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RELIABILITY ANALYSIS OF A PLASTIC PROCESSING EQUIPMENT: A CASE STUDY SUPPORTED BY STATISTICAL SOFTWARE

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Abstract: The extrusion process of plastic transformation involves a series of variables and components which must be associated with the concept of reliability to achieve an expected performance in operational and quality terms. This paper describes the reliability framework of an extruder of a packaging company located in Brazil through the following mathematical representations: probability density function $f(t)$, reliability curve $R(t)$ and function rate of failure $h(t)$. Through a statistical software the set of representations was able to develop the reliability framework of the machine, which can be used to support a FMEA analysis. Besides that, it was evidenced that in the current operating conditions of the machine, approximately 50% of the failure observations happen on the hour 100 of operating time. The main outcome is that it is recommended a systematic preventive maintenance based on 100h cycles. It is expected that this work may act as a guide for future implementation of improvement activities.

Keywords: maintenance management. reliability analysis. reliability mathematical representations

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1 Introduction

Among the productive processes of plastic transformation, extrusion is the most used, and represents, according to data from ABIPLAST - Brazilian Association of the Plastic Industry (<http://www.abiplast.org.br/>, retrieved 15 July 2019), 65% of transformation operations. This process can be classified into several categories, among which tubular film extrusion is one of the most common and refers to the operation in which the polymer is melted and pumped into the machine towards to a ring matrix that will mold the plastic to the shape of a tube that, in turn, will be blown and originate the "balloon" that is cooled and then flattened and wound into coils (VERCELLINO, 2014). It is then observed that this transformation process involves a series of variables and components to which it is necessary to associate the concept of reliability in order to ensure operational and quality performance at expected levels.

In this context, for Fogliatto and Ribeiro (2009) and Fernandes (2010) reliability is the probability of a product or service operating correctly, that is, of satisfactorily performing the required function for a specified period of time under established operating conditions without failure. Therefore, some indicators are usually used to represent the reliability of an equipment or unit, namely: mean time to failure, reliability function $R(t)$, risk function $h(t)$, mean time to repair.

Each of these representations of reliability stated derives from the identification of the probability distribution which, according to Fogliatto and Ribeiro (2009), describes the random behavior of a given phenomenon under analysis. By knowing the probabilistic distribution that best fits the time units in which the failures occur, that is, time to failure, it is possible to make estimates of the unit's probability of survival, as well as other reliability measures, among which are those previously announced. From this perspective, it is evident that the mathematical modeling of representations for reliability functions is a phase that precedes decision making in this field, which makes this stage an essential element for the reliability analysis.

Based on the above, this work aims to mathematically model the failure observations of a packaging company extruder located in Rio Grande do Norte in terms of the following reliability representations: probability density function $f(t)$, reliability curve $R(t)$ and failure rate function $h(t)$. In addition, it is proposed to represent each of these functions graphically so that the reliability framework of the equipment can be described and used in the future to support improvement activities.

2 LITERATURE REVIEW

2.1 Reliability measures

In order that the reliability framework of a particular equipment or unit can be described, some measures are useful. For this purpose, the probabilistic approach of failure observations is necessary so that some of the functions can be enunciated mathematically.

For Callegari-Jacques (2003), a random variable, such as the useful life of a given equipment, assumes a specific frequency distribution, which can present varied forms. The theoretical distributions available in the statistical literature are configured as models that seek to represent the behavior of a given event according to the frequency of its occurrence. This allows estimates to be made without the need to access all the information since the purpose of the distribution is precisely to determine the behavior of the group of data observed under a certain theoretical model.

Thus, frequency distributions are probability distributions that assume that for each event there is an associated probability of occurrence (Leotti, Birck & Riboldi, 2005).

2.2 Estimation methods

In general, two methodological approaches are widely used to estimate the parameters of the reliability representations: the least squares method and maximum likelihood method. It is important to stress that some properties must be met to with respect to population estimators, namely: non-biased, consistency, efficiency and sufficiency. In reliability analysis, the probability distributions that are generally used to describe the behavior from time to failure are, according to Fogliatto and Ribeiro (2009), exponential, Weibull, Gamma and Lognormal. Even though the distribution fitting depends on the data set under analysis, the Weibull is known to represent the time to failure behavior of distinct physical systems mainly for its flexibility to model both systems where the number of failures increases or decreases over time, even situations where failures remain constant over time (MONTGOMERY, 2009). The estimation of parameters by Minitab® Statistical Software least squares method takes as its starting point the calculations by adjusting the regression line to the points of a data set with the minimum sum of the standard deviations squared, that is, minimum square error. In the case of reliability analyzes, the line and data are represented in a probability graph (MINITAB, 2019).

