Analysis of Water Consumption in Toilets with Shewhart Control Charts

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Abstract

The article aims to show if it is possible for Shewhart Control Charts to have competent data monitoring capabilities when observing a switch in toilet flush equipment from single flush to dual flush in a public University building located in Joinville, southern Brazil. Sensors collected data such as volume of water and time length of the flush. Such data was then trimmed and compiled into days and finally plotted into a Shewhart Control Chart. The switch in flush equipment indicated a reasonable reduction in water consumption for both male and female bathrooms presenting an average total reduction of 33.15% in water consumed during a day and a reduction in the average time length of flush of 23.95%. With periodic monitoring Shewhart Control Charts proved to be useful for observing large shifts of data, water consumption reduction and events such as leakages and droughts that occurred during the data gathering period.

Keywords: *Water consumption, monitoring, Shewhart Control Charts.*

1. Introduction

Humans have a very close relationship with water, a biological one that also regards global aspects of human society such as environment and sustainability thus originating concerns involving wasteful water distribution around the globe. Such worries have been assessed by researchers like Rockström et al. (2009); Willis et al. (2011); Anand and Apul. (2011); Lee et al. (2011); Proença and Ghisi (2012); Velazquez et al. (2012); Carvalho et al. (2013); Guerry et al. (2015); Sant'Ana and Mazzega (2017); Valles-Casas et al. (2017). Additionally, saving water means more than just environmental benefits, also resulting in financial savings in the long run as mentioned by Cranston et al. (2015). Public buildings due to their large population size are more sensible to water consumption policies and technology (Fidar et al., 2010; Agudelo-Vera et al., 2013; Marinoski et al., 2017). When considering the most regular bathroom appliances found in buildings, the one with the highest water consumption per user is the toilet flush, which accounts to roughly 15.000 liters of water per user per year according to Quitzau (2007). Toilets and their impact in the environment have been researched by Lute et al. (2015); Liu et al. (2016) and Cheng et al. (2017).

Potable water savings in buildings has been thoroughly studied and thus economically viable options to rationalize water have been presented, such as the usage of greywater and/or the installation of dual-flush toilets. Considering these choices alongside with environmental and social factors installing newer and more effective flushing equipment comes as a solution in order to reduce the amount of water per flush as researched by Proença and Ghisi (2012) and Marinoski et al. (2012). Dual-flush equipment, unlike its regular flush counterpart that consist of only one button, contains two buttons for different flushes options giving the user a choice between a small or a large amount of water per flush. In order to monitor expected changes in water consumption with accuracy, collecting reliable data and subsequently doing a statistical analysis are required. X-bar Shewhart Control Charts (SCC) are a simple, yet effective, method to observing if a given statistical process is under control and proven useful for easily observing large shifts of data (Montgomery, 2009). Due to this fact SCC are very popular amongst the quality control sector in many companies (Montgomery et al., 2018). SCCs data monitoring capabilities have been thoroughly studied by many researchers such as Duclos et al. (2008) and Noorossana et al. (2014). SCCs can operate under certain rules called the West Electric Rules (Montgomery, 2009). This set of four rules are all based on chart analysis and dictate if a given process is under control given considerations such as random fluctuations in variables (Noorossana et al. 2014).

The objective of this article is to show that with proper analyzed data alongside with a controlled SCC and its correct interpretation can demonstrate a correlation between water consumption and data shifts that occurred from the switch of single-flush to a dual-flush equipment. Another complimentary goal is to further analyze variations between the SCC Phases 1 and 2 given the multiple key variables in context, thus pointing to seemingly random events that occurred during the data gathering period.

2. Methods

The selected data gathering subject building is a two floors building with 4 bathrooms, 2 for each gender, located inside of the Center of Technological Sciences (CCT) campus which belongs to the Santa Catarina State University of (UDESC), in the city of Joinville (south Brazil). The CCT started its activities in 1st August 1965 and is well-known for its courses and research centered on engineering and information technology fields.

The building has a population of 2500 students and it’s used for weekday classes and occasional third-party organization meetings. The building consists of two floors, each floor containing two (male and female) bathrooms. Male bathrooms also contain urinals which are not taken into account in the data gathering, although it is important to consider the fact that when urinals are present they indirectly lead to reduced toilet use.

