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USABILITY OF CONTROL CHARTS TO MONITOR VARIATION OF QUALITY PARAMETERS IN COAL-FIRED THERMAL POWER PLANTS

KÖMÜR YAKITLI TERMİK SANTRALLERDE KALİTE PARAMETRELERİNİN DEĞİŞİMİNİN İZLENMESİ İÇİN KONTROL GRAFİKLERİNİN KULLANILABİLİRLİĞİ

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ABSTRACT

During the production of electrical energy from coal-fired thermal power plants, calorific and unit power values are the most important indicators for evaluating the productivity of the process. These values are measured periodically, and the resulting measurements are monitored to detect root causes of variation that may occur in production process. As this application is currently performed by manual methods, the probability of obtaining incorrect results is quite high. This study aims to statistically analyze process control on the variation of quality parameters and detect root causes of unusual variations using Shewhart and cumulative sum control charts. For this purpose, the usability of these control charts was tested on Afşin-Elbistan B thermal power plant. As a result, these charts identified fluctuations in the efficiency of generating electrical energy and unusual variations in the process. Furthermore, it is recommended that these control charts could be developed and applied in similar type of process.

Anahtar Sözcükler:
Enerji verimliliği,
İstatistiksel proses kontrol,
Kontrol grafikleri,
Kalori değeri,
Ünite gücü.

ÖZ

Kömür yakıtlı termik santrallerden elektrik enerjisi üretimi sırasında prosesin verimliliğini değerlendirmek için kalorifik değer ve birim güç değeri en önemli parametrelerdir. Bu değerler periyodik olarak ölçülür ve ölçüm sonuçları üretim sürecinde ortaya çıkabilecek dalgalanmaların temel nedenlerini tespit etmek için izlenir. Bu uygulama mevcut durumda manuel yöntemlerle gerçekleştirildiğinden, hatalı sonuçların elde edilme olasılığı oldukça yüksektir. Bu çalışma, Shewhart ve kümülatif toplam kontrol grafiklerini kullanarak kalite parametrelerinin değişimi üzerindeki proses kontrolünü istatistiksel olarak analiz etmeyi ve olağandışı dalgalanmaların temel nedenlerini tespit etmeyi amaçlamaktadır. Bu amaçla, bu kontrol grafiklerinin kullanılabilirliği Afşin-Elbistan B termik santrali üzerinde test edilmiştir. Sonuç olarak, bu grafikler kullanılarak elektrik enerjisi üretme verimliliğindeki dalgalanmaları ve süreçteki olağandışı değişimler belirlenmiştir. Ayrıca, bu kontrol grafiklerinin geliştirilmesi ve benzer prosesler için de uygulanması önerilmektedir.

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INTRODUCTION

Monitoring the production process of coal-fired thermal power plants is crucial in many industries. To ensure stable production improving the performance of the process and reducing the variability in critical quality parameters are necessary. Statistical process control (SPC) method has been developed to accomplish this goal. The control charts are powerful, effective and important tools for the SPC method. These are generally used to detect unusual variation in the manufacturing process and to monitor the industrial processes (Guo and Dunne, 2006; Noorossana and Vaghefi, 2006; Montgomery, 2009; Aldosari et al., 2018).

Walter A. Shewhart has developed the concept of statistical control chart (Shewhart, 1924). Presently, this concept is known as the formal beginning of SPC (Montgomery, 2009). Recently, new statistical control charts have been developed along with the classical Shewhart charts. These are exponentially weighted moving average (EWMA), adaptive EWMA (AEWMA), cumulative sum (CUSUM), adaptive CUSUM (ACUSUM), double sampling (DS) and sequential probability ratio test (SPRT) control charts (Ou et al., 2012; Haq, 2018).

Control charts are defined as graphical representations of the change in time of the quality parameter that has been measured or calculated from a sample in the process (Montgomery, 2009). The main purpose of control charts is to monitor the process and determine the reasons affecting the process stability by visually defining the behavior of critical quality parameters (Yerel et al., 2007; Hachicha and Ghorbel, 2012; Abbas et al. 2013; Deniz and Umucu 2013; Alcantara et al., 2017). These charts contain three horizontal lines: upper control limit (UCL), control limit (CL) and lower control limit (LCL). CL is the line representing the average of the process, LCL and UCL, located below and above the average line, respectively, are the lines representing the control limits of the process. If a plotted statistic is between the control limits, then it indicates that the process is in control and no action is required. But if a plotted statistic is outside the control limits, then it indicates that the process is out of control. Therefore, root cause needs to be identified and corrective actions are required to be implemented to eliminate such disruptive events (Montgomery, 2009).

