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Remote monitoring of water consumption in bank branches using statistical control charts

Monitoramento remoto do consumo de água em agências bancárias utilizando gráficos de controle estatístico

Monitoreo remoto del consumo de agua en sucursales bancarias utilizando gráficos de control estadístico

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Abstract

The aim of this work was to assess the performance of two distinct types of statistical control charts, Shewhart and EWMA, when used to monitor water consumption in bank branches located in southern Brazil. The control charts were used in an attempt to detect unusual events that happened during the data collection period, ranging from 10/31/2018 to 11/03/2019. Three bank branches, located in the municipalities of Joinville, Criciúma and Curitiba, were selected for this analysis. The water consumption averages found for the Joinville's branch were 4.51 m^3/day, 81.82 L/employee/day, 11.14 L/service/day and 1.47 L/m^2/day. For the Criciúma's branch, the averages were 4.18 m^3/day, 34.73 L/employee/day, 21.02 L/service/day and 1.27 L/m^2/day. After the replacement of all toilet flushing systems, the consumption was reduced to 2.48 m^3/day, saving a total of 298.69 m^3 of water. Finally, for the Curitiba's branch, the averages were 0.61 m^3/day, 34.69 L/employee/day, 1.98 L/service/day and 0.29 L/m^2/day. Both charts displayed an acceptable performance for detecting leakages, excessive water consumption and other unusual events. The EWMA chart exhibited a better performance for detecting small variations.

Keywords: Statistical control charts, Water consumption, Remote monitoring, Sustainability, Public buildings, Statistical monitoring.

Resumo

O objetivo deste trabalho foi analisar o desempenho de dois tipos de gráficos de controle estatístico de processos, Shewhart e EWMA, para o monitoramento de consumo de água em agências bancárias localizadas na região Sul do Brasil. Os gráficos de controle foram utilizados para identificar eventos atípicos que ocorreram durante o período de análise, de 31/10/2018 até 03/11/2019. Três agências bancárias, localizadas nos municípios de Joinville, Criciúma e Curitiba foram selecionadas para análise. As médias diárias de consumo de água encontradas para a agência de Joinville foram de 4,51 m^3/dia, 81,82 L/funcionário/dia, 11,14 L/atendimento/dia e 1,47 L/m^2/dia. Na agência de Criciúma os indicadores foram de 4,18 m^3/dia, 34,73 L/funcionário/dia, 21,02 L/atendimento/dia e 1,27 L/m^2/dia. Após a substituição de todos os mecanismos de acionamento das válvulas de descarga ocorreu a redução do consumo para 2,48 m^3/dia, totalizando a economia de 298,69 m^3. Os indicadores para a agência de Curitiba foram de 0,61 m^3/dia, 34,69 L/funcionário/dia, 1,98 L/atendimento/dia e 0,29 L/m^2/dia. Ambos os gráficos analisados apresentaram resultados satisfatórios quanto à detecção de vazamentos, consumos excessivos de água e outros eventos atípicos. O gráfico EWMA apresentou um melhor desempenho para a detecção de pequenas variações no consumo.

Palavras-chave: Gráficos de controle; Consumo de água; Monitoramento remoto; Sustentabilidade; Edificações públicas; Monitoramento estatístico.

Resumen

El objetivo de este trabajo fue analizar el desempeño de dos tipos de gráficos de control estadístico de procesos, Shewhart y EWMA, para el monitoreo del consumo de agua en sucursales bancarias ubicadas en la región sur de Brasil. Los gráficos de control se utilizaron para identificar eventos atípicos que ocurrieron durante el período de análisis, desde el 31/10/2018 hasta el 03/11/2019. Se seleccionaron tres sucursales bancarias, ubicadas en los municipios de Joinville, Criciúma y Curitiba, para el análisis. Los promedios diarios de consumo de agua encontrados para la agencia de Joinville fueron de 4,51 m^3/día, 81,82 L/empleado/día, 11,14 L/servicio/día y 1,47 L/m^2/día. En la agencia de Criciúma, los indicadores fueron de 4,18 m^3/día, 34,73 L/empleado/día, 21,02 L/servicio/día y 1,27 L/m^2/día. Después de la sustitución de todos los mecanismos de accionamiento de las válvulas de descarga, el consumo se redujo a 2,48 m^3/día, totalizando un ahorro de 298,69 m^3. Los indicadores para la agencia de Curitiba fueron de 0,61 m^3/día, 34,69 L/empleado/día, 1,98 L/servicio/día y 0,29 L/m^2/día. Ambos gráficos analizados presentaron resultados satisfactorios en cuanto a la detección de fugas, consumos excesivos de agua y otros eventos atípicos. El gráfico EWMA mostró un mejor desempeño para la detección de pequeñas variaciones en el consumo.

