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The implementation of a calibration plan of instruments in a metrological laboratory

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ABSTRACT

It is noticeable the importance of calibrating measuring instruments, as this process seeks to ensure metrological reliability. Therefore, it becomes possible to verify if the instruments present consistent results. This way, the metrological laboratory needs to keep its equipment calibrated, aiming to offer a satisfactory service to its customers. As the periodicity of instrument calibration is variable, i.e., they have different periods, due to the fact that this time depends on the usage frequency of the equipment, its manufacturing nature, the quality of its material, the environment in which it is being submitted, among other factors. This period variability leads to problems in the quality of the provided services, increase the costs in the logistics sector, in addition to causing managerial difficulties. For this reason, a calibration plan was presented, based on historical data of standard unavailability, aiming to estimate fixed calibration periods and, consequently, mitigate the observed problems.

Keywords: metrological reliability, calibration plan, standard unavailability.

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1. INTRODUCTION

Currently, the importance of measurement in all levels of society is visible, both regarding industrial activities and activities related to daily life, as it is used in processes of quality assurance for products, in the comparison of equipment performance, to define manufacturing specifications, among other uses.

As such, it becomes essential to utilize instruments which can guarantee accurate measurement results that present acceptable values within a certain confidence level.

One of the most common ways of checking if a piece of measurement equipment presents reliable readings is through calibration, which, according to the International Vocabulary of Metrology [1], consists in a process that seeks to define error and inconsistency of a certain equipment in various aspects though a comparison between the measured values and the standard indications under specific conditions, associating sources of uncertainty and establishing relations between the equipment being calibrated and the reference standard.

In other words, it is a process in which occurs a comparison between a laboratory standard and whichever equipment from a client is submitted to calibration. Therefore, a very precise and traceable instrument is compared to an instrument chosen to have its performance checked through calculated parameters.

The laboratory reference standards calibrate clients' measuring instruments, which, on their turn, can calibrate other devices. Thus, it becomes a metrological traceable chain, which according to Santana et al. [2], is a property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty, working in a similar fashion to a pyramid, in which equipments from a higher level in this structure serve as standards and calibrate the ones from the lower levels, and each calibration contributes to the measurement uncertainty.

Thus, this article presents studies performed in a company located in Recife-PE, which has a calibration laboratory in possession of a series of standards used in the calibration of equipments of various units, such as: temperature, pressure, acoustic, and electrical. These standards also need to be calibrated and have different periodicities regarding when they need to be submitted to the process of calibration, for each ideal timing depends on factors as usage frequency, device maintenance, environmental conditions they are exposed to, among others.

This time variation in calibration for each standard of the laboratory causes problems due to the lack of control of available pieces of equipment. Therefore, clients can become unsatisfied for not having the deadlines for these processes met, besides having to perform frequent verifications about the instruments' conditions.

Because these are high precision standards, there are no other laboratories in the nearby region capable of performing their calibration, causing logistic difficulties. Besides, the company has multiple branches and therefore needs to send standards to each of them. All of these factors cause delays in meeting their demand, equipment unavailability, and troubles for the technical management of the laboratory for disrupting planning and scheduling of activities.

Considering this situation, a calibration plan was proposed to them in order to help the laboratories of this calibration company to define a more assertive timing for the calibration of their standards. This plan is based in statistical studies about historical data which enables the asserting of the most adequate period for calibration within the conditions and limitations of this study to submit an instrument to calibration.

This article presents a methodology which, according to the characteristics and models of the instruments used, statistically relate a goodness-of-fit test and linearization of density function to define the calibration plan for the instruments.

2. CALIBRATION AND ITS PROCEDURES

Upon receiving a device for calibration, the first step to be taken is to clean the instrument, removing any impurities and old calibration seals, and also to perform primary tests.

Depending on the type of reading of the instrument, it is necessary to observe if it is operating within normal rates and if it needs any maintenance according to the device's instruction manual.

In order to obtain relevant readings for the process, it is necessary to submit the measurement instruments to specific conditions of: temperature, humidity, lighting, and background radiation for nuclear devices.

After collecting these readings, these values are worked through statistical studies which generate a calibration certificate containing data referring to the place the calibration was performed, a description of the standard used in the process, and the environmental conditions.

The most important information obtained from the calibration results are the error and uncertainty values of the measurement, so that the client is able to observe if these results are within the acceptance criteria defined by themselves.

If a result shown does not satisfy the criteria established by the client, they may ask for an adjustment to achieve better results or chose not to use the device anymore.

According to Lima [3], the measurement error is calculated through the difference between the true value and the value found in the measurement process, thus allowing one to verify how distant these values are.