To understand if replacing the toilet flush equipment in bathrooms on institutional buildings can in fact reduce the amount of water consumed per flush, considerations regarding human behavior and social environment are deemed important as they can explain possible seemingly random events. Smart-meters equipment was installed in the pipes responsible for filling the toilets, providing data such as volume of water, time duration, date and hour of the flush. This device also tracks individually both male and female bathroom flushes. The sensor tracks every flush, 24 hours per day. By manipulating the available sensor data, key variables were selected to be further analyzed on a daily basis. These are shown in Table 1.

Table 1. Data setting analyzed (Key variables).

Key Variables (per day)	Description
Volume	The total amount of water, measured in liters, used by all of the toilets in the course of an entire day.
Volume per flush	The average volume, measured in liters, of water per flush in a given day.
Flush duration	The average time duration, in seconds, of a flush in a given day.
Number of flushes	The number of flushes in a given day.

While the single-flush equipment was still being used, smart meter sensor data was collected in a period from 04/12/2017 to 06/28/2017. After July 2017 (July’s data has been ignored because of UDESC’s summer break) all toilets in the building had their equipment replaced with the dual-flush version. Data was then collected from 08/01/2017 up to 12/11/2017. In order stabilize the data, weekends, holidays, college breaks and other disruptive days (previously registered leaks and droughts) were removed from the data pool. To obtain stable SCC's data outliers were removed. Fig. 1 shows the data gathering process.

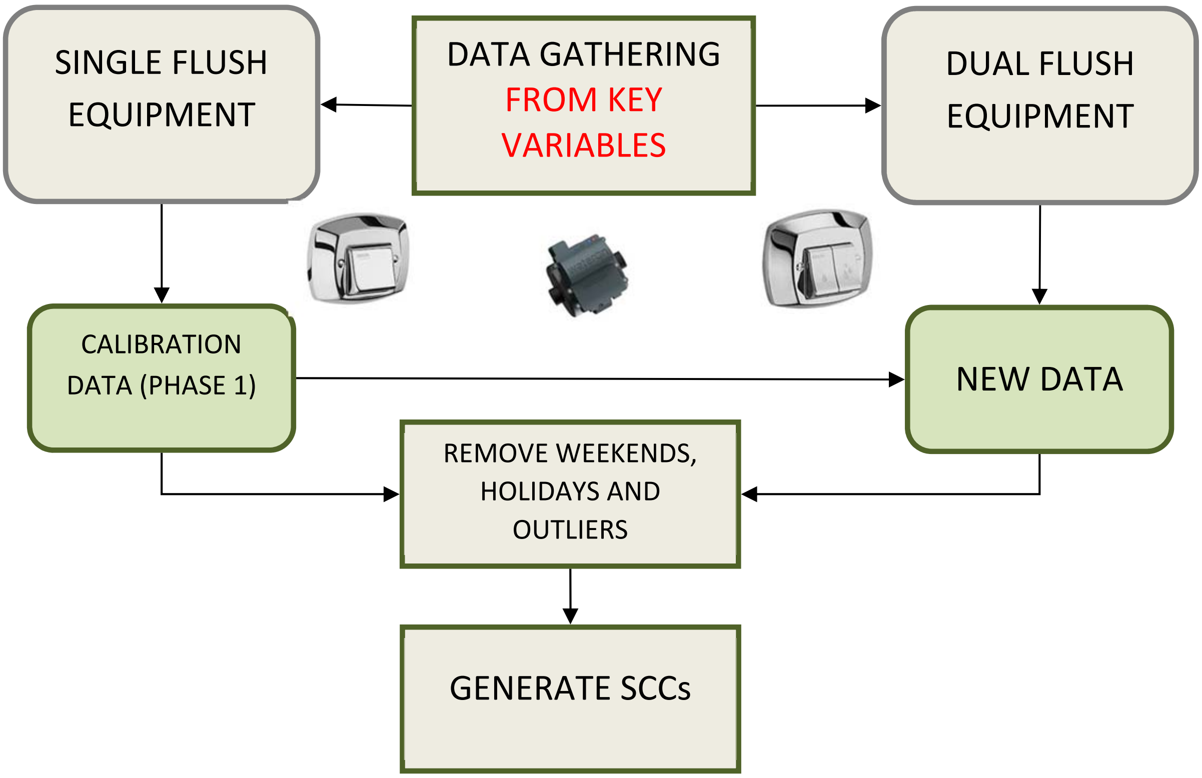

Fig. 1. Data gathering method flowchart.