Palabras-clave: Gráficos de control; Consumo de agua; Monitoreo remoto; Sostenibilidad; Edificaciones públicas; Monitoreo estadístico.

1 Introduction

Society's current development is strongly dependent on the relationship between social ambitions and the availability and quality of natural resources such as water (Cosgrove; Loucks, 2015). However, in recent decades, the global water consumption increase rate has surpassed the population growth rate, leaving several regions of the world in a water shortage crisis (Cosgrove; Loucks, 2015). To ensure a steady, reliable and economically viable water supply, planning and implementing new water demand management strategies is crucial (Cosgrove; Loucks, 2015). In this regard, consumption monitoring is an essential step towards an effective control of water usage, as it provides a deeper understanding of water consumption patterns (Cominola *et al.*, 2015). Britton *et al.* (2008) mention that the use of remote water monitoring systems can offer benefits such as reducing water consumption, optimizing water pumping processes and extending the lifespan of infrastructural water systems. Kim *et al.* (2008) state that new monitoring technologies and methods for hydric resources are vital to reducing water losses due to inefficiency and/or leakages.

Statistical Control Charts (SCC) are tools used in statistical process control. Although originally developed for the manufacturing sector, their use has expanded in recent decades to various areas of society (Shamsuzzaman *et al.*, 2016). Vasconcellos *et al.* (2020) applied control charts to monitor the water flow rate in small-scale Brazilian hydroelectric power plants. Wan *et al.* (2022) proposed a leakage detection system, running on a network, that utilizes modified control charts. Freitas *et al.* (2019) used control charts to monitor water consumption in toilets before and after replacing old single-flush valves with new dual-flush models in a building on a college campus. Thus, Statistical Control Charts have proven to be an alternative for monitoring water consumption. The main goal of this paper is to evaluate the use of Statistical Control Charts for monitoring water consumption in bank branches, based on a case study analysis. This article is structured as follows: Section 2 provides an explanation of Statistical Control Charts and the statistical control of processes; Section 3 details the methods and procedures used in the case study; Section 4 presents the results and discussions; and Section 5 contains the conclusions and final considerations.

2 Statistical control charts and statistical processes

Statistical quality control can be broadly defined as a combination of statistical and engineering methods used to measure, monitor, control and improve the quality of a given process (Montgomery; Runger, 2003). A control chart is a time series of points (observations), in which each point represents a statistical measurement of a sample obtained from a specific process (Montgomery, 2012). By calculating the mathematical average of the samples from a given process, a Central Line (CL) can be generated, which represents the average value of the data collected at a specific stage of the process, known as the under-control stage. A process is considered under control when all of its sample points align with the expected values within the context of the process application. Control limits are used to determine whether the collected sample points fall within the expected parameters (Montgomery, 2012).

Control limits are represented by two horizontal reference lines: the Upper Control Limit (UCL) and the Lower Control Limit (LCL). They determine if a process is under control, which is the case when almost every sample point lies between the UCL and the LCL. Control charts are typically divided into two phases: Phase 1 represents data that is under statistical control and is used to calculate the UCL and the LCL, while Phase 2 represents newly collected data, which is compared to the control limits to determine whether the new sample points are under control or not (Montgomery; Runger, 2003).