As far as the results of the least squares method and the maximum likelihood method are concerned, according to Minitab (2019) the differences between the methods are insignificant, which allows them to be used interchangeably. However, for small samples, the least squares method has the advantages of being non-addictive while the maximum likelihood approach becomes addicted to this occasion (MINITAB, 2019).



2.3 Adhesion tests

When performing a data adjustment analysis using analytical adherence tests, the chi-square and Kolmogorov-Smirnov are the most used, as stated by Fogliatto and Ribeiro (2009). The adherence tests are non-parametric kind of tests used to verify if a sample data set can be described according to a theoretical probability distribution (Barbetta, Reis & Bornia, 2010).

It is by comparing the sample frequencies together with the theoretical frequencies expected by the probabilistic model that it is possible to certify whether a given distribution fits well with the sample data (Silva, Souza, Castro, Ferreira, Campos, 2015).

When using the least squares estimation approach in Minitab®, two adjustment indicators are presented: Pearson's correlation coefficient (r), which the closer its value is to 1, the better the adjustment; and Anderson-Darling's adjusted statistic (AD) which, according to Silva *et al.* (2015), the smaller its value the better the adjustment of the distribution to the data under analysis.

3 METHODS

3.1 Methodological procedures

In order to achieve the proposed objective of mathematical modeling of failure observations, three macro-stages were performed: the first consisted in collecting data, the second in preparing the database to make the study viable, and finally, the third was configured by analyzing the data with the support of the statistical software Minitab® (2020) with the purpose of modeling and describing the behavior of the collected data in terms of typical reliability functions. It is important to point out that this software was set due to its applied character. Also, since this study aims to develop the extruder's reliability framework, but not a comparative analysis between statistical packages, this decision was judged adequate. Figure 1, below, schematically represents the stages described:

Figure 1

Research macro stages

Source: Authors (2020).

In order to enable the modeling of the reliability functions, data were collected from time to failure observations (TTF), in hours, during the period between January 2018 and April 2019, referring to an extrusion machine of a packaging company in Rio Grande do Norte (RN), Brazil; with the respective technical specification: three-layer tubular film extruder. TTF observations were extracted from the ERP software (enterprise resource planning) and from a database stored on Microsoft Office[®] Excel, totaling 57 observations.

In step 2, to avoid duplicate TTFs, a preparation of the database was performed, also on Excel, from the crossing of the observations stored in the two extraction sources. Therefore, the spreadsheets were used to correct any inconsistencies identified in the ERP system database, whether they are of unit conversion order or data tabulation.

Finally, the statistical software Minitab[®] was operated to identify the probability distribution that adjusted to the data's behavior, as well as to model the probability density functions $f(t)$, reliability curve $[R(x)]$, risk function $[h(x)]$ and accumulated failure graph.

Regarding the software analysis procedure, the "Reliability/Survival" module commands were used to generate the results and, regarding this aspect, it is important to highlight that the analysis step itself was preceded by a reflection about the consideration of the data regarding censorship, which led to the conduction of the tests by the "Parametric distribution analysis on the right" submenu of the "Reliability/Survival" module. Therefore, the analyses performed assumed that the data are censored on the right; which means that, in view of the time cut from January 2018 to April 2019, there is no interest on the part of the study to consider the failures that occurred after the period considered. Thus, the analysis of this research is based on the Type I censoring on the right: the data are censored by time.



3.2 Considerations for statistical analysis

In view of the achievement of the objective proposed in this work, the least squares approach was performed to estimate the parameters for the reliability representations instead of the maximum likelihood method since the first one approach is more appropriate on small occasions. In consideration of the 57 observations of this reliability analysis, the choice of the least squares was judged appropriate.