The control charts have been used in different fields in the literature. Duclos et al (Duclos et al., 2009), have used control charts to monitor the outcomes of thyroid surgery and stated that these are useful for identifying potential issues related to patient's safety. Bayat and Arslan (Bayat and Arslan, 2004), have observed a variation of chromite concentrates obtained from three different chromite mines using control charts. Freitas et al (Freitas et al., 2019), have statistically analyzed the consumption of water in toilet flush devices in a public university building using Shewhart, EWMA and combined Shewhart-EWMA control charts. Dubinin et al (Dubinin et al., 2018), have used control charts to identify problem zones in the mathematical preparation of students. Fu et al (Fu et al., 2017), have conducted a study on the usability of the Shewhart control chart as a major statistical tool to monitor the production of clean ash during coal preparation.

A case study is presented in this paper, and the results are evaluated to determine the effect of using statistical control charts on the performance of Afşin-Elbistan B, which consists of 4 units and has an installed power of 1440 MW. thermal power plant. Two critical quality parameters, calorific and unit power values, are measured in six shifts per day in this power plant. A data set was created using these measured values over 30 days. Then, the Shewhart and CUSUM control charts were plotted for both quality parameters and these charts are interpreted in detail.

1. STATISTICAL CONTROL CHARTS

1.1. Shewhart Control Chart

As the Shewhart control charts are easy to construct and interpret, these are prevalently used for monitoring processes in the industry. The and R (or s) charts are the most important and useful among them. These control charts are particularly effective in detecting a large change in the process (Montgomery, 2009; Aldosari et al., 2018; Ottenstreuer et al., 2019).

If are the measurements of each sub-group, then the average of these measurements is calculated using Equation (1).

$$\bar{x} = \frac{x_1+x_2+\cdots+x_n}{n} \quad (1)$$

Let be the average of each sample. Then, the best estimator of mean, or the process average, is the grand average, as shown in Equation (2). Thus, would be used as the center line on the chart.

$$\bar{x} = \frac{x_1+x_2+\cdots+x_n}{n} \tag{2}$$

The formulas for constructing the control limits on the chart is given in Equations (3-5).

$$UCL_x = \bar{\bar{x}} + A_2\bar{R} \tag{3}$$
$$CL_x = \bar{\bar{x}} \tag{4}$$
$$LCL_x = \bar{\bar{x}} - A_2\bar{R} \tag{5}$$

If are the measurements of each sub-group, then the range of these measurements is the difference between the largest and smallest and calculated by subtracting the smallest from the largest (Equation (6)).

$$R = x_{max} - x_{min} \tag{6}$$

Let $R_1, R_2, \ldots, R_m$ are the ranges of m samples. The average range is given in Equation (7).

$$\bar{R} = \frac{R_1+R_2+\cdots+R_m}{m} \tag{7}$$

The center line and control limits of the R chart are given in Equations (8-10).

$$UCL_R = D_4\bar{R} \tag{8}$$
$$CL_R = \bar{R} \tag{9}$$
$$LCL_R = D_3\bar{R} \tag{10}$$

where, A_2, D_3 and D_4 are the constants determined from factors for constructing variable control charts according to various sample sizes (Montgomery, 2009).

1.2. Cusum Control Chart

Page (1954) introduced the CUSUM control chart for monitoring the process dispersion. This control chart directly incorporates all the information in the sequence of sample values by plotting cumulative sums of the deviations of the sample values from a target value (Montgomery, 2009). The CUSUM control chart is more successful than Shewhart chart in detecting sudden, small and persistent changes and can be used as an alternative statistical tool. Many researchers have studied about the use of this chart (Page, 1961), Ewan (Ewan, 1963), Lucas (Lucas, 1976), Gan (Gan, 1991), Hawkins (Hawkins, 1981; Hawkins, 1993), Woodall and Adams (Woodall and Adams, 1993)

Let assume the samples of size n ≥ 1, and is the average of the j_{th} sample. If is the target for the process mean, then the CUSUM control chart parameters are calculated using Equation (11).

$$C_i = \sum_{j=1}^{i}(\bar{x}_j - \mu_0) \tag{11}$$

If is accepted as the mean of the distribution (,the CUSUM chart is plotted by using Equation (12).

$$C_i = (x_i - \mu_0) + C_{i-1} \tag{12}$$

where, is generallyaccepted as the mean of the distribution (Montgomery, 2009).