Shewhart control charts, developed in 1931, are widely used for process control in various industry sectors, and can be applied to both grouped samples and individual observations (Qiu, 2014). The UCL, CL and LCL control limits in a Shewhart control chart are shown, respectively, in Equations 1, 2 and 3 (Montgomery; Runger, 2003).

$$LCS = \bar{X} + 3 * \hat{\sigma} \quad (1)$$

$$LC = \bar{X} \quad (2)$$

$$LCI = \bar{X} - 3 * \hat{\sigma} \quad (3)$$

Where $\bar{X}$ is the sample average and $\hat{\sigma}$ the estimated standard deviation of the original observations. As Equation 3 shows, the $\hat{\sigma}$ parameter is multiplied by a value of 3, which is a well-established industry standard used in Shewhart control charts (Montgomery; Runger, 2003). The $\hat{\sigma}$ parameter is defined in Equation 4:

$$\hat{\sigma} = \frac{\overline{MR}}{d_2} \quad (4)$$

Where $\overline{MR}$ is the moving interval of two consecutive observations, as defined in Equation 5 (Montgomery; Runger, 2003), and d_2 represents the average interval distribution relative to the given process. The value of d_2 is 1.128 for a control chart with data containing individual observations (Montgomery; Runger, 2003).

$$\overline{MR} = | X_i - X_{i-1}| \quad (5)$$

One disadvantage of the Shewhart chart is that it does not perform well at detecting small variations over the lifetime of a process. One of the reasons is that it only uses the most recent data point as a control parameter, ignoring the information contained in a sequence of data points (Montgomery; Runger, 2003). An alternative to the Shewhart chart is the Exponentially Weighted Moving Average (EWMA) control chart (Roberts, 2000). It is constructed using the weighted average of all available data points up to a specific time, assigning weights to each of them. Assuming the original observations to be X_1, X_2, ... X_i, and Z_1, Z_2, ... Z_i their respective weights, the EWMA chart is defined in Equation 6 (MONTGOMERY; RUNGER, 2003).

$$Z_i = \lambda * X_i + (1 - \lambda) * Z_{i-1} \quad (6)$$

Where X_i is the most recent data point, λ is the weight parameter ($\lambda \in (0,1]$), and its initial value (Z_1) is equal to its first data point (Z_1 = X_1). Equation 7 can be derived from Equation 6 (Montgomery, 2012).

$$Z_i = \lambda * \sum_{j=1}^{i} (1 - \lambda)^{i-j} * X_j + (1 - \lambda)^i * \bar{X} \quad (7)$$

The weight λ is defined in Equation 8 (Montgomery, 2012).

$$1 = \lambda * \sum_{j=1}^{i} (1 - \lambda)^{i-j} * X_j + (1 - \lambda)^i \quad (8)$$

Where Z_i is the weighted average of $\bar{X}$ in combination with all the observations collected up to i, and the weight component $\lambda * (1-\lambda)^{i-j}$, corresponding to the current observation i, decays exponentially as the difference between i and j increases. It can also be inferred that, as λ increases, a larger weight is assigned to the current X_i observation, while a lower weight is assigned to previous ones. The opposite occurs when λ decreases. In the case where $\lambda = 1,$ it can be inferred that $Z_i = X_i$ and, therefore, the EWMA chart becomes a Shewhart chart (QIU, 2014).

Assuming the observations X_i to be independent variables with variance σ^2, then the variance of Z_i is given by Equation 9 (QIU, 2014).

$$\sigma_{Zi}^2 = \sigma^2 * \left(\frac{\lambda}{2-\lambda}\right) * (1-(1-\lambda)^{2i}) \tag{9}$$

The Central Line (CL) represents the average of all observations, and the control limits UCL and LCL are given by Equations 10 and 11, respectively (QIU, 2014).

$$UCL = \mu_0 + L * \sigma * \sqrt{\left(\frac{\lambda}{2-\lambda}\right)(1-(1-\lambda)^{2i})} \tag{10}$$

$$LCL = \mu_0 - L * \sigma * \sqrt{\left(\frac{\lambda}{2-\lambda}\right)(1-(1-\lambda)^{2i})} \tag{11}$$

