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Application of statistical control chart X-Rm for monitoring the water vapor pressure in a thermoelectric power plant

Aplicación de la carta de control estadístico X-Rm para monitorear la presión de vapor agua en una planta termoeléctrica

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ABSTRACT

The principles of the statistical control chart are satisfactory for identifying situations where assignable causes may be adversely affecting the quality of a process or product. The purpose of this research was designing a control chart for monitoring the water vapor pressure (Pv) in the outlet stream of a vapor generator in a thermoelectric power plant. Moving range control chart (X-Rm) was selected, this included 1595 measurements coming from a normal distribution. The Center Line was 13,33 MPa, Lower Control Limit 13,22 MPa and Upper Control Limit 13,44 MPa. Non-random variation patterns were identified such as downward and upward trend, downward and upward shift, and data stratification; possibly due to general causes: little standardization, mismatches and gradual deterioration of equipment, instruments and accessories, and deposition of waste. This project is expected to contribute to the proper use of the installed thermal power capacity.

Keywords: control chart; normality; thermoelectric; vapor pressure.

RESUMEN

Los principios de la carta de control estadístico son satisfactorios para identificar situaciones donde las causas asignables pueden estar afectando de manera adversa la calidad de un proceso o producto. El propósito de esta investigación fue diseñar una carta de control para monitorear la presión de vapor (Pv) de agua en la corriente de salida del generador de vapor de una planta termoeléctrica. Se seleccionó una carta de mediciones individuales y rangos móviles (X-Rm). Las mediciones se tomaron directamente del sistema de supervisión y control (SCADA) en línea, para un total de 1595 puntos individuales que procedieron de una distribución normal. La Línea Central resultó 13,33 MPa, el Límite de Control Inferior 13,22 MPa y Límite de Control Superior 13,44 MPa. Se identificaron patrones de variación no aleatorios de la Pv como tendencia ascendente y descendente, cambio de nivel y estratificación; debido posiblemente a las causas generales: poca estandarización, desajustes y el deterioro gradual del equipo, instrumentos y accesorios, y la deposición de residuos. Se espera que el trabajo contribuya al adecuado aprovechamiento de la capacidad térmica instalada.

Palabras clave: carta de control, normalidad, termoeléctrica, presión de vapor.

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Introduction

Thermal power plants (TPP) are an important component of fossil fuel-based electricity generation worldwide[(1)]. Efficient use of installed capacity has a significant impact on both the development of nations and the generation of global CO_2 emissions. Combustion of upgraded crude oil with high sulfur and asphaltene content increases maintenance cycles in TPP due to the formation of deposits, slags and corrosive compounds.[(2)]

In light of this situation, the principles of the statistical control chart are satisfactory for identifying situations where assignable causes may be adversely affecting the quality of a process or product[(3, 4)]. The unusual power losses through an electrical power transmission and distribution system were detected using an individuals and moving range chart (X-MR)[5]. The X-MR chart was also used in the control system of the combustion process and protection against explosions[6]. A monitoring scheme based on energy profiles generated from wavelet spectrum analysis in a multivariate T^2-control chart was proposed to detect the abnormality of temperature signals measured from a steam turbine generator.[7]

Predictive maintenance techniques[8] are extensively applied to the decision-making process in thermoelectric power plants, based on control charts and mathematical-statistical modeling. A chart of means and standard deviation (X-S), the Nelson´s run rules and statistical modeling were used to analyze the operation of an internal combustion engine[9, 10, 11]. For a coal-grinding subsystem, the outputs of T^2-control charts for hidden Markov model were applied [12]. Likewise, the X-bar control charts, Long Short Term Memory Model (LSTM) based Useful Remaining Life (URL) were used for generator electrical.[13]

The control chart represents the distribution of measurements in an ordered time sequence, the mean value using a Central Line (CL), the Lower Control Limit (LCL) and Upper Control Limit (UCL). The limits identify the range of variation of the quality characteristic, such that there is a high probability that the data are within the limits and the process is under statistical control.