Statistical analysis was performed using the computing environment R (R Development Core Team, 2018) with the qcc package (Scrucca, 2004).

3. SHEWHART CONTROL CHARTS

A control chart is a statistical tool used to highlight special causes that originate variation on the process. A control chart consists of a center axis or center line (CL), which indicates the average of the sample values, and two parallel lines, called the upper control limit (UCL) and the lower control limit (LCL). A process is in statistical control when the variation of the samples in the chart is small, oscillating around the threshold of CL, without going outside the limits of UCL and LCL. If there are subgroups that go outside the LCL and UCL, it indicates that the process can be out of statistical control and it need to be analyzed (Samohyl, 2009).

SCCs were developed by Shewhart in the 1920s and are the most common charts in Statistical Process Control. SCCs are developed in two phases, Phase 1 and Phase 2. Phase 1 refers to the period where the process distribution is not yet defined and subsequently variations in the chart can be expected due to special causes or even unforeseen events, as they both need to be identified and removed. Considering that control limits are defined in the Phase 1, therefore it should only be completed once all the irregular causes have been removed. Phase 2 represents new data collected after the stabilized Phase 1 and the control chart in its entirety presents a combination of Phase 1 and Phase 2 (Montgomery, 2009).

4. RESULTS

The data for Phase 1 were collected while the single-flush equipment was still in use, that being between 04/12/2017 and 06/28/2017. The disruptive readings (volume higher than 30 liters or time duration higher than 30 seconds) were removed by using the Median and Interquartile Deviation Method (Leys et al., 2013) to find and trim data outliers for both volume of flush and time duration of flush variables. Days considered that presented problems such as leakages and droughts were identified and removed from the data pool in order to stabilize the Phase 1, leading to 6,775 readings, 4,217 from the female bathrooms and 2,558 from the male bathrooms.

As part of the Phase 1, a Shapiro-Wilk normality test was applied on the data, resulting in a p-value for each key variable as shown in Table 2. For these same key variables an autocorrelation test was applied indicating no autocorrelation thus pointing that the data series is independent and normally distributed.

Table 2 – Shapiro-Wilk normality test p results for key variables.

	Volume per day	**Volume per flush per day**	**Flush duration per day**	**Number of flushes per day**
p-value	0.9257	0.8862	0.3813	0.8944

Following the installation of the dual flush equipment a total of 13,521 readings (9,164 for the female bathroom and 4,356 for the men bathroom) were obtained in a period of 82 days. The variable volume per flush presented a mean value of 6.6454 liters and standard deviation of 3.3259 liters, and the variable time duration of flush presented a mean of 7.8176 seconds (s) and SD of 2.8455s.

Table 3 presents the LCL, UCL, CL and Standard Error (SE) for Phase 1 and CL for Phase 2 from SCCs for the key variables from Table 2. And the last row of Table 3 also shows the reduction of mean value. As seen in Table 3, all key variables presented an evident reduction in the mean value alongside a stable Phase 2 for the process.

Table 3 – Parameters from SCCs from Phase 1 and Phase 2.

Phase	**Parameters from SCC**	**Volume per day**	**Volume per flush per day**	**Flush duration per day**	**Number of flushes per day**
1	**LCL**	872.9333	8.15	8.6787	101.0364
	UCL	2398.438	9.2293	9.7572	275.3535
	SE	254.2508	0.1786	0.1797	29.0527
	CL	1,635.686	8.6935	9.2180	188.1944
2	**CL**	1,093.505	6.6331	9.2180	164.5488
	Reduction (%)	33.15	23.70	14.29	12.56

Table 4 presents the mean, median, minimum and maximum values for all key variables.

Table 4 – Values from SCC from Phase 1 and Phase 2.