As for the measurement uncertainty, it is a parameter that allows the quantification of the interval in which the true value may be within a confidence level. For this estimate, diverse factors that can interfere in the final result are considered, such as: environmental conditions, usage frequency, standard uncertainty, uncertainty from the instrument being calibrated, reading repeatability, among other aspects.

Measurement uncertainties can be classified in two types: A and B.

Type A uncertainties are based in statistical methods, involving a series of readings considering the repeatability of measurements.

Differently from type A uncertainties, type B uncertainties involve data which does not depend on the readings performed during the calibration itself, but on data from the nature of the instrument's standard, the instrument's deviation through time, instability, resolution, among others.

According to Donatelli et al. [4], type A uncertainties can be estimated through statistical analysis of a set of experimental results, while type B uncertainties can be obtained through other means.

3. GOODNESS-OF-FIT TEST

According to Ferreira et al. [5], goodness-of-fit tests are statistical methods used to measure if a certain population adjusts to a random variable. They can also be used to verify if the behavior of this population is similar to a certain known probability distribution, such as exponential, normal, log-normal, Weibull, etc. Being so, it becomes possible to estimate certain parameters, such as: mean time between downtimes for maintenance or calibration, repairing time, availability, among others.

For Bussab and Moretin [6], these tests are useful to verify if a determined random sample can originate from a specific population or probability distribution through the comparison of the sampling distribution to the considered distribution. The most known and used tests of this kind are the chi-square test and the Kolmorov-Smirnov test.

By selecting the set of collected samples referring to the historical data of the instrument and linearizing the density function to a certain probability distribution, the goodness-of-fit test is applied to measure the quality of the fit, by comparing the collected data to the distribution parameters in question in order to verify if the chosen distribution is adequate.

According to Degroot [7], these tests are a particularity of hypothesis tests in which two possibilities exist: the null hypothesis states that the population follows a determined distribution, while the alternative hypothesis proposes the opposite.

Consequently, the chosen hypothesis will depend upon the proposed conditions and which one of them followed the established restrictions. Table 1 presents the steps taken to perform the goodness-of-fit tests.

Table 1: *Steps of the goodness-of-fit tests.*

1st step	Graph analysis, standards recognition
2nd step	Model selection
3rd step	Parameters estimating
4th step	Adjust quality measuring

4. PROBABILITY DENSITY FUNCTION LINEARIZATION

Aiming to verify if the population obeys a behavior similar to a determined probability model, linearization is performed, a process in which graphs are made using graph paper or mathematical softwares, with the objective of transforming the unknown curve into a line and allowing one to check if that set of points approaches the behavior of a known distribution.

The first step to be taken is to write down the collected times in crescent order and to attribute a value (i) for each point. Next, using Bernard and Bos-Levenbach's approximation [8] to estimate the cumulative distribution, the rank is calculated through Equation 1, presented as follows:

$$Rank = [(i - 0.3) / (n + 0.4)] * 100 \tag{1}$$

In which:

Rank: rank considered to build the graphs;

I: value attributed to the time order, distributed in crescent order starting at 1;

N: sample size;

Observation: the values of 0.3 and 0.4 are the constants used by the method.

For each probability distribution the axes x and y were calculated, allowing us to build the graphs and to obtain parameters which will serve as base to estimate the indicator guiding the proposed calibration plan.

According to Vaccaro [9], when building graphs for each probability distribution studied, the axes will be obtained through the collected times and rank estimator of each instrument, as determined by equation 1.

For some distributions it is necessary to use the natural logarithm, shown in Table 2, which also presents the formulas for calculating the parameters of population mean (μ) and population standard deviation (σ) for normal and log-normal distributions.

In the exponential distribution a parameter λ is calculated to represent the variable's coefficient in the linear regression with the minus sign added to it. As for the Weibull distribution, there are the parameters β and η, which are also calculated through the coefficient. Table 2 presents all the axes and parameters of the probability distributions used in this study.

Table 2: *Axes and parameters of the probability distributions.*

Probability Distribution	Axes and Parameters
Normal	*Axis (X) = time* *Axis (Y) = rank (n)* μ *= mean (t)* σ *= deviation (t)*
Log-normal	*Axis (X) = LN (time)* *Axis (Y) = rank (n)* μ *= mean ln (t)* σ *= deviation ln (t)*
Exponential	*Axis (X) = (time)* *Axis (Y) =* $ln(1 - rank_n)$ $\lambda = -(X1)$
Weibull	*Axis (X) = LN (time)* *Axis (Y) =* $LN(-LN(1 - rank_n))$ $\beta = (X1)$ $\eta = exp^{(-(\text{int er sec ao}) / \beta)}$

5. MEAN TIME BETWEEN FAILURE

As Fogliatto [10] says, this indicator is rather important in the context of maintenance, since it is directly connected to the reliability of the equipment. It serves as a guide for preventive maintenance plans since it determines the frequency which instruments should be submitted to activities of maintenance, repair, calibration, among others.