4 Results

4.1 Identification of probability distribution

First, it was necessary to define the probability distribution describing the behavior of failure time of the extruder under study. Chart 1, below, summarizes the Anderson-Darling (adjusted) fitting quality statistics and Pearson correlation coefficient (ρ) so that the ordering of probability distributions follows a ranking in terms of fitting quality:

Chart 1

Adjustment quality test

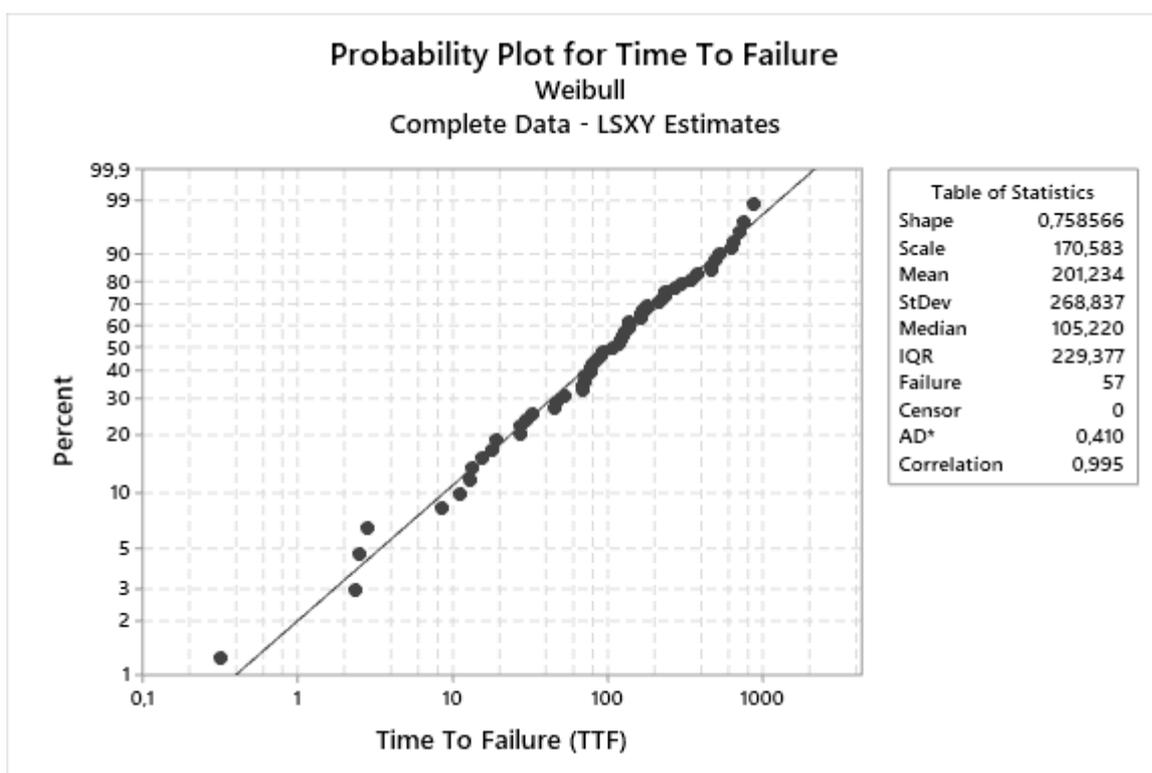
| Distribution | Anderson-Darling (adj) | Correlation Coefficient |
|-------------------------|------------------------|-------------------------|
| Weibull | 0,410 | 0,995 |
| Lognormal | 1,108 | 0,964 |
| Exponential | 1,998 | * |
| Loglogistic | 1,075 | 0,965 |
| 3-Parameter Weibull | 0,411 | 0,996 |
| 3-Parameter Weibull | 0,494 | 0,991 |
| Lognormal | | |
| 2-Parameter Exponential | 1,437 | * |
| 3-Parameter Exponential | 0,666 | 0,984 |
| Loglogistic | | |
| Smallest Extreme Value | 18,105 | 0,776 |
| Normal | 4,996 | 0,886 |
| Logistic | 4,792 | 0,887 |

Source: Designed from Minitab® (2020)

Thus, the Weibull distribution was chosen because it was the one with the lowest (adjusted) AD value, as well as because it presented the Pearson correlation coefficient (r) value closest to 1. In addition, the probability plot of the distribution under analysis was also observed, which is represented in Figure 2 below, where LSXY means that the distribution identification test was performed under the least squares estimation method:

Figure 2

Weibull's distribution identification



Source: Authors (2020).

From the graphical analysis it can be seen that the percentiles, represented by the black dots, accumulate along the adjusted line; this shows that the Weibull adjusts the TTF data well.

4.2 Reliability analysis

Once the probability distribution was identified, the following modeling steps were continued: probability density function $f(t)$, reliability curve $R(t)$, referenced by Minitab® by survival curve, risk function, also known as failure rate function $h(t)$ and accumulated failure graph. Each of these steps are described below.