2. RESULT AND DISCUSSION

In this study, as the thermal power plant, in which the data was obtained, worked six shifts per day, the number of sub-groups was determined to be 6. Also, the case study was conducted on two different parameters: the calorific and unit power values. The and R values of these parameters were calculated using Equations (1) and (6). The obtained results are shown in Table 1.

The constants used for calculating control limits were taken from factors for constructing variable control charts. It has been considered the values n = 6 as a sub-group size, A_2 = 0.483, D_3 = 0 and D_4 = 2.004 (Montgomery, 2009).

For calorific value;

$$\bar{\bar{x}} = \frac{27843.8}{31} = 898.2$$

$$\bar{R} = \frac{3626.8}{31} = 117.0$$

$$UCL_x = 898.2 + 0.483 * 117.0 = 954.7$$
$$CL_x = 898.2$$
$$LCL_x = 898.2 - 0.483 * 117.0 = 841.7$$

$$UCL_R = 2.004 * 117.0 = 234.5$$
$$CL_R = 117.0$$
$$LCL_R = 0 * 117.0 = 0$$

The $\bar{x}$ and R control charts were plotted for the calorific value and these charts are given in Figures 1-2.

Table 1. The and R values for Shewhart control charts

Days	Calorific Value (kcal)		Unit Power (MWh)	
		R		R
1	876.2	88.4	237.3	19.9
2	906.0	82.8	243.9	5.9
3	931.9	105.0	238.5	9.5
4	886.6	91.9	194.1	143.1
5	882.4	76.7	223.2	18.5
6	887.0	66.3	250.1	39.5
7	859.0	85.7	197.4	257.7
8	860.7	77.6	205.2	196.8
9	897.4	22.9	253.9	1.6
10	912.3	90.5	230.9	56.8
11	893.0	104.5	211.8	35.4
12	863.0	113.1	231.7	28.8
13	907.1	176.2	251.9	3.8
14	1015.4	136.5	236.4	38.0
15	722.4	396.5	178.9	165.4
16	852.0	177.1	227.9	82.8
17	860.4	72.2	207.2	229.9
18	846.2	183.8	236.6	60.4
19	941.6	102.5	249.0	26.9
20	893.9	68.7	247.1	21.3
21	880.5	51.9	249.3	16.8
22	944.8	40.9	258.5	14.3
23	954.6	83.7	263.0	3.5
24	867.8	300.4	241.5	82.7
25	933.4	65.3	259.8	6.6
26	927.2	375.1	232.0	99.8
27	936.7	75.0	225.7	117.0
28	954.5	83.9	259.3	12.8
29	938.6	129.1	214.4	121.9
30	926.4	49.9	252.9	38.0
31	884.8	52.9	248.9	21.8