Through studies and data collection from the pieces of equipment it becomes possible to calculate the MTFB for each instrument, but each calculation is modified to each distribution.

In the considered distributions for this study, the parameters already calculated in the axes presented in Table 2 were used.

However, for the Weibull distribution, the Gamma function is used, which according to Reyes [11] is estimated through the calculation presented in the Table 3 shown next:

Table 3: *MTBF for each probability distribution.*

Probability Distribution	Mean Time Between Failure
Normal	$MTBF = \mu$
Log-normal	$MTBF = e^{(\mu + \frac{\sigma^2}{2})}$
Exponential	$MTBF = 1/\lambda$
Weibull	$\alpha\Gamma(1+1/\beta) = MTBF$ with $\alpha = [\frac{\sum_{i=1}^{n} t_i^{\beta}}{n}]^{\frac{1}{\beta}}$ and $\Gamma(x) = \frac{x^{x-\frac{1}{2}}}{e^x}[\frac{0.2119184}{x^{1.00357}} + 2.5066283]$

6. METHOD

The methodology adopted to perform this study was based on historical data from the pieces of equipment regarding the dates they became unavailable for use due to lack of calibration in a metrological laboratory.

Having such data, the probability density function linearization was found for each set of times the equipment became unavailable for use due to the need of calibration, of the need for maintenance, for being in another place, etc.

Four types of distribution were taken into consideration for the analysis: normal, log-normal, exponential, and Weibull. Next, the graphs for the behavior of each standard for each probability distribution were build, in order to estimate the parameters and to obtain the resulting correlation coefficients.

To facilitate the building of graphs and the data's linear regression, and to observe which was the best model for the behavior of each standard, the software Excel was used to help making the statistical calculations needed to develop the process.

Thus, it was possible to verify which distribution was more adequate to the set of times of each standard, to calculate the MTBF for each instrument, and to develop the calibration plan.

In face of the elaborated calibration plan for the five standards of the metrological laboratory, a discussion about its viability took place, considering the positive and negative aspects pointed by the company's managers.

After being approved, it was put in place and consequently it brought meaningful results to the laboratory.

7. RESULTS AND DISCUSSION

In order to organize the data collected for this study, Table 4 shows the times each standard was available until the moment it needed to be calibrated.

These values were put in crescent order and the times converted to years to facilitate the application of the methods seeking to discover which distribution resembles the standard's behavior the most.

Table 4: Calibration periods of each standard in crescent order (years).

Standard/Calib.	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**
Standard 1	0.1	0.8	1.5	1.6	1.7	2.8	3.1	3.3	-
Standard 2	0.3	0.7	1.0	1.3	5.2	5.6	-	-	-
Standard 3	0.8	1.1	1.5	1.5	1.9	2.0	2.8	3.1	3.2
Standard 4	0.1	0.5	0.6	2.4	3.1	3.5	4.2	4.3	-
Standard 5	0.3	0.5	0.8	0.8	1.5	1.6	1.7	2.2	2.6

Standard 1, for example, has been through 8 calibrations since its acquisition, and has its periods represented in the first row of Table 4. These are the intervals in which it was able to be used to the moment of its downtime for calibration.

The ordering of times and classification by the indicator from Equation 1, and the calculation of the axes and parameters used in the building of the graphs for each distribution were shown in Table 2.

For each graph a linear regression to 95% of confidence level was found. Next, in order to conclude which distribution best adjusts to the data set, the correlation coefficients were analyzed.

The closer to 1 the value is, the more goodness of fit the set of times has to the distribution. For standard 1, the correlation coefficient (multiple R) which came closer to 1 was the one from normal distribution. The found values are shown in Table 5.

Table 5: *Parameters used for building the graph of normal distribution of standard 1.*

i	*time*	*Rank*	*Axis (x)*	*Axis (y)* %
1	0.1	0.0833	0.1	8.33
2	0.8	0.2024	0.8	20.24
3	1.5	0.3214	1.5	32.14
4	1.6	0.4405	1.6	44.05
5	1.7	0.5595	1.7	55.95
6	2.8	0.6786	2.8	67.86
7	3.1	0.7976	3.1	79.76
8	3.3	0.9167	3.3	91.67

Figure 1 shows the behavior of standard 1 in normal distribution with standard deviation being approximately 1.13 and correlation coefficient at about 0.98, which highlights its closeness to the line.