4.2.1 Probability density function

From the parametric distribution analysis, it was identified that the reliability representations of the extruder based on TTF observations present the respective parameters defined by Weibull in shape (β) and scale (θ) equal to, respectively: 0.758566 and 170.583. Chart 2 below summarizes the parameters of interest and their fitting statistics, previously calculated with Minitab® support:

Chart 2

Weibull distribution parameter estimates

| Parameter | Estimate |
|-----------|----------|
| Shape | 0.758566 |
| Scale | 170.583 |

Source: Designed from Minitab® (2020)

Equation 1 below expresses mathematically the density function $f(t)$ for Weibull:

$$f(t) = \frac{\beta}{\theta} t^{\beta-1} e^{\left(\frac{-t^\beta}{\theta}\right)} \quad (1)$$

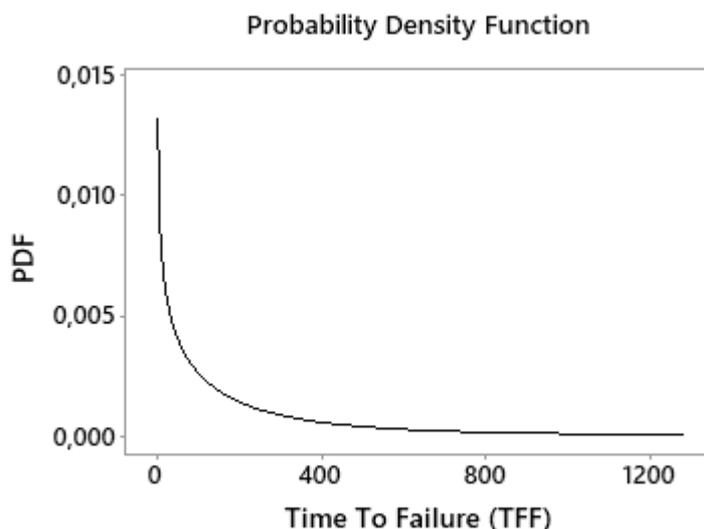
Based on Equation 1 and the distribution parameters calculated by the software, the density function describing the fault observations of the extruder under study is described by Equation 2 below:

$$f(t) = \frac{0.758566}{170.583} t^{0.758566-1} e^{\left(\frac{-t^{0.758566}}{170.583}\right)} \quad (2)$$

Based on the expression defined by Equation 2, Figure 3 below graphically represents the probability density function:

Figure 3

Probability density function plot



Source: Authors (2020).

The graphical analysis shows a behavior that decreases exponentially over the operating time horizon. Besides of that, in face of distribution parameters it is possible to mention that once $\beta < 1$, probable causes of failure may be associated with improper material or operation, equipment in the start-up phase (adjustments) or even operating error on the part of the task executer (Pinto, 2003 as cited in Mendes, Maria, Radin, De Sá & Cordeiro, 2014). Moreover, the scale parameter it is also known as characteristic life and such estimate informs the lifetime at which 63,2% of the failures happen (MacDiarmid & Morris, 1984). In the reality of this study, it means that between the (0, 170) interval, 63.2% of the failures occurs in the investigated system since the scale estimate was around 170.

4.2.2 Survival function R(t)

Similarly to the previous subtopic, the representation of the machine reliability in terms of the R(t) survival curve was obtained through the parameters of form and scale summarized in Table 1. Thus, Equation 3, below, defines mathematically and generically the reliability function R(t) for the Weibull distribution:

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^\beta} \tag{3}$$

Based on Equation 3 and the parameters of form and scale, the reliability function for the extruder failures under study is described by Equation 4 below:

