Shewhart and EWMA Control Charts in the analysis of water consumption in buildings

Elisa Henning
Santa Catarina State University, Joinville, Brazil elisa.henning@udesc.br

Andrea Cristina Konrath*
Federal University of Santa Catarina, Florianópolis, Brazil andrea.ck@ufsc.br

Andreza Kalbusch
Santa Catarina State University, Joinville, Brazil andreza.kalbusch@udesc.br

Thaliane Aparecida de Freitas
Santa Catarina State University, Joinville, Brazil thaliane.de.freitas@gmail.com

Abstract

Statistical Process Control Charts (SPC) are effective tools for investigation, analysis and inference in all kinds of events in the several knowledge areas. Their applications can be understood as tools to measure, monitor, control, and improve quality. The main purpose of this article is to present partial results of the use of exponentially-weighted moving average charts (EWMA) in monitoring variables related to potable water consumption in buildings. The chart was applied to real data from lavatory taps of a building. Two distinct situations have been assessed: the exchange of ordinary equipment for water-saving ones and possible occurrence of equipment problems. The EWMA and combined Shewhart-EWMA charts indicate a decrease in the water consumption level, right after the equipment exchange, while the Shewhart and combined Shewhart-EWMA charts clearly indicate equipment failure and possible leaks.

Keywords: EWMA Chart; Shewhart chart, monitoring; water consumption.

1. Introduction

Quality has played an essential role, being a core theme in decision-making processes both in the corporate environment and in the public area. Quality improvement and maintenance are crucial for the survival of organizations. Therefore, control and monitoring activities have as their main goal the search for quality and a continuous improvement of products and services.

The search for systematic change elimination, as for example, waste, is a quality improvement-oriented action. As a consequence, this search can present several positive results, as a commitment to the environment. However, in order for these measures to become effective, they need appropriate measurement techniques. Measures must be accurate, consistent and their figures close to the real ones. Besides, the change detection techniques must be effective as to allow quick problem searching and taking corrective actions (Berthouex & Brown, 2002). In this field, control charts are essential.

Quality, regarding a built environment, implies in safe, functional and sustainable buildings. This concept is extended to building facilities, namely the water supply network, and it is related to good building practices and the supply network preventive maintenance.

The monitoring of water consumption indicators suggested in this article is justified mainly by the concern with the environment. As it regards water consumption, there is a necessity for a quick answer when an issue, such as a leak, is indicated. Likewise, there is a need to investigate effective statistical techniques to identify water consumption factors.

Until not long ago, control charts had been directed exclusively to monitoring industrial processes, but this tool has already expanded to other fields. (Samohyl, 2009). There is a growth in the application of Statistical Process Control Charts used in the health area and environmental monitoring (Gomes; Oliveira & Mingoti, 2011; Frisen, 2011; Smeti *et al.*, 2007, Aizenchtadt; Ingman & Friedler, 2008; Cruz *et al.*, 2014; Henning *et al.*, 2014).

This study, therefore, presents partial results to a research that proposes the use of statistical process control charts to help to monitor water consumption related variables, focusing mainly on building facilities. The water consumption of lavatory taps in a university building has been analyzed. Shewhart and EWMA charts and the combination of both have been chosen as a way to identify changes with diverse magnitudes. As a small and persistent change, there is a flow alteration originated by the exchange of the ordinary equipments for water-saving ones. On the other hand, technical problems in the pumping system and possible leakages created changes of higher magnitudes.

2. Control charts overview

The control charts basic operation lies in process improvement by means of learning and understanding the variables attributed to it. Through control charts, casual variations in the process can be differentiated from those called special ones. Thus, it is possible to detect when a process is out of its predictability condition (under statistic control) and starts to behave in an unpredictable matter (outside statistic control). When a variation caused by an assignable cause is found, a remarkable opportunity for process improvement arises (Hawkins & Olwell, 1998).

A control chart, in a general overview, consists of a central line (CL) that represents the average value of the quality characteristic corresponding to the process status under control and two control limits: one of them located below the central line called lower control limit (LCL) and, another one above the central line, called upper control limit (UCL). Conventionally, both limits are at a three standard error distance from the average or the target of the process (± 3) (Samohyl, 2009).