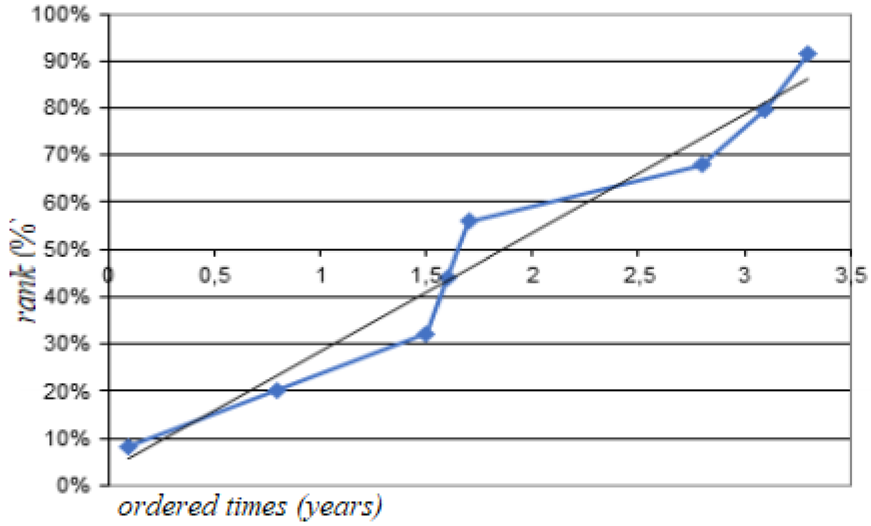

Figure 1: *Normal distribution: Standard 1.*

Similarly, the calculation process was repeated for the 5 standards from the laboratory, and the probability distributions which better adjusted to its calibration times were chosen. This made possible to discover each MTBF. This indicator guides the study to define a calibration plan by estimating a mean time in which the equipment needs to be calibrated. Table 6 shows which distribution was chosen for each standard as well as its MTBF, calculated according to the parameters of its model.

Table 6: *Probability distribution and MTBF for each equipment.*

Equipment	Distribution	MTBF (years)
Standard 1	Normal	1.86
Standard 2	Log-normal	2.74
Standard 3	Weibull	2.01
Standard 4	Normal	2.34
Standard 5	Weibull	1.39

A calibration plan for this case study was made from the calculated indicators which stipulate the periodicity each standard shall need a calibration, as shown on Table 7.

Table 7: *Calibration Plan.*

Equipment (measurement instrument of the laboratory)	Periodicity to be submitted to calibration
Standard 1	1 year and 10 months
Standard 2	2 years and 9 months
Standard 3	2 years and 1 month
Standard 4	2 years and 4 months
Standard 5	1 year and 5 months

8. CONCLUSIONS

According to the data verified, it was possible to attest the applicability of this study, since it allows the implementation of a calibration plan for the metrological instruments of a laboratory. The study proposed the definition of determined periods to submit the pieces of equipment to calibration, and resulted in the mitigation of negative impacts due to the unavailability of measurement devices due to the need of calibration. Thus, the improvements obtained through this plan’s implementation are presented as follows, according to the company’s areas:

a) Financial - reduction of costs with calibration due to a greater level of control regarding when to submit an instrument to calibration. Services required were better scheduled, consequently avoiding the need of taking place in a short period of time and making it possible negotiate a decrease in prices. It was also possible to strike deals with the service providers to send the instruments in pre-defined periods which allowed a discount for other services;

b) Logistics - as the pieces of equipment dealt with are high precision devices, the company has the habit of sending a representative to the destination of the reference standards. Thus, by implementing the calibration plan, it was possible to better plan the trips taken by the representatives, which caused a more assertive scheduling of trips and a reduction in their costs, in comparison to the previously trips taken which were unplanned due to the lack of control of calibration times;

c) Quality - there was a reduction in cases a client’s demand was met past the established deadline due to unavailability of equipment. There was an improvement in scheduling the activities in order to meet the contracted services;

d) Management - the plan facilitated the planning of activities for the working team, because it made possible to check which services were priorities and which pieces of equipment could be sent to the external units for not being in the use schedule. Besides, there was a higher level of control of the instruments which were able to be used.

As so, there was an increase in productivity for the laboratory through the implementation of the calibration plan based in preventive times. It is worth mentioning that the more samples are collected through the following years, the more meaningful the results for the company will be.

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