Key variables	**Phase**	**Mean**	**Median**	**Minimum**	**Maximum**
Volume per day	1	1,635.686	1,630.375	1,127.333	2,176.012
	2	1,093.505	1,131.581	61.001	1,854.168
Volume per flush per day	1	8.694	8.696	8.333	9.061
	2	6.633	6.655	5.030	7.483
Flush duration per day	1	9.218	9.225	8.889	9.585
	2	7.901	7.884	6.977	10.100
Number of flushes per day	1	188.194	186.500	129.000	248.000
	2	164.549	170.500	9.000	280.000

SCCs were generated for both male and female bathrooms. Figs. 2, 4, 6 and 8 show SCCs for female bathrooms and Figs. 3, 5, 7 and 9 for male bathrooms. For the volume per day in female bathrooms (Fig. 2) the control limits presented the following values: LCL = 458.1734; UCL = 1,555.5680; SE = 182.8991 liters. The mean before the replacement was 1,006.871 liters/day while the new data presented a mean of 722.3007 liters/day, showing a reduction of 28.26%. As for the male bathrooms counterpart shown in Fig. 3 the control limits presented the following values: LCL = 270.5982; UCL =

986.7503; SD (calibration data) = 119.3587 liters. The calibration data had a mean value of 628.6742 liters while the new data presented a mean of 377.9277 liters, showing a reduction of 39.88%.

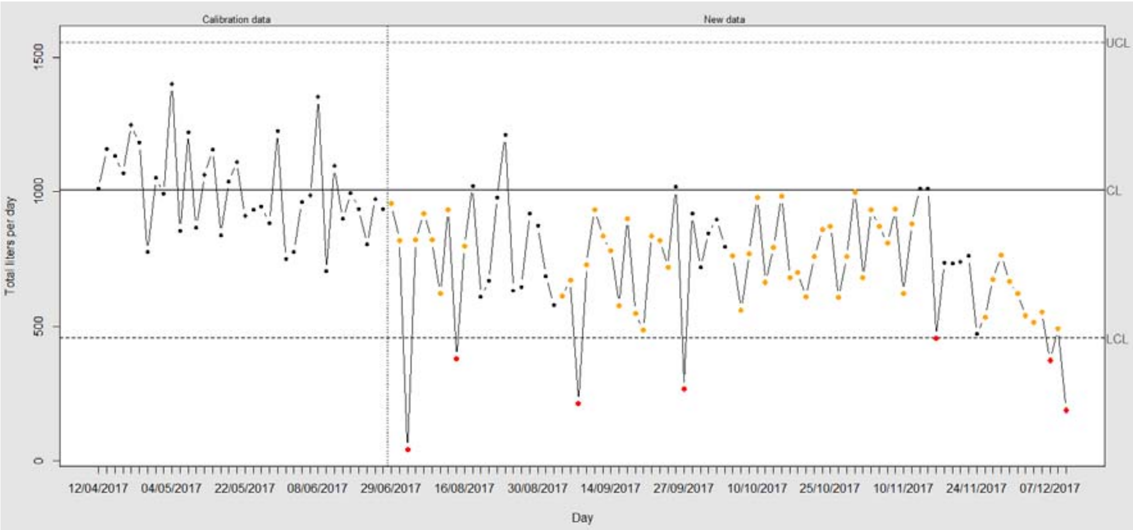

Fig. 2 – Volume per day (female bathrooms only).

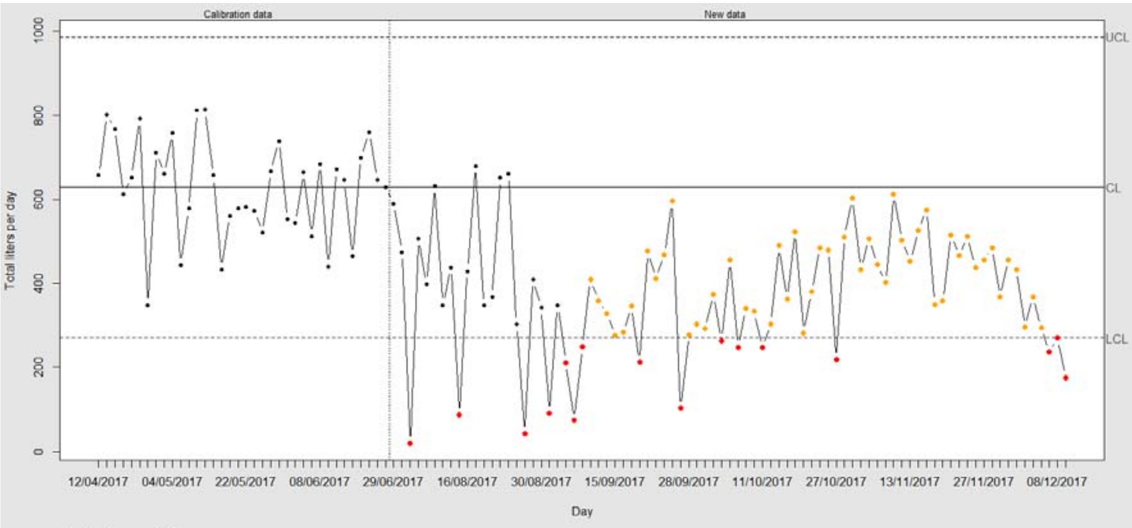

Fig. 3 – Volume per day (male bathrooms only).