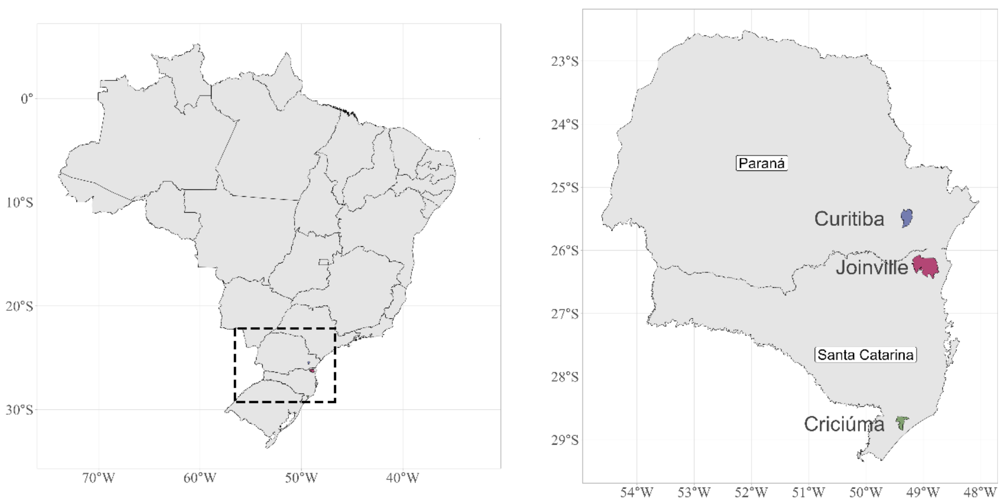
Where L corresponds to the control limits' extension, frequently receiving a value of 3 (MONGOMERY; RUNGER, 2003). Small values of λ are recommended to detect smaller variations in a process, while larger values are more effective at detecting larger changes (QIU, 2014). For this study, a value of 0.2 was used.

3 Metodology

3.1 Object of study

The three bank branches are in the southern region of Brazil, spread across two different states: Paraná (Curitiba's branch) and Santa Catarina (Criciúma's and Joinville's branches). Figure 1 shows the geographic location of all three.

Figure 1: Geographic location of all three branches in Brazil.



The branch in Joinville is located downtown, with an indoor area of 2,032.23 m^2 and an indoor parking area of 321.08 m^2. Combined with the outdoor area, the total built area is 3,165.40 m^2. It was opened on June 1, 1978 and, at the time of this study, employed 57 people. The structure consisted of a ground floor, the first floor, a mezzanine and a basement. It had 2 water tanks: one located in the basement with a capacity of 30,000 L and the other on the upper floor with a capacity of 20,000 L. It had the following plumbing fixtures: 28 toilets (2 with dual-flush valves and 26 with close-coupled cisterns), 1 urinal, 18 washbasins, 6 drinking fountains (3 open to the public and 3 for employees only), and 3 faucets. The branch did not have any alternative water supply systems, and it employed a central air-cooling unit that consumes water through evaporation.

The branch in Criciúma is downtown, with an internal area of 1,158.44 m^2 and an indoor parking area of 835.43 m^2. Combined with the outdoor area, the total built area is 3,554.06 m^2. It was opened on March 26, 2006 and, at the time of this study, employed 35 people. The structure consisted of two sections: the first was the main business area (on the ground floor and part of the first floor) and the second served as an administrative office (occupying the remainder of the first floor and the second floor), in a total of 3 floors. It had 3 water tanks: 2 in the basement, each with a capacity of 3,000 L, and 1 on the top floor, with the same capacity. It was equipped with the following plumbing fixtures: 18 toilets (4 with regular flush valves and 14 with close-coupled cisterns), 3 urinals, 13 washbasins and 4 drinking fountains (1 open to the public and 3 for employees only). The branch did not have any alternative water supply system.