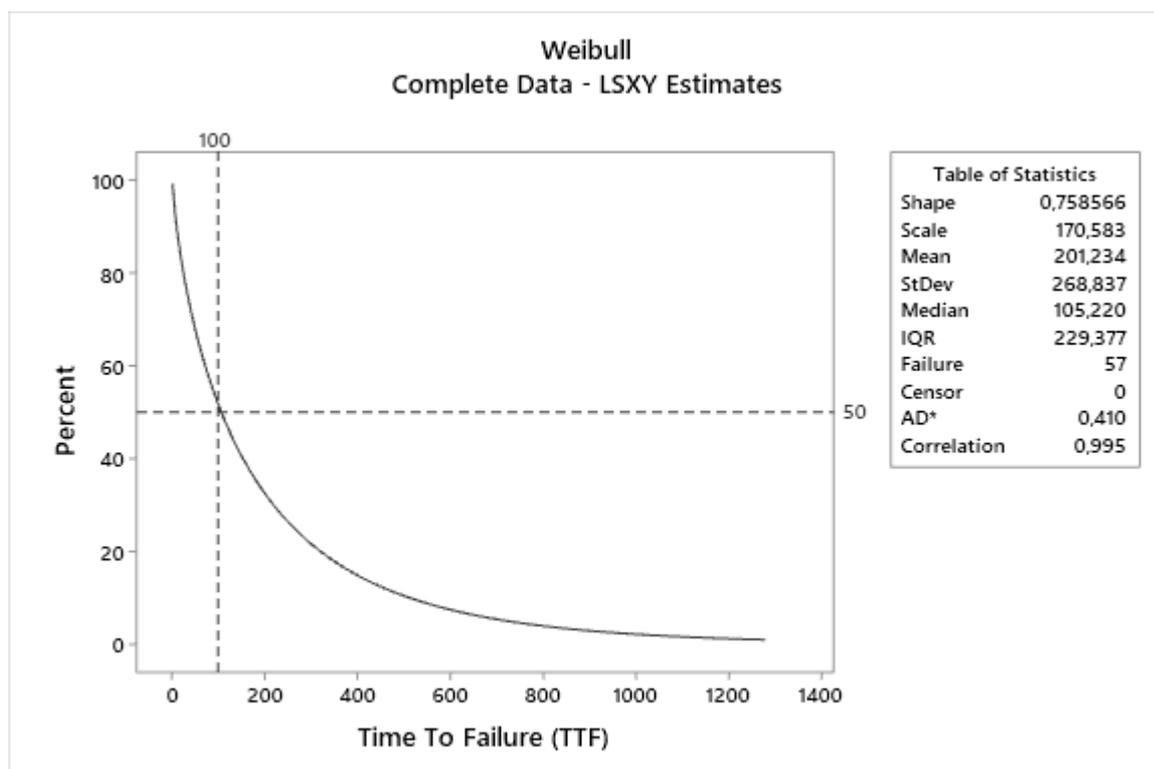


$$R(t) = e^{-\left(\frac{t}{170.583}\right)^{0.758566}} \quad (4)$$

The reliability curve defined by Equation 4 is graphically represented in Figure 4 below:

Figure 4

Survival plot for TTF



Source: Authors (2020)

The area under the reliability curve therefore informs the probability of the extruder continuing to operate in the time interval of interest (0, t). It can be observed that in the first 100h of operation there is a reliability loss around 50 units, what can indicate a need for systematic preventive maintenance at the time 100h.

4.2.3 Hazard function h(t)

Repeating the analysis procedures that were performed for the previous reliability representations, the risk function h(t) was also calculated based on the parameters defined by the adjustment distribution. Equation 5 below defines mathematically and generically the failure rate function h(t) for the Weibull distribution:

$$h(t) = \frac{\beta}{\theta} \left(\frac{t}{\theta} \right)^{\beta-1} \quad (5)$$