Regarding the volume per flush per day in female bathrooms (Fig. 4) the control limits presented the following values: LCL = 8.0869; UCL = 9.1861; SE = 0.1832 liters. The calibration data had a mean value of 8.6365 liters per flush per day while the new data presented a mean of 6.4323 liters per flush per day, showing a reduction of 25.52%. For male bathrooms (Fig. 5) the control limits presented the following values: LCL = 7.4646; UCL = 10.1104; SE = 0.4410 liters. The calibration data had a mean value of 8.7875 liters while the new data presented a mean of 7.0416 liters, showing a reduction of 19.87%.

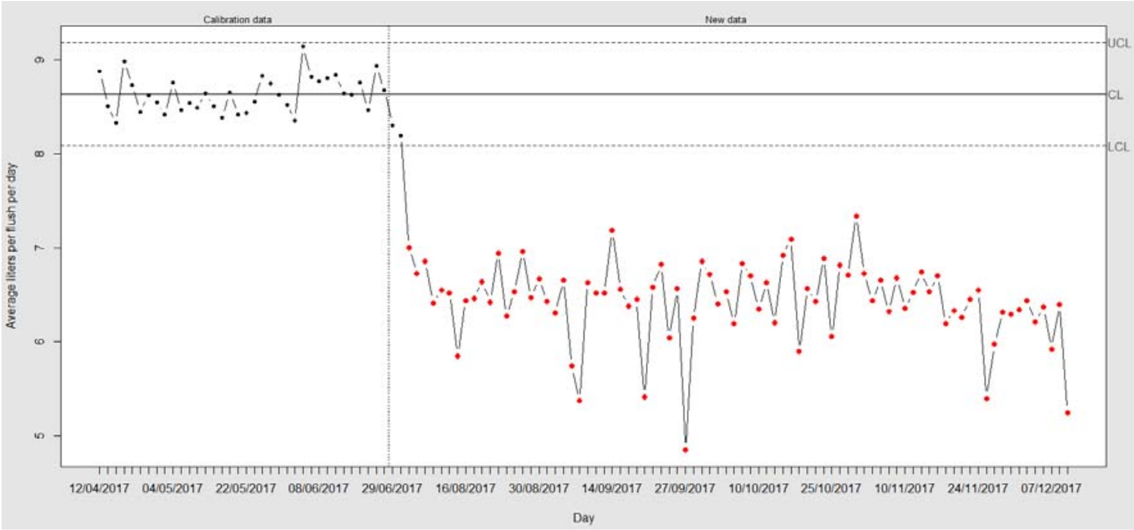

Fig. 4 – Volume per flush per day (female bathrooms only)