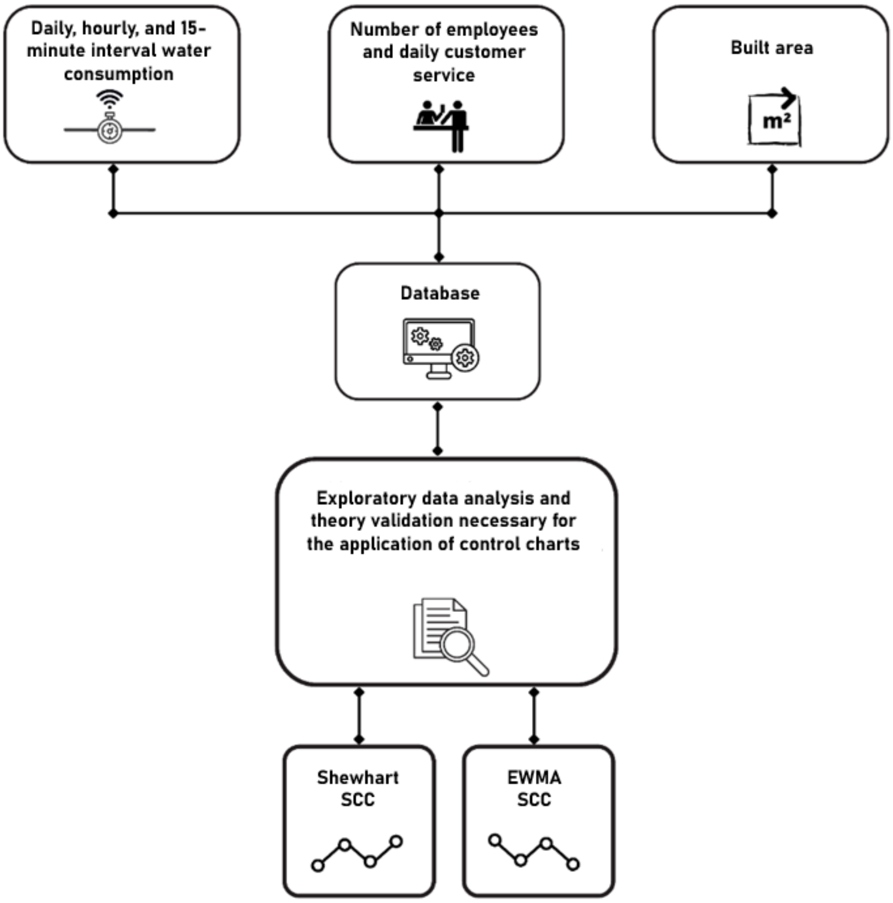
The branch in Curitiba is in one of the city's districts, with an internal area of 1,187.89 m^2 and an indoor parking area of 931.00 m^2. Combined with the outdoor area, the total built area is 2,118.89 m^2. It was opened on October 22, 2010 and, at the time of this study, employed 18 people. The structure consisted of the ground floor and the first floor. It had 2 water tanks: one located in the basement with a capacity of 5000 L, and the other on the top floor with a capacity of 2,000 L. It had the following plumbing fixtures: 9 toilets (4 with regular flushing systems and 5 with close-coupled cisterns), 1 urinal, 11 washbasins, 3 drinking fountains (2 open to the public and 1 for employees only) and 4 faucets. The branch also had a grey water reuse system with a capacity of 1000 L, primarily used for cleaning the sidewalk and watering the garden.

3.2 Statistical Control Charts for monitoring water consumption

To generate the control charts for water consumption monitoring in the branches, data were collected using a telemetry system. A total of 35,424 readings (one every 15 min) were registered by the sensors installed in the branches during the period from October 31, 2018 to November 03, 2019, in a total of 369 consecutive days of data collection, 262 of which were weekdays. The remote monitoring system consists of a multi-jet water meter (installed in series after the local water utility's meter, without interfering with the existing measurement), a pulsed reading sensor, a data logger, and a transmission system via a telephone network to a server accessible through a standard web browser. The sensor coupled to the water meter records one reading every 15 min, resulting in 2,880 readings every 30 days. The data are stored in the logger and synchronized with a cloud server, enabling remote access.

The data were obtained in three different formats: daily consumption, hourly consumption, and consumption every 15 min. Additionally, complementary data such as water quality and volume of tanks, number of employees, daily customer interactions, and the total built area of the branches were collected. The flowchart presented in Figure 2 shows the methodological procedures used. Analyzing the 15-minute interval data posed some challenges, as this format is less common than hourly or daily readings. Furthermore, some apparently inconsistent values were observed, likely due to the low precision limits of the sensor, particularly at lower flow rates. By aggregating the data into hourly intervals, with four readings per hour, these challenges were successfully addressed.

Figure 2: Methodological procedures.



The data collected underwent statistical treatment, during which weekends and holidays were excluded to balance the dataset and ensure a more reliable analysis. Given the nature of the process, in this specific case of water consumption monitoring, the control charts' LCL could not be below zero (0), as negative water consumption is not possible. Additionally, variations in consumption related to the branches' opening hours resulted in several false alarms, particularly zero-consumption data points during the nighttime period. To address these issues, the LCLs of the control charts were set to zero, which improved the charts' visualization without compromising the integrity of the monitoring process.