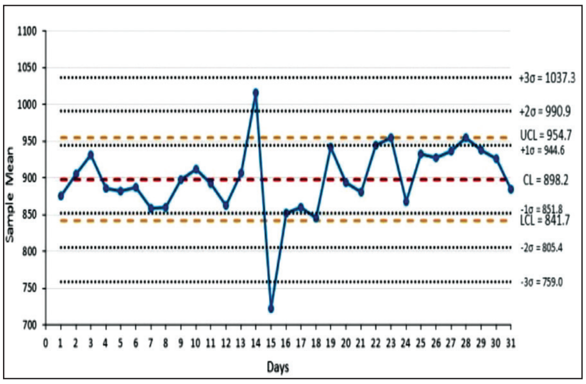

Figure 1. $\bar{x}$ Control chart for the calorific value

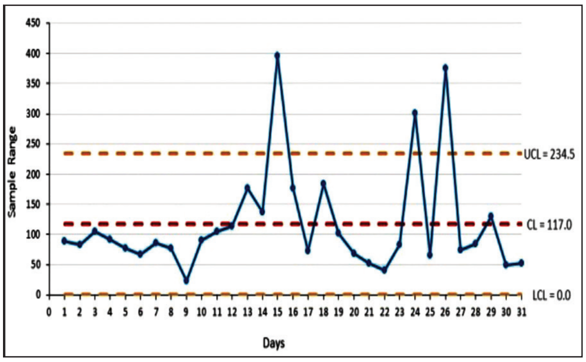

Figure 2. R Control chart for the calorific value

From Figure 1, it is observed that the process is in control except for 14th and 15th days. The calorific value was highest on the 14th day and lowest on the 15th day this fluctuation caused the process to go out of control. On the 15th day and between 23rd and 27th days, it is appeared that the sample range was very high during the process (Figure 2). Except for these, very little fluctuation was detected in the process during the period. It is determinated that this high fluctuation was caused by a problem in the production or in the blending stages.

For unit power;

$$\bar{\bar{x}} = \frac{7257.9}{31} = 234.1$$

$$\bar{R} = \frac{1977.0}{31} = 63.8$$

$$UCL_x = 234.1 + 0.483 * 63.8 = 264.9$$
$$CL_x = 234.1$$
$$LCL_x = 234.1 - 0.483 * 63.8 = 203.3$$

$$UCL_R = 2.004 * 63.8 = 127.8$$
$$CL_R = 63.8$$
$$LCL_R = 0 * 63.8 = 0$$

The $\bar{x}$ and R control charts were plotted for the unit power value and these charts are given in Figures 3 and 4, respectively.

When Figure 3 is examined, it is observed that three points (4, 7 and 15) in the process are out of control. Although there are periodic fluctuations for other points, the process is in control. At Figure 4, it is seen that five points (4, 7, 8, 15 and 17) in the process are out of control and the fluctuations in other points in control are quite high. It is understood from these control charts that the process is highly variable. Therefore, the reasons for this variability in the process should be identified and corrective measures should be taken to reduce them. The quality parameters for CUSUM control charts are calculated using Equation (12), and the obtained results are shown in Table 2.