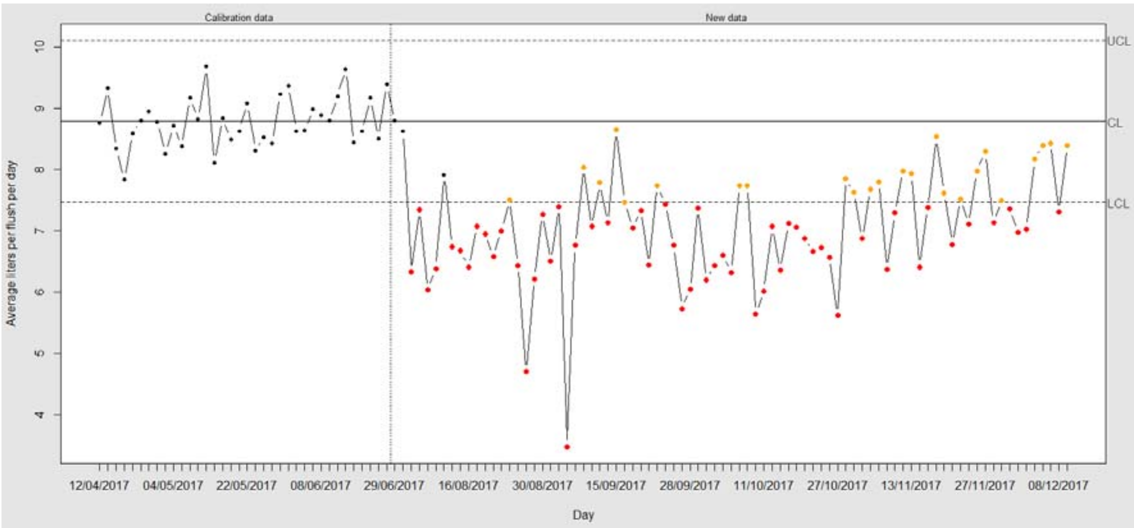

Fig. 5 – Volume per flush per day (male bathrooms only)

Fig. 6 shows the control chart for flush duration per day in female bathrooms. The control limits presented the following values: LCL = 8.6577; UCL = 9.9754; SE (calibration data) = 0.2196 seconds. The calibration data had a mean value of 9.3166 seconds while the new data presented a mean of 7.9284 seconds, showing a reduction of 14.90%. It is important to consider that the irregular reading above the UCL line presented in the Phase 2 likely causes a spike in the mean value. As for the flush duration for male bathrooms shown in Fig. 7 presented: LCL = 8.0211; UCL = 10.0925; SE = 0.3452 seconds. The calibration data had a mean value of 9.0568 seconds while the new data presented a mean of 7.9406 seconds, showing a reduction of 12.32%. In both Figs. 6 and 7 it is possible to observe dots above the UCL line, these could be related to a cleaning day or some unregistered leak which in turn may have caused the increased daily average, since the cause is unclear, it is important to conduct some further investigation regarding these observations.

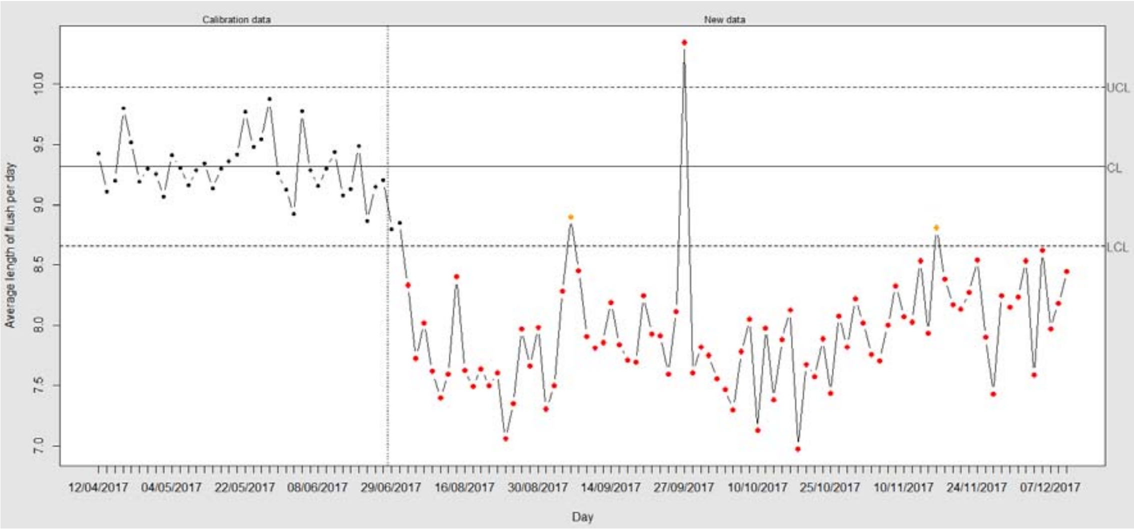

Fig. 6 – Flush duration per day in seconds (female bathrooms only)