The Shewhart and the EWMA control charts were generated using data in two formats: hourly consumption and daily consumption. Due to the large and sudden variation observed in hourly readings, the sigma limits (standard deviation) were increased from 3 to 6. Doing so is also an alternative to address the issues related to autocorrelated data (Claro *et al.*, 2007). The R (R Core Team, 2023) programming language and the QCC package (Scrucca, 2004) were used to generate the control charts.

3.3 Calculation of water consumption indicators for bank branches

The daily consumption per employee (in L/employee/day) and the daily consumption per m^2 of built area (in L/m^2/day) indicators were calculated for the three branches. To complement the consumption analysis, the number of daily customer interactions was recorded for each day during the data collection period. Based on this data, the daily consumption per customer interaction indicator (in L/service/day) was calculated. A line chart depicting the daily number of customer interactions was generated to analyze the variation in number of customer interactions across the bank branches during the data collection period. It is important to note that the automated teller machine (ATM) usage was not included in the number of customer interactions.

A box plot chart was generated for each indicator (customer interactions, employees and built area) to observe the daily per capita consumption variation across the bank branches. Additionally, a Shewhart control chart was created for each indicator to analyze and compare the variations between the three branches.

4 Results and discussion

4.1 Water consumption analysis – Joinville branch

Figures 3 and 4 present the Shewhart and the EWMA control charts, respectively, for daily water consumption at the Joinville branch. The average consumption was 4.51 m^3/day, with a maximum of 25.68 m^3/day and a standard deviation of 2.94 m^3/day. An unusual reading was detected on January 30, 2019, appearing in the charts as points above the UCL. An inspection conducted at the branch revealed that this anomaly was likely caused by homeless individuals using an external faucet. According to the branch managers, these individuals used an improvised wrench to open the faucet but failed to close it afterward, leaving it running throughout the night, resulting in the atypical reading (25.68 m^3/day) observed in the charts.

Figure 3: Shewhart control chart – Daily consumption – Joinville branch.

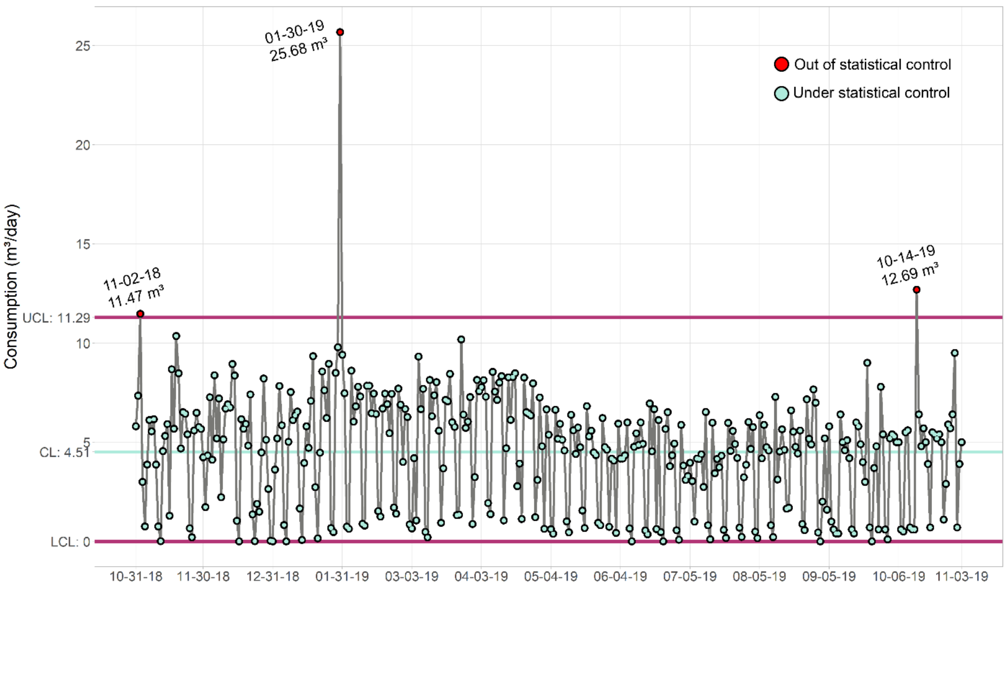