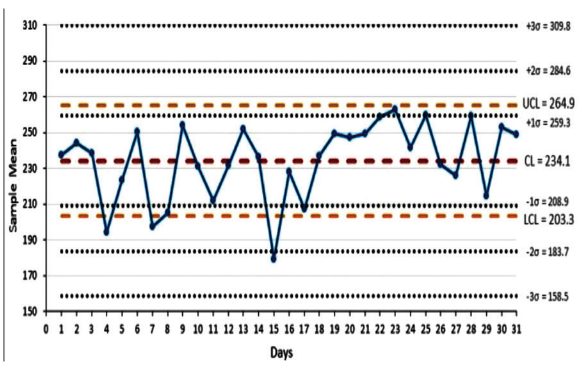

Figure 3. The control chart for the unit power

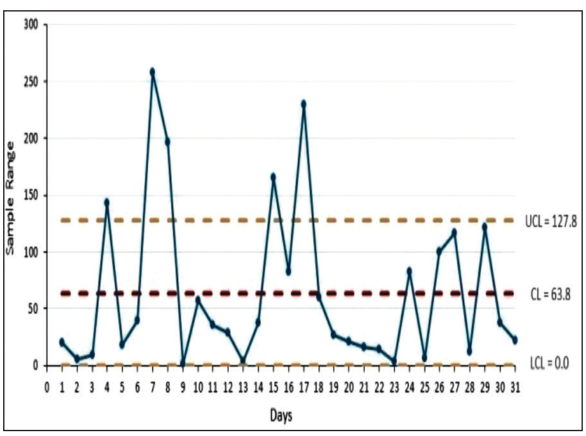

Figure 4. The R control chart for the unit power

Table 2. The calculated values for CUSUM control charts

Days	Calorific Value (kcal)			Unit Power (MWh)		
1	876.2	-22.2	-22.2	237.3	3.2	3.2
2	906.0	7.7	-14.5	243.9	9.7	12.9
3	931.9	33.5	19.0	238.5	4.4	17.3
4	886.6	-11.8	7.3	194.1	-40.0	-22.7
5	882.4	-16.0	-8.7	223.2	-10.9	-33.7
6	887.0	-11.3	-20.1	250.1	15.9	-17.7
7	859.0	-39.4	-59.5	197.4	-36.7	-54.4
8	860.7	-37.7	-97.1	205.2	-28.9	-83.4
9	897.4	-0.9	-98.1	253.9	19.7	-63.7
10	912.3	14.0	-84.1	230.9	-3.3	-66.9
11	893.0	-5.4	-89.5	211.8	-22.4	-89.3
12	863.0	-35.4	-124.9	231.7	-2.4	-91.7
13	907.1	8.7	-116.1	251.9	17.7	-73.9
14	1015.4	117.0	0.9	236.4	2.2	-71.7
15	722.4	-176.0	-175.1	178.9	-55.2	-127.0
16	852.0	-46.4	-221.5	227.9	-6.2	-133.2
17	860.4	-38.0	-259.4	207.2	-27.0	-160.2
18	846.2	-52.2	-311.6	236.6	2.4	-157.7
19	941.6	43.2	-268.4	249.0	14.9	-142.9
20	893.9	-4.5	-272.9	247.1	12.9	-129.9
21	880.5	-17.9	-290.7	249.3	15.1	-114.8
22	944.8	46.4	-244.3	258.5	24.4	-90.4
23	954.6	56.3	-188.0	263.0	28.9	-61.5
24	867.8	-30.5	-218.6	241.5	7.4	-54.1
25	933.4	35.0	-183.6	259.8	25.7	-28.5
26	927.2	28.9	-154.7	232.0	-2.1	-30.6
27	936.7	38.4	-116.4	225.7	-8.4	-39.0
28	959.9	61.6	-54.8	259.3	25.2	-13.7
29	938.6	40.2	-14.5	214.4	-19.7	-33.5
30	926.4	28.1	13.5	252.9	18.7	-14.7
31	884.8	-13.5	0.0	248.9	14.7	0.0

The CUSUM control charts were plotted for the calorific value and unit power value and these charts are given in Figures 5 and 6, respectively.

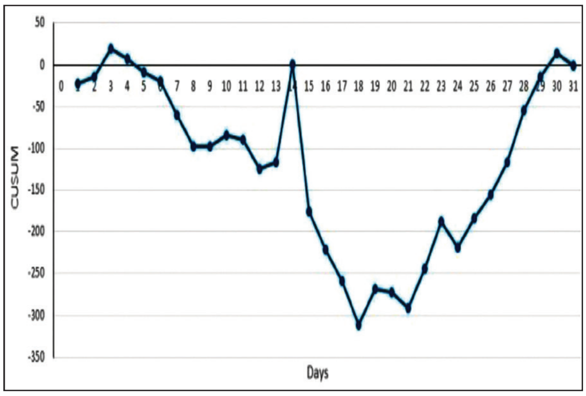

Figure 5. The Cusum control chart for the calorific value

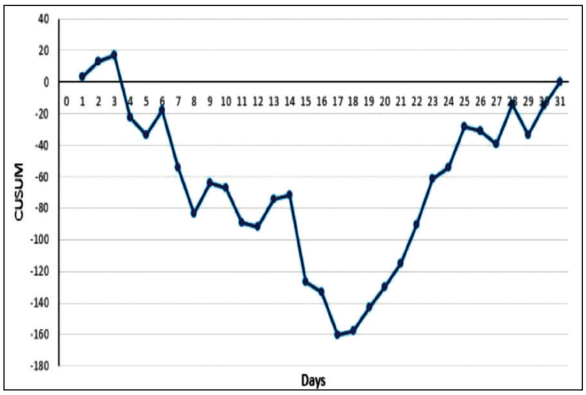

Figure 6. The Cusum control chart for the unit power

If the Figures 5 and 6 were evaluated together, the same change was observed in both the graphs. A negative trend up to point 17 and a positive trend after that point are observed. These trends were not observed in Shewhart chart.

CONCLUSION

In this study, the usability of statistical control charts for monitoring the calorific and unit power values in the production of electrical energy from the coal-fired thermal plant was investigated. This process was monitored for a month using Shewhart and CUSUM control charts. It is concluded that these charts proved very effective for detecting the unusual variation of productivity in the production of electrical energy. These charts are very useful to determine whether the process is in control or not. Furthermore, it is recommended using different combined structures of control charts for the higher level of productivity during the production of electrical energy.

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