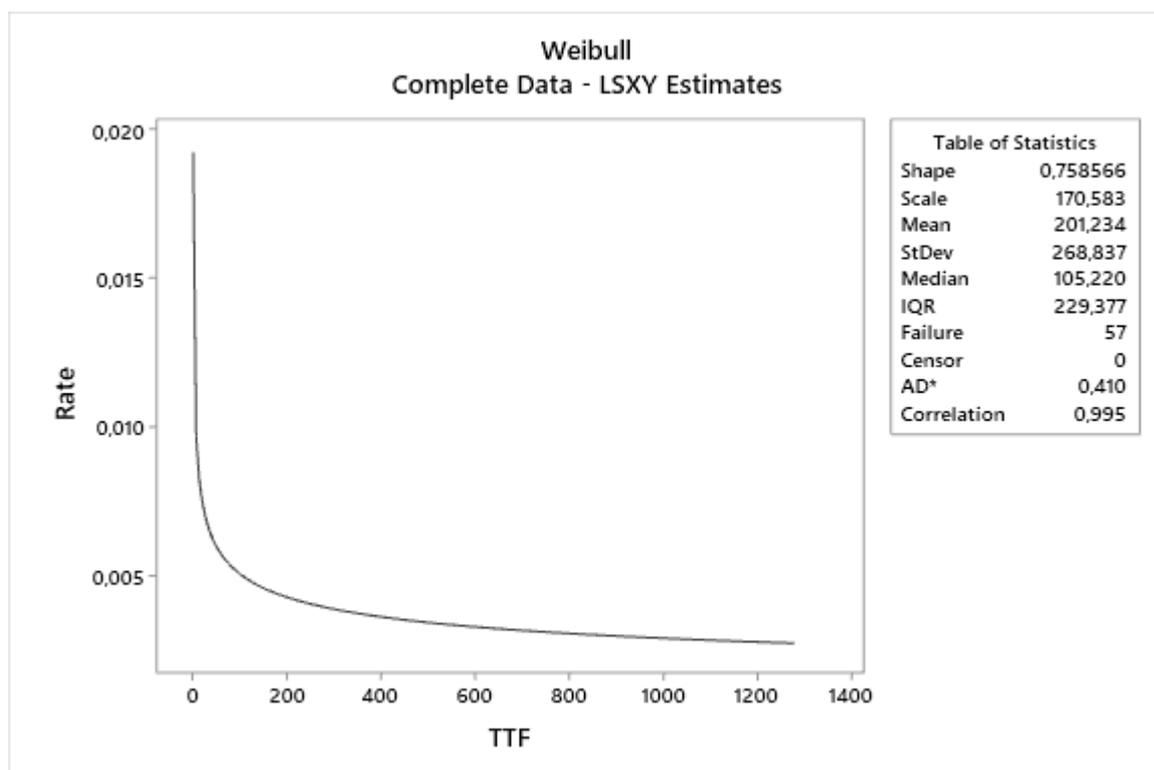
Based on Equation 5 and the distribution parameters calculated with the support of the software and which are shown in Table 3, the failure rate function is described by Equation 6 below:

$$h(t) = \frac{0.758566}{170.583} \left(\frac{t}{170.583} \right)^{0.758566-1} \quad (6)$$

Figure 5 below graphically represents the risk function $h(t)$ expressed by Equation 6:

Figure 5

Hazard plot for TTF



Source: Authors (2020).

Based on the graphical analysis of Figure 5, it is possible to notice that initially the failure rate is high, which decreases over time. This behavior can be explained by the relationship between the beta parameter and the form of the hazard function. When $\beta < 1$, $h(t)$ is decreasing (Fogliatto & Ribeiro, 2009). The direct implication of the decreasing risk function is that, throughout the life cycle of the system under analysis, failures are more likely to occur at the beginning of the operating time (Kızılersü,



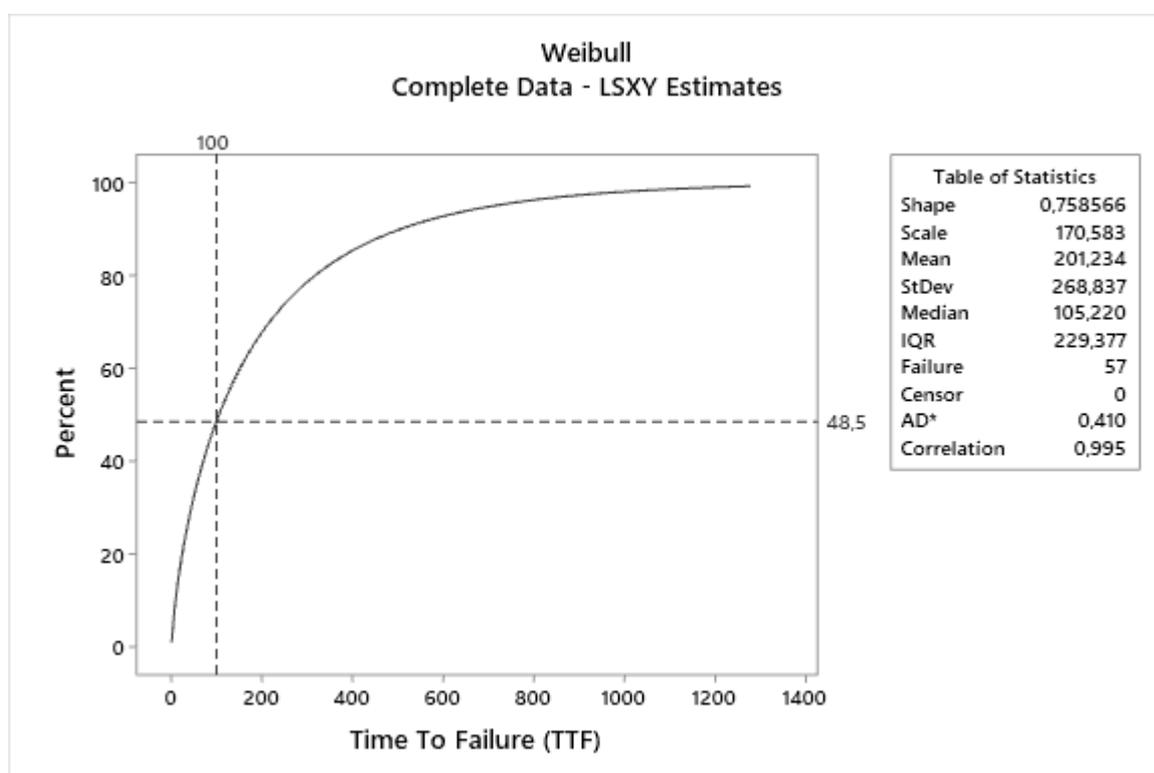
Kreer, & Thomas, 2018). So that, it can be ratified the recommendation suggested by the survival plot analysis of a systematic preventive maintenance based on 100h cycle.