A process under control means that it is operating stably and is predictable over time. This can be seen on the control chart when the points fall within the limits, with a tendency towards the central line, and present a random variation (erratic or without order) across the chart due to common-causes variation. Even so, it may happen that the process does not satisfy the design tolerances, because the limits are determined from the variation of the statistic represented on the chart.[3, 4, 14]

On the other hand, individual points may follow non-random behavior due to special-causes variation (attributable or assignable causes) for example: points beyond the control limits, downward-trend pattern, upward-trend, downward shift, upward shift, cyclic, systematic and stratification pattern. These causes can be eliminated or minimized once appropriate actions are taken[14, 15, 16]. Automatic control chart pattern recognition is known as an important research area. Methods such as convolutional neural network and information fusion[15], multiclass support vector machine and genetic algorithm[17], and locally linear embedding algorithm are used.[18]

Electricity generation in TPP consists of the production of high-enthalpy steam in steam generators from the combustion of oil. In the fixed blades of the turbine, steam's thermal energy is transformed into kinetic energy, and in the moving blades, into the mechanical energy of the rotor. Finally, the transformation into electrical energy takes place in the electric generator.

Based on Rankine cycle analysis, the thermal efficiency during the heat-addition process can be improved by increasing the operating pressure of the boiler, this raises the temperature at which boiling occurs. Furthermore, it is combined with the expansion of the steam in the turbine in two stages, and reheats it in between, so that excess moisture in the final stages of the turbine can be corrected. As a result, the average temperature at which heat is transferred to the steam increases.[19]

The purpose of this work was to design the statistical control chart for monitoring the water vapor pressure at the steam generator outlet in a thermoelectric power plant. In addition, variation pattern on the control charts and the possible assignable causes were identified.

Materials and methods

The research was carried out using the following steps.

a) Choose the appropriate metrics

The quality characteristic must meaningfully reflect the process being evaluated.

b) Select the control chart

The control chart is selected based on the quality characteristics. These characteristics are generally classified into two categories, by variables and attributes.[3, 4, 14, 16]

c) Sampling and data collection

The sample size was determined to estimate a mean (1).

$$n = \left[\frac{Z \cdot \sigma(x)}{\frac{\sigma(x)}{\sqrt{n}}} \right]^2 = \left[\frac{Z \cdot \sigma(x)}{e} \right]^2 \qquad (1)$$

Where, Z=1.96 for a 95% confidence level, two-sided test. Assuming a standard deviation σ(x) = 0.041, error or precision e = 0.002, the size of 1537 measurements is obtained.

Data was taken every two hours during eight months of operations from Supervisory Control and Data Acquisition (SCADA) System applied in the power generation block.

d) Determination of control limits

Control limits of an individuals and moving range (X-MR) chart are determined from the average, mean range and standard deviation. [3, 14]

For a process under control (2-4):

$$\bar{X} = \mu = \frac{\sum_{i=1}^{n} X_i}{n} \quad (2)$$

$$Rm = [X_i - X_{i-1}] \quad (3)$$

$$\overline{Rm} = \frac{\sum_{i=1}^{n} Rm_i}{n} \quad (4)$$

The control limits result (5-8):

$$LCI = \mu - k\,\frac{\bar{R}m}{d_2} \quad (5)$$

$$LC = \mu \quad (6)$$

$$LCS = \mu + k\,\frac{\bar{R}m}{d_2} \quad (7)$$

$$\sigma(X) = \frac{\bar{R}m}{d_2} \quad (8)$$

where, the random variable is X, measurement (i) is X_i, sample size (n), average of the measurements ($\bar{x}$), mean value (μ), moving range of order two (R_m), mean moving range (Řm), lower control limit (LCL), upper control limit (UCL), and the constants are d_2=1.128, k [1, 2, 3].