The SPC operationalization process can be separated into two phases: phase 1 (or of definition of control limits) and phase 2 (or of process control). In phase 1, the process distribution is not yet defined and it is needed to wait for variables originated by special causes, which need to be identified and eliminated, to emerge on the charts. During phase 1, the control chart operates mostly as an exploratory tool (Woodall, 2000). One of the most important results of this phase is the control limit definition. Phase 2 consists of using the control chart, with samples being taken sequentially through time aiming to detect changes in a process that seemed to be under control in phase 1. Any changes that emerge must be analyzed. In this phase, the decision to interfere in the process is based solely on the statistical value and in the regions defined by the control limits.

A control chart performance evaluation is measured by how quickly it detects changes in the process. The parameter used to evaluate such performance is the Average Run Length (ARL). ARL is the average number of points that must be placed in the chart before the latter produces a signal from outside the control limits. A good chart is expected to contain a high under control ARL value (ARL_0), in other words, a false alarm emission probability that quickly indicates when a change has really happened.

The best known and widely used control charts, for variables and attributes, are the traditional Shewhart type charts. The simplicity of the decision rule conditioned only to the last point signaled in the chart makes it easier to analyze if this point is interfering in the process. A great disadvantage of these charts is that they only use the information regarding the process contained in the last point, and ignore any information provided by the full point sequence. This characteristic makes this control charts to be indifferent/irresponsive to small variations in the process, in the order of 1,5 (standard errors) or less (Montgomery, 2008).

Despite being extremely efficient, these charts are not the only tools available to the statistical process analysis. In other cases, other types of control charts can complement or substitute the traditional methodologies of the Shewhart charts, advantageously. It is the case of the memory control charts such as the Exponentially Weighted Moving Average (EWMA), developed to correct this gap. These charts are recommended to a faster detection of small process changes and to make fewer mistakes when processes are truly stable (Samohyl, 2009).

3. Shewhart control charts, EWMA and combined Shewhart-EWMA

The Shewhart control charts are the most used charts in Statistical Process Control nowadays, being efficient to monitor the process and to improve the result in a continuous and permanent way. As stated in the above subsection, the Shewhart control charts used for sample sizes of n = 1 are called individual charts. This usually occurs when it is not possible to obtain samples higher than one (1). The calculation of UCL, CL e LCL limit controls are respectively $LSC = \bar{X} + E_2\overline{MR}$; $LC = \bar{X}$ and $LIC = \bar{X} - E_2\overline{MR}$, in which $\overline{MR} = (1/m)\sum_{i=1}^{m}\overline{MR_i}$; $\overline{MR_i} = |x_i - x_{i-1}|$ for i = 1, 2, ..., n and $E_2 = 3/d_2$ is a table constant, which depends on the value of m, the number of samples. Usually, $\bar{X}$ chart is followed by a chart with (MR) Moving Range Charts, to monitor the variability. For some authors however, this chart is not effective (Smeti *et al*., 2007). Therefore, it is not going to be showed in this paper.

The Exponentially Weighted Moving Average Chart (EWMA) (Roberts, 1959) provides greater weight to more current information and less weight to older information. The exponentially weighted moving average chart is defined by $Z_i = \lambda X_i + (1-\lambda)Z_{i-1}$ where X_i is the most recently observed value, λ is the parameter that corresponds to the weight given the observations, usually 0,1 or 0,1, and the initial value is the nominal value. Assuming that the observations x_i are independent random variables with variance σ^2, then the variance of z_i is $\sigma_{z_i}^2 = \sigma^2(\lambda/(2-\lambda))(1-(1-\lambda)^{2i}$. The central line is CL = 0 and for calculating the control limits, the equations $UCL = \mu_0 + L\sigma\sqrt{(\lambda/(2-\lambda))(1-(1-\lambda)^{2i}}$ (*upper control limit*) and $LCL = \mu_0 - L\sigma\sqrt{(\lambda/(2-\lambda))(1-(1-\lambda)^{2i}}$ (*lower control limit*) are applied, where L is the width of the control limits. A frequent value for L is 3(three) (conventional three-sigma limits). Being a chart that uses a weighted average of samples, this chart is more robust for the normality assumption (Montgomery, 2008).

An approach to increase the EWMA chart responsiveness for great changes is the Shewhart-EWMA chart. It is a probabilistic procedure that includes in the same axis the observed values, the Shewhart control limits, the EWMA statistics and the EWMA decision interval. It is made of a simple modification to the EWMA procedure, adding the Shewhart control chart. Generally, four control lines are expected: the upper and lower Shewhart control limits (UCL and LCL) and the EWMA h control limits (h+ and h-). It must also indicate the corresponding sample statistic values (observed or standardized) e the EWMA statistic values (positive and negative).