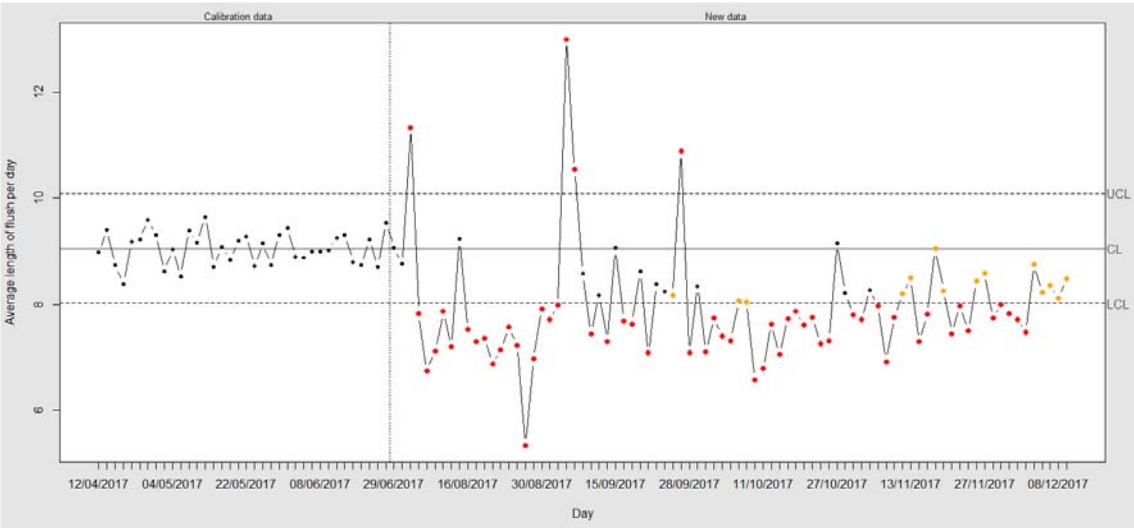

Fig. 7 – Flush duration per day in seconds (male bathrooms only)

Fig. 8 shows the chart for the number of flushes per day in female bathrooms. The control limits presented the following values: LCL = 54.4253; UCL = 178.7414; SE = 20.7194. The calibration data had a mean value of 116.5833 flushes while the new data presented a mean of 111.7561 flushes. It is noticed that there is no reduction in the number of flushes per day, although it is recommended to investigate a possible increase in the variability of the data.

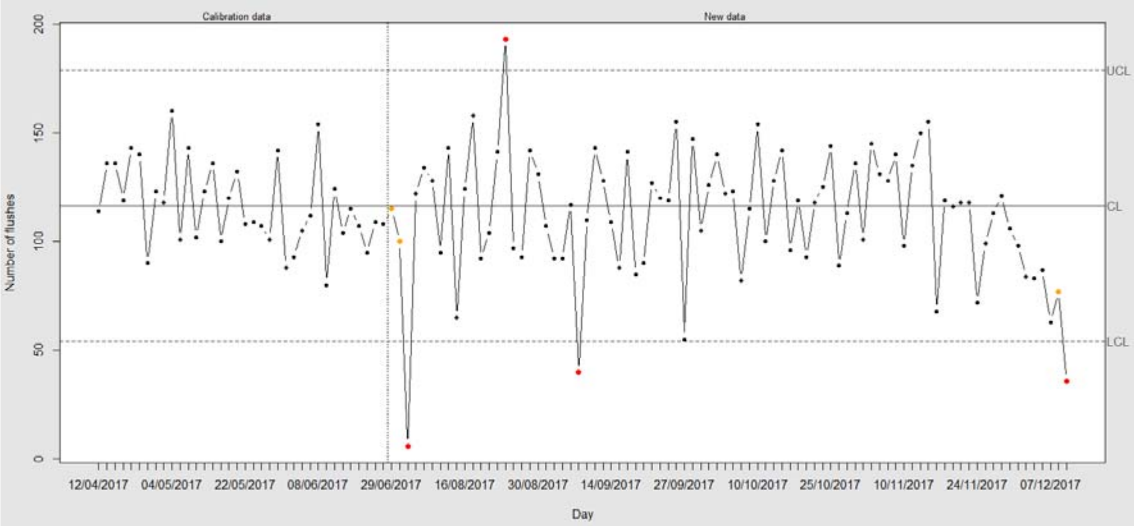

Fig. 8 – Number of flushes per day (female bathrooms only)

For Number of flushes per day in male bathrooms (Fig. 9) the control limits presented the following values: LCL = 32.9815; UCL = 110.1852; SE = 12.8673. The calibration data had a mean value of 71.5833 flushes while the new data presented a mean of 53.7901 flushes, showing a possible increased in variability as occurred in the female bathrooms.