The k=3 limits structure, from the hypothesis testing point of view, represents a probability of 0.0026 that X-value falls beyond the control limits given that the process is in control, and that the analyst erroneously determines that the process is out-of-control. [4]

e) Recalculation of control limits

If at least one measurement point falls beyond the control limits on the control chart, the assignable cause must be determined. New limits are then calculated after removing the corresponding sample from the data set. It may even happen that one or more points fall beyond the new limits, in which case the removal and recalculation process is repeated. [3]

f) Checking control chart assumptions

Control chart is based on the assumption of normality of measurements. Analytical checking of normal distribution is performed using several tests, including: Chi-Square, Kolmogorov-Smirnov, Kuiper V, Cramer-Von Mises W^2, Watson U^2 and Anderson-Darling A^2. [3, 20, 21]

g) Quality characteristic monitoring and recognizing control chart patterns

Once the control chart has been designed, the next step is to judge whether the process is in control or not, which presupposes the collection of new measurements. This involves identifying points beyond the control limits, variation patterns (non-random behavior) within the limits and analyzing special-causes variation [15, 17, 18, 22]. Nelson's run rules were applied for recognizing control chart patterns, these are a set of eight rules (R1 - R8) concerning to variation patterns within six different zones on the control chart. [5, 9, 10, 14, 23]

A software application for recognizing control chart patterns was developed, which consist of shape features and statistical features (mean, standard deviation, determination coefficient of the least-square line, positive and negative deviation from the cumulative average of up to three previous points). Special points contributing to Nelson's run rules were re-examined to avoid double counting. Then, the instability index (S) was calculated as the quotient between the number of points indicating the occurrence of a special cause variation and the number of points represented in the same period. [14]

Results and discussion

Water vapor pressure (Pv, MPa) values were obtained every two hours for eight months from the SCADA real-time database. Control limits were determined after gradually separating the most dispersed points beyond the control limits (or assignable causes). Each month was analyzed individually and the limits were compared with the entire universe of samples. Two months were excluded from the data set because these affected the normality assumptions. The control chart finally consisted of 1595 measurements, standard deviation 0.041 MPa and mean range 0.036 MPa (figure 1).

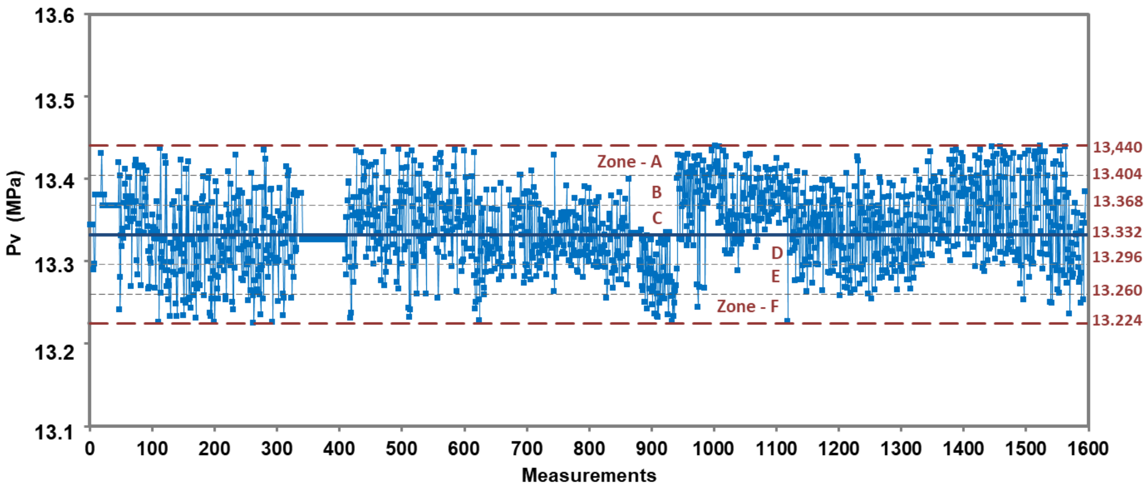

Fig. 1 – Statistical control chart of water vapor pressure (Pv)

The vapor pressure (Pv) was distributed for 51.1% of the time above the central line (CL) and 49.7% below CL. In addition, measurements fell for 10.1% within Zone-A, 19.7% Zone-B, 25.5% Zone-C, 25.7% Zone-D, 14.0% Zone-E, 5.0% Zone-F (figure 1).