4.2.4 Cumulative failure plot

Finally, based on the reliability representations described above, Minitab® was used to generate the accumulated failure graph for the extruder under analysis, which is represented in Figure 6, below:

Figure 6

Cumulative failure plot for TTF



Source: Authors (2020).

The representation of accumulated failures allows to obtain information of accumulated percentage of occurrences at a time of interest t . In the study, this graphic therefore informs the cumulative percentage of failures that occur in the extruder over the operating time. The graphical analysis suggests that at the 100h operation time there is a 48.5% percentual of accumulated failure which reinforces the recommendation of systematic preventive maintenance in 100h cycles.

4.2.5 Discussion

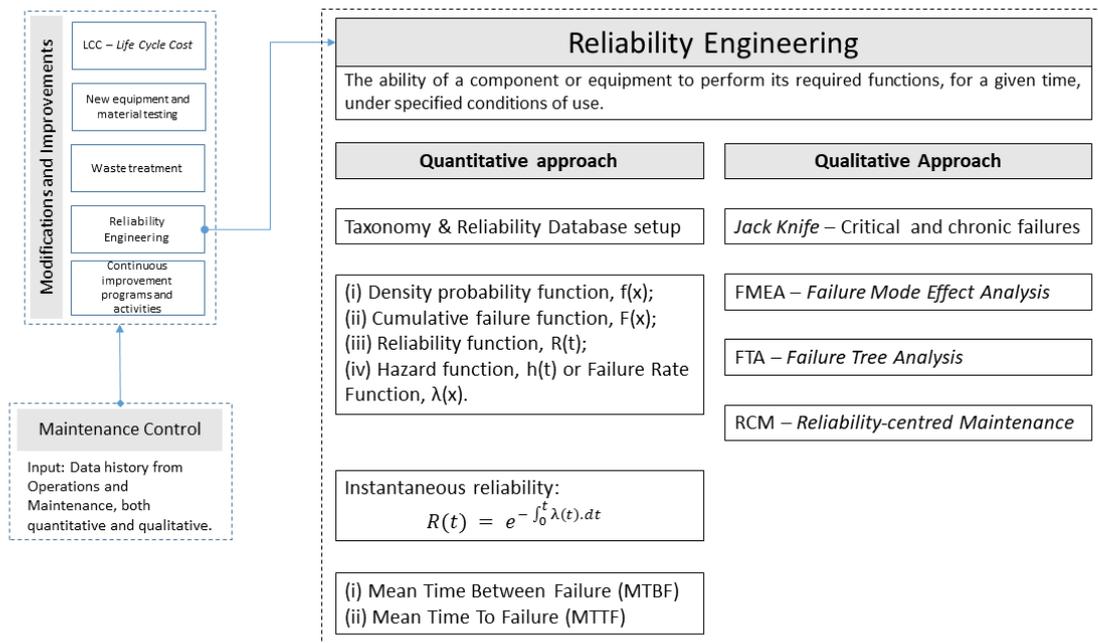
According to Viana (2021), the way in which the components of physical assets fail is the basis of their relationship with reliability, therefore, the study of failure, its modes and causes leads to a reliability engineering, which is able to define better operational controls that provide an increase in performance.