4. Methodological Procedures

The collected data is part of a bigger project, in which equipment in a building has been exchanged, such as toilet flush valves and taps; and other water consuming devices, such as drinking fountains, were regulated. In this document, only the tap-related data has been approached. Water meters and ordinary mechanical taps were installed, which were later replaced by water saving (self closing) taps. The water meter installation was performed in a way to enable isolated measurement of each class. The first data collecting period happened before the equipment exchange. For the second stage, ordinary taps were replaced by water- [illegible] been leakages and problems in the building pumping system. The ARL_0 value of 370 was chosen for chart parameter definition. The chart parameters are shown in Table 1. Data analysis was done with R (R Core Team, 2014) software and the qcc (Scrucca, 2004) package.

Table 1: *Parameters of the Combined Shewhart-EWMA chart and individuals Shewhart and EWMA charts*

Chart		λ	LCL	UCL
Combined Shewhart-EWMA	EWMA	0.2	0.4152964	0.6347161
	Shewhart		0.2621191	0.7878934
EWMA		0.2	0.4152516	0.6347609
Shewhart		-	0.2662161	0.7878331

4. Results e Discussion

Figure 1 shows the time series chart regarding consumption level (liters/users/days). In the period before the replacement (phase 1) there were 38 measurements and in the period after the equipment exchange (phase 2) there were 89. If the equipment replacement generated an effective water reduction, it is expected for this trend (negative) to be shown in the phase 2 chart. Likewise, problems in the pumping system occured around the 60th measuring day, generating a lack of flow. Some points with a high consumption value can indicate leakages. The data applied meets the assumptions, not only of normality but also regarding autocorrelation.

The Shewhart chart (Figure 1) signals, in phase 2, red points beyond the control limits (LCL= 0.2662161; UCL = 0.787833), the problems in the pumping system, and consumption peaks that can be understood as leakages. There is no indication of level change due to water consumption reduction.

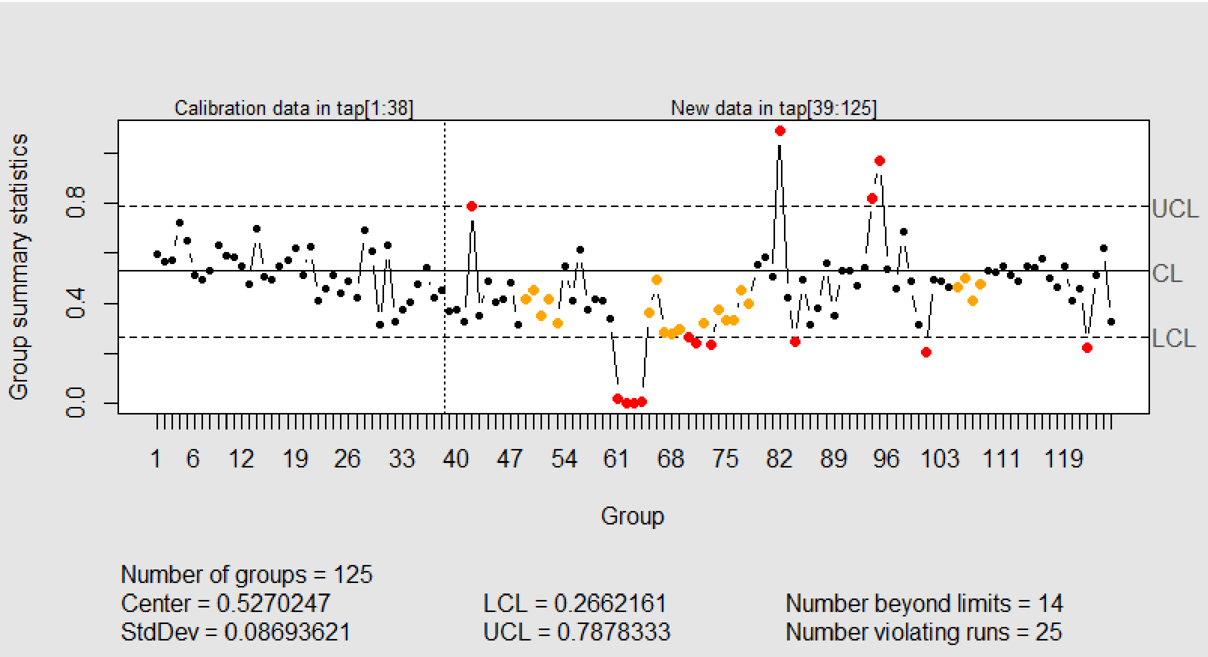

Figure 1: *Shewhart chart for washbasin water consumption measurement data.*

In the EWMA chart, (Figure 2) from sample 39 on, the lower control limit (LCL) is exceeded, indicating a redution on water consumption. However, the problems with the pump cannot be seen in the chart and the consumption peaks indicate an average increase from sample 80 and on.