Checking assumptions of normality

Normality was check by graphical and numerical methods using StatGraphic Centurion v.19.0 (figure 2).

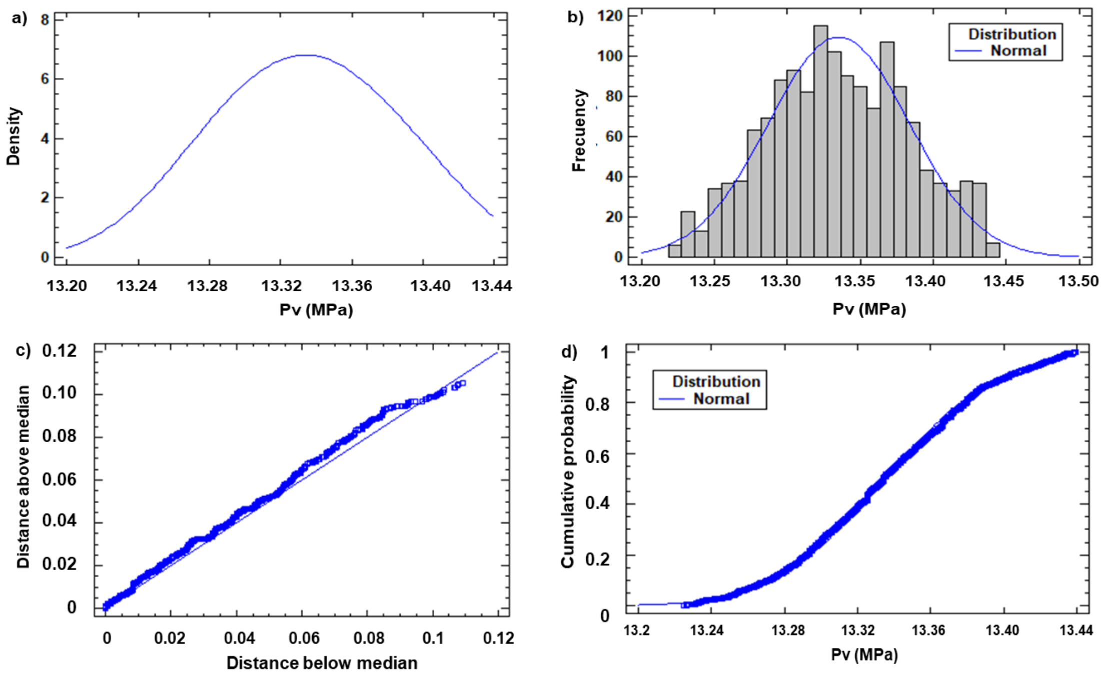

Fig. 2 – Normality check of the water vapor pressure (Pv) statistical control chart, a) Distribution density, b) Frequency histogram, c) Symmetry, d) Cumulative probability

Form figure 2a, density trace shows a shape similar to a Gaussian bell curve with moderate asymmetry. The frequency histogram shows the top of the bars moderately close to the superimposed line for the fitted normal distribution (figure 2b). The data were arranged on the trend line in the symmetry graph, but points positively skewed between 0.06-0.09 can be seen (figure 2c). Furthermore, the points were located on the curve cumulative distribution for the standard normal curve (figure 2d).

As for numerical methods, the vapor pressure can be modeled by normal distribution with 95% confidence according to Kolmogorov-Smirnov, modified Kolmogorov-Smirnov D, Cramer-Von Mises W^2, and Anderson-Darling A^2 tests. However, Kuiper V and Watson U^2 tests were not satisfactory (p-value < 0.01). This could be because of the presence of non-random variation patterns within the limits on the control chart. The standardized Skewness statistic obtained a value of 0.1538 in the expected range [-2; 2]. According to the log likelihood statistic for the comparison of alternative distributions, the normal distribution presented good agreement with dates. As a result, the hypothesis that the sample came from a normal distribution was accepted.