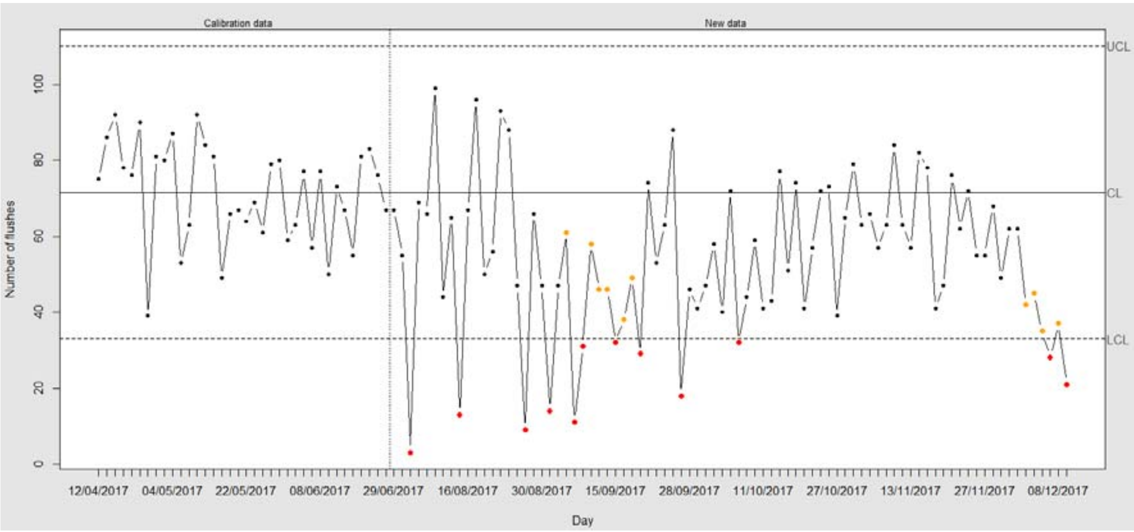

Fig. 9 – Number of flushes per day (male bathrooms only)

The extreme lower reading presented 3 days after the calibration data, as shown in Figs. 2; 3; 8 and 9 indicates the day when UDESC's winter break was about to end (early august) and there had been only a few toilet uses by the staff. The sudden decline in the last 3 days, shown in Figs. 6 and 9 were caused due to the end of school year when most of the students had already finished their classes leaving the subject building with a smaller population.

Water consumption per day was reduced as shown in Figs. 2; 3; 4 and 5, also a reduction in flush duration can be observed in Figs. 6 and 7. Considering that the number of uses per day is roughly the same in both stages, indicating that these changes were caused by the installation of new equipment that not only wastes less water but also operates quicker than the old single flush equipment. By analyzing tables 3 and 4 alongside with Figs. 2; 3; 4; and 7 it is evident that by switching flush equipment an overall reduction in water consumption can be observed as the data period goes on. The SCCs ability to point large shifts of data in a controlled process is eagerly shown in Figs. 4; 5; 6 and 7 and not so evident, although still visible, in Figs. 2 and 3. This is rather helpful since SCCs are easy to read and plot, maintaining a good balance in providing fast and reliable results.

4. CONCLUSIONS

Shewhart-type control charts proved very effective for detecting large shifts of data in the water consumption process, the charts also proved useful for detecting seemingly non-random events connected to water consumption. Such data monitoring capabilities can lead to more efficient and economic water consumption policies and thus leading to environmental and economic benefits in the long run.

Switching from single-flush to dual-flush equipment, accompanied by the control chart usefulness in data monitoring, presented significant reduction in both water consumption and flush duration in the building for both male and female bathrooms. There were leakages and droughts during the data collection period, even though some of these were visible in the SCCs, they are not the focus of this article and therefore removed from the data pool, being a topic for future studies.

Due to the SCCs potential, its data monitoring capabilities can be applied for monitoring other plumbing fixtures such as lavatories or even showers. The charts also proved very useful to correlate data variance such as variation in number of uses with certain events like leakages, droughts and college schedule changes, provided that the these events were known beforehand. Additionally to this, the charts can also show previously unknown events in the process, hence providing a fresh overview of the process and more precise identification of causes for data variance.

ACKNOWLEDGMENTS

The authors thank FAPESC (Fundação de Amparo à Pesquisa e Inovação do Estado de Santa Catarina) for the financial support.

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