The mathematical representations described above represent behavior models of the studied physical asset, describing its reliability status, as well as being appropriate to propose reflections about the maintenance planning of the machine under analysis, since, through such representations, some observations can be made. This study can also contribute as a bibliographic collection about the application of reliability studies in specific equipment such as the extruder described above.

Viana (2021) proposes an articulation between reliability engineering and maintenance management systems in organizations. Figure 7 illustrates the relationship between the subject and its quantitative and qualitative techniques with the process called "Modifications and Improvements", described by this author.

Figure 7

Linking Reliability Engineering and Maintenance Management



Source: Viana (2021)



It is noted that the data input for the activity development comes from the "Maintenance Control" process, with the calculation of indicators, and also with the availability of raw failure databases. The systems and equipment reliability can be analyzed and improved through the use of tools derived from probability and statistics, supported by reliability engineering.

This paper observes and uses data from the operation by processing them through the techniques established in reliability engineering producing not only the learning of the application of such tools, but also the development of a model of the equipment's behavior, which is capable of subsidizing the development of improvements both in the process and in its applied technical context.

An equipment failure can be defined by the moment that a system fails to perform one of its required functions (Viana, 2021). In this view, it is observed in the found models that under the machine's current operating conditions there is a 50% chance that the extruder will not fail in the interval (0,100) and is still operating in the time 100h, as evidenced through the reliability curve of the system. The reduction by half of the extruder reliability measure in this operating interval reveals a need for systematic preventive maintenance of 100h cycles.

Such recommendation is also supported by the asset's characteristic life, represented by the estimate of the distribution scale parameter since, in this study, as $\theta \cong 170$ it is possible to affirm that 63.2% of failures occur between the interval (0, 170). In addition, the Weibull's shape estimate $\beta = 0.758566$, indicates probable causes of failures, as pointed out by Mendes et al (2014), namely: (i) improper material or operation, (ii) equipment under adjustment or at the beginning of the life cycle or (iii) even operational error due to human failure.

Hence, future investigations about this equipment are directed, in the probable behavior of its characteristic life, as also, in subjective causes linked to the managerial practices applied in the processes of the Maintenance Function, establishing metrics capable of elevating the discussions from a mere accountability of people, to a propositional posture about the processes and routines that support the attendance to the technical demands of the equipment.

It is noted that this paper opens up a line of thought centered on reliability, grounded by the investigative and analytical efforts of the company on a technical basis, thus generating an increase in the debate level for problem solving and decision making, also leading to efforts directed to the expansion of this behavior by encouraging the further investigation into the use of qualitative reliability tools, such as FMEA, which is capable of qualifying the causes of failures that generate the behavior presented in the found models.

Thus, our work mathematically points out the equipment's behavior, as well as indicates paths for future investigations that qualify their causes, and especially, contributes to the organization by strengthening the corporate culture to perceive the value in a reliability centered maintenance.

5 CONCLUSION

Based on the above, this research has outlined the status of the extruder studied in terms of functions and typical graphical representations of reliability analysis. Thus, it is possible to state that the objective was successfully achieved, since all the reliability representations of interest were defined based on time to failure.

In view of the evidence manifested by this mathematical approach, it is suggested to conduct in-depth studies to investigate the systematic preventive maintenance schedule, such as a failure modes and effects analysis (FMEA) studies capable of defining the scope of the maintenance analysis. At a practical level, the mathematical representations calculated in this study are able to support the FMEA technique in relation to the scale construction of the indicator "Occurrence", expressed as a formula based on the component failure rate.

In the theoretical sphere, this article reiterates scientific statements from the maintenance management field by confirming relationships between the estimated parameters of the Weibull distribution and the behavior of the extruder's failure occurrences, which in turn allowed for the elaboration of recommendations that are in fact adequate to the machine's operational reality.

In the social field, the mathematical approach presented provides a scientifically based mechanism by which the organization is able to optimize machine utilization. As a result, with improved operations performance, end-customer expectations regarding lead time and product quality can be met more effectively. Finally, the methodological description of the analysis conducted by this paper and the clarification of the mainly reliability representations through a case study could be seen as a potential didactic tool.

It is perceived the need for articulation between quantitative and qualitative methods for a better decision making about physical assets, as seen, the observations about the parameters beta and theta associated with qualitative investigations via FMEA contributes to the exploratory process about causes, configuring itself as a combining techniques approach that can contribute to various problems found in capital-intensive manufacturing environments.

As a limitation, it is important to point out that our interpretations about the nature of data censorship and the resulting simplifications can have a direct impact on the behavior of variables from the analytical point of view.

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