Variation patterns in the control chart

Variation patterns were determined on the control chart such as downward shift and upward shift (R-2), downward and upward trend (R-3), over control (R-4), large shift (R-5) and small shift (R-6), and stratification (R-7) (figure 3).

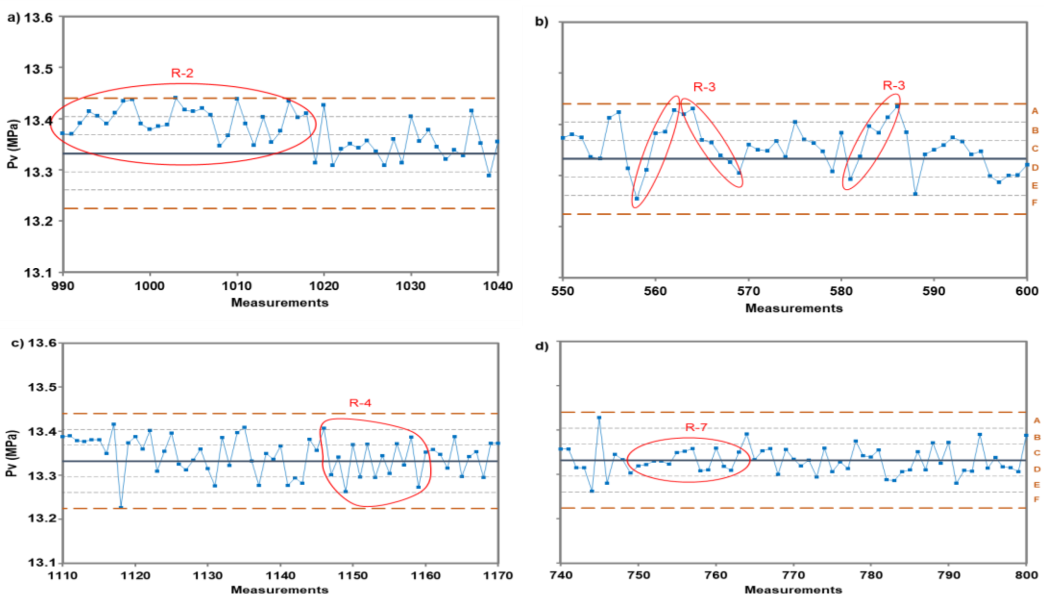

Fig. 3 – Variation patterns on the steam pressure (Pv) control chart, a) upward shift, b) upward and downward trend, c) over control, d) stratification

The patterns showed non-random behavior due to possible special-causes variation such as little standardization (R-2, 7), training, and failures in the industrial network (R-7); mismatches and gradual deterioration of equipment, instruments and accessories (R-2, 3); worker fatigue and deposition of waste (R-3). [15, 23]

Quality characteristic monitoring

Statistical control chart was applied to monitor the water vapor pressure (Pv) for 1162 h consecutive. Pv was distributed for 63.2% of the time above the central line (CL) and 36.8% below LC. The measurements fell for 21.6% within Zone-A, 21.7% Zone-B, 19.9% Zone-C, 27.2% Zone-D, 8.5% Zone-E, 1.1% Zone-F. In addition, the points fell beyond the control limits for 2.1% of the time. Pv measurements tended to span the entire width of the control chart at the end of the period. Then, the proposed limits were accepted as appropriate for monitoring quality characteristics (figure 4).