The combined Shewhart-EWMA chart (Figure 3) indicates a consumption reduction, the pump issue and the consumption peaks. On the other hand, when analyzing the consumption peaks that do not have a reasonable explanation, such as a university event or students Olympics, one may think that the peaks represent leakage or equipment failure. Thus, even when replacing ordinary equipment for water-

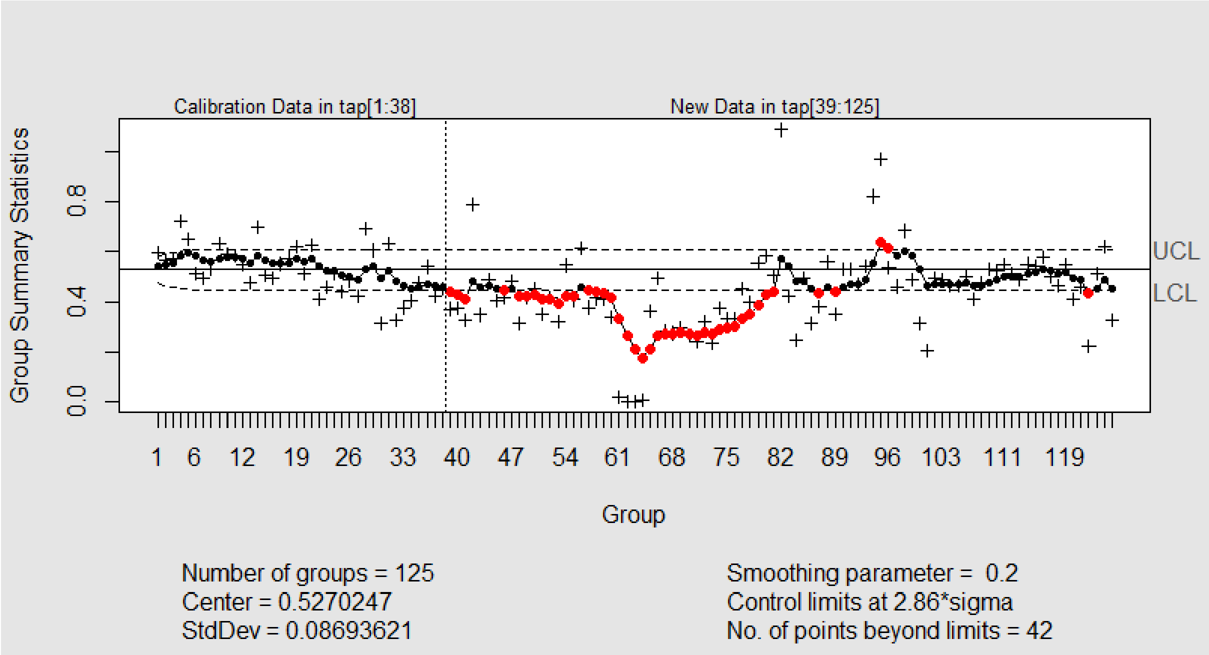

Figure 2: *EWMA chart for washbasin water consumption measurement data.*

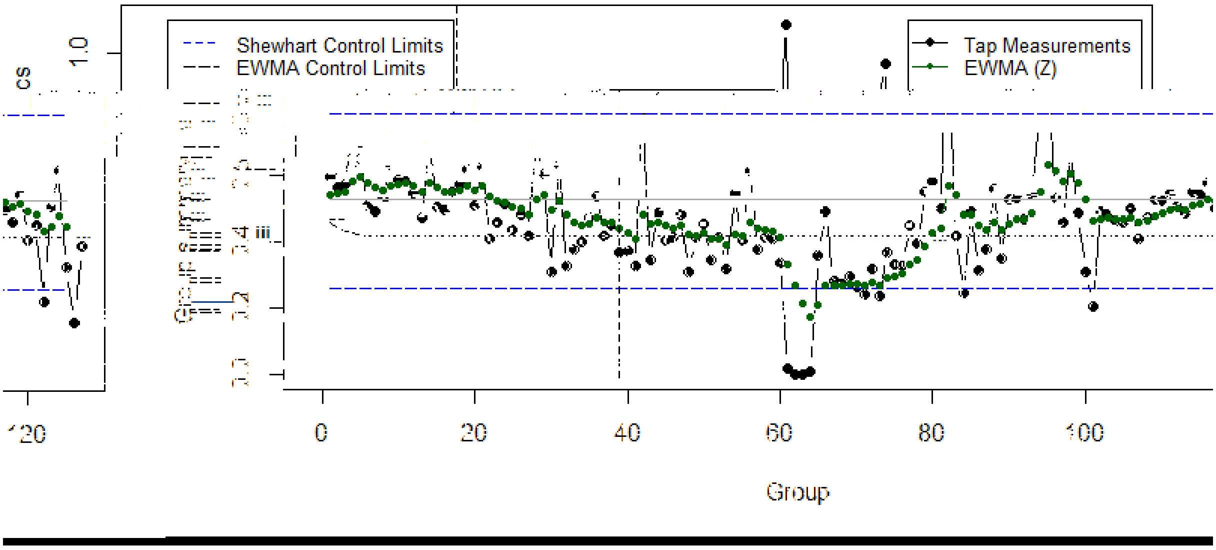

Figure 3: *Combined Shewhart-EWMA chart for washbasin water consumption measurement data.*

Thus, the EWMA and combined Shewhart-EWMA charts indicate a water consumption level reduction right after the equipment exchange; the Shewhart and combined Shewhart-EWMA charts better indicate the pump problems and possible leakages.

5. Conclusions

The objective of this article is to propose the use of statistical process control charts to analyze if the exchange of ordinary equipment for water-saving equipment is effective in reducing water consumption. For such, Shewhart control charts, EWMA and combined Shewhart-EWMA charts have been used. The results generated from using EWMA charts combined with Shewhart-EWMA indicate that the replacement was effective and specific after most issues are detected by the Shewhart and combined Shewhart-EWMA charts. As this research is not over yet, it is important to evaluate the efficiency of other control charts.

References

Aizenchtadt, E.; Ingman, D. & Friedler, E. (2008). Quality control of wastewater treatment: a new approach. *European Journal of Operations Research*, **189**(2), 445-458.

Berthouex, P.M. & Brown, L.C. (2002) Statistics for Environmental Engineers. 2 ed. Boca Raton, FL: Lewis Publishers. p. 489.

Cruz, D.V.; Cunha Filho, M. & Falcao, A.P.S.T. (2014). Controle estatístico de processo aplicado ao monitoramento do ph e turbidez das águas no abastecimento de Campina Grande PB. *Rev. Bras. Biom.*, **32**(4), 459-477.

□ □ □ □ □ □ . *Produção*, **21**(2), 235-241.

Gomes, I. C.; Oliveira, C. L. & Mingoti, S. A. (2011). A novel experience in the use of control charts for the detection of nosocomial infection outbreaks. *Clinics*, **66**(10), 1681-1689.

Henning, E., Konrath, A. C., Walter, O. M. F. C., Alves, C. C. & Samohyl, R. W. (2014), Aplicação de um gráfico CUSUM binomial no monitoramento de um indicador de água potável, *Revista Produção Online*, **14**(1), 84-114.

Hawkins, D. M. & Olwell, D. H. (1998). *Cumulative Sum Charts and Charting for Quality Improvement*, New York: Springer.

Montgomery, D.C. (2008). *Introdução ao Controle Estatístico de Qualidade*, Rio de Janeiro: LTC.

R Core Team (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: http://www.R-project.org/.

Roberts, S.W. (1959), Control Chart Tests Based on Geometric Moving Averages, *Technometrics*, **1**, 239-250.

Samohyl, R.W. (2009), *Controle Estatístico de Qualidade*, Rio de Janeiro: Elsevier.

Scrucca, □ □ □ □ □ □ □ □ □ □ □ □ □ □ *R News*, **4**(1), 11-17.

Smeti, E. M.; Thanasoulias, N. C.; Kousouris, L. P. & Tzoumerkars, P. C. (2007). An approach for the application of statistical process control techniques for quality improvement of treated water. *Desalination*, **213**, (1-3), 273-281.

Woodall, W. H. (2000). Controversies and Contradictions in Statistical Process Control. *Journal of Quality Technology*, **32**(4), 341-350.

Acknowledgements

Acknowledgements to the Brazilian National Council for Scientific and Technological Development CNPq, for supporting the research that originated this paper.