, could be to perform individual reliability analyzes for each critical production line equipment.
- In addition, in a future study it is intended to analyze the impacts of predictive maintenance of hibernation on the conservation of a plant's assets during the off-season period, seeking to reduce maintenance costs and inappropriate replacement of surviving parts from the previous crop.

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