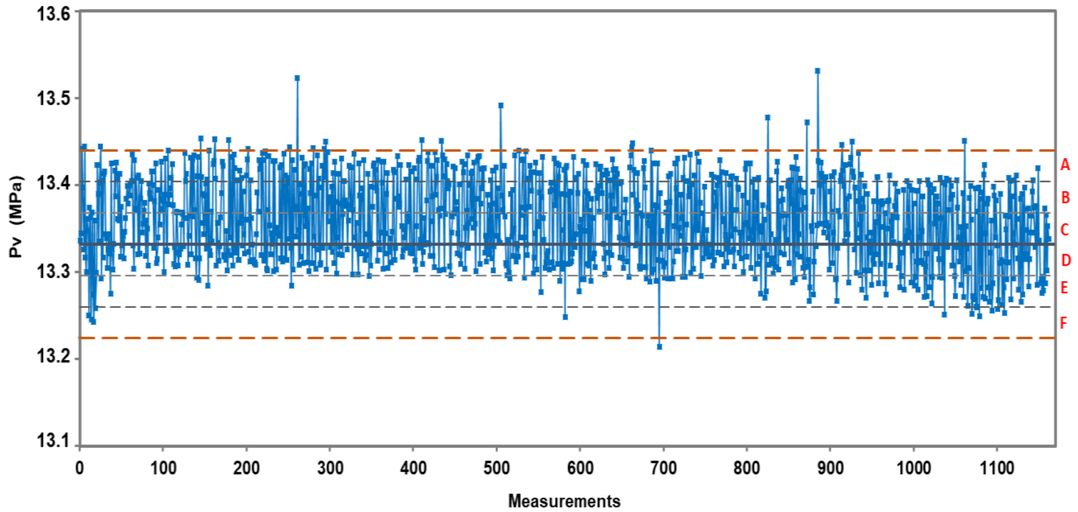

Fig. 4 – Vapor pressure (Pv) monitoring for 1162 h

The process was more stable during the monitoring stage for an instability index (S) of 7,1 %; however, this indicates an out-of-control condition and therefore needs major improvements in operation (table 1).

Table 1- Non-random variation patterns on the steam pressure control chart in monitoring stage

Rules name		Pattern description	Code	SP[b]
R-1	Beyond Limits	One or more points beyond the control limits	Above +3σ	23
			Below -3σ	1
R-2	Shift-trend	9 or more consecutive points on one side of the average.	Above CL[a]	11
			Below CL	0
R-3	Trend	6 or more consecutive points trending up or trending down.	Upward	12
			Downward	4
R-5	Large shift	2 out of 3 consecutive points in Zone A (or F) or beyond	A	31
			F	0
R-6	Small shift	4 out of 5 consecutive points in Zone B (or E) or beyond	B	4
			E	0

[a] CL: Central Line; [b] SP: Special Point

The unnatural pattern large-shift (R-5) presented the highest number of special points due to the possible general causes: incorrect setup, measurement error, overcorrection (figure 5). (15, 17, 23)

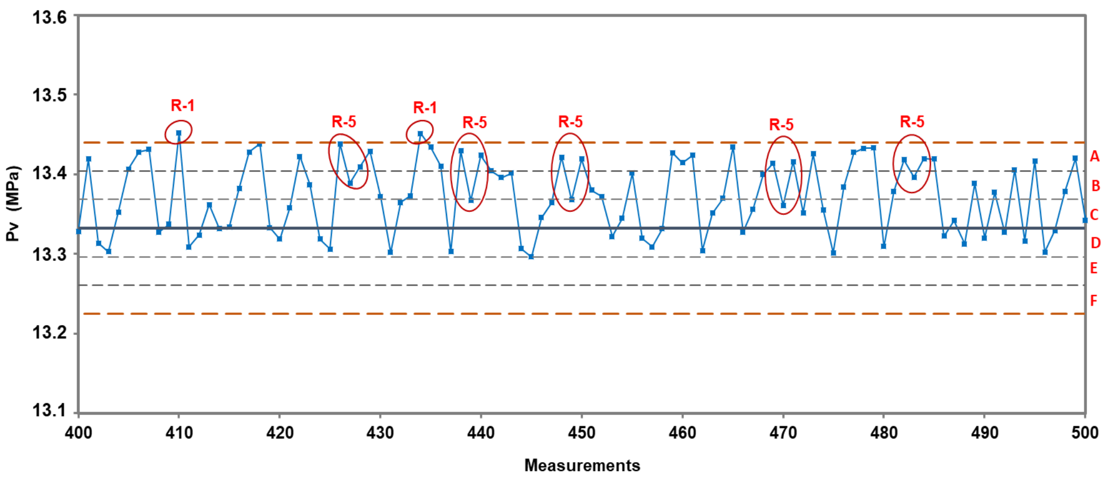

Fig. 5 - Variation patterns on the control chart in monitoring stage

The cumulative stability index (1-S) was determined as a function of the Remaining Useful Life (RUL) in several periods. It is expected that (1-S) tends to one at each instant, which means that the special-causes variation (SP) are minimal or equal to zero (Figure 6a). In addition, the area between the function f(x)=1 and the (1-S) curves was calculated using the definite integral method (Figure 6b).

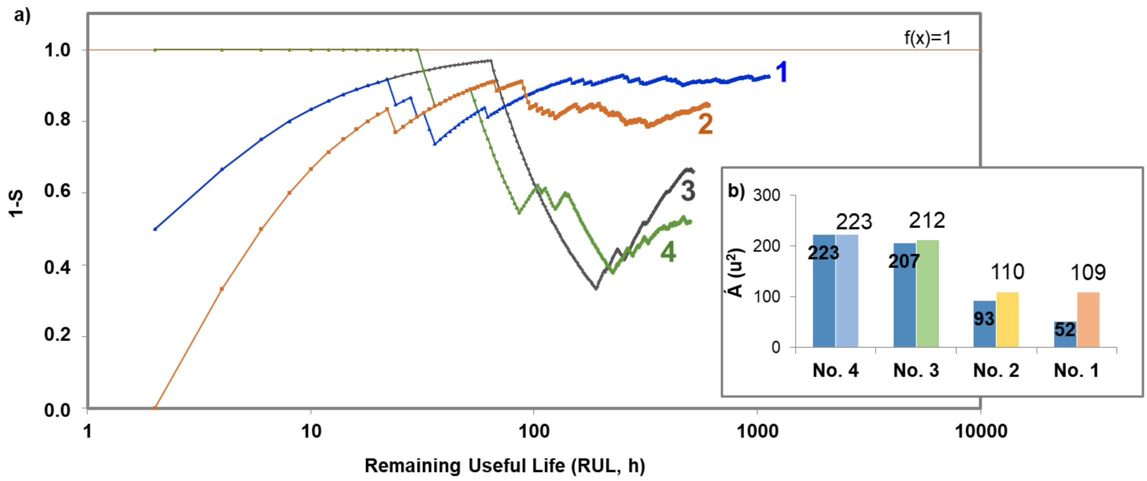

Fig. 6 – a) Cumulative stability index (1-S) *versus* Remaining Useful Life (RUL, h), and b) total area (A, u^2) between f(x)=1 and the curve, corresponding to four periods of operation

From figure 6, after a RUL of 502h, an area of 223 u^2 was determined for the operation period represented by curve No. 4; also, 212 u^2 (No. 3), 93 u^2 (No. 2), and 52 u^2 (No. 1); on the other hand, the operation represented by curve No. 3 was extended to a RUL of 518h and an area of 212 u^2, curve No. 2 with 610h and 52 u^2, and No. 1 with 1196h and 110 u^2. The analysis suggested including new variables, extending the evaluation time, and determining the assignable causes of the behavior in each period, in order to predict the remaining useful life (RUL) and contribute to the improvement of existing predictive maintenance strategies.

This project is expected to contribute to the proper use of installed thermal capacity.

Conclusions

Individuals and moving range (X-MR) chart was designed to monitor water vapor pressure, which included 1595 points, with central line of 13.332 MPa, lower control limit (LCL) of 13.224 MPa, and upper control limit (UCL) of 13.440 MPa.

Non-random variation patterns were determined such as downward and upward trend, downward and upward shift, and data stratification; possibly due to general causes little standardization, misadjustments and gradual deterioration of equipment, instruments and accessories, and deposition of waste.

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Conflict of interest

The authors declare that there are not conflicts of interest.

Authorship contribution

Armando Rojas Vargas**:** conceptualization, methodology, investigation, software, writing–original draft preparation, writing – reviewing and editing.

Luis Manuel Conté Mendoza: conceptualization, investigation, formal analysis, data curation, writing–original draft.

Liudmila Pérez García: conceptualization, investigation, formal analysis, writing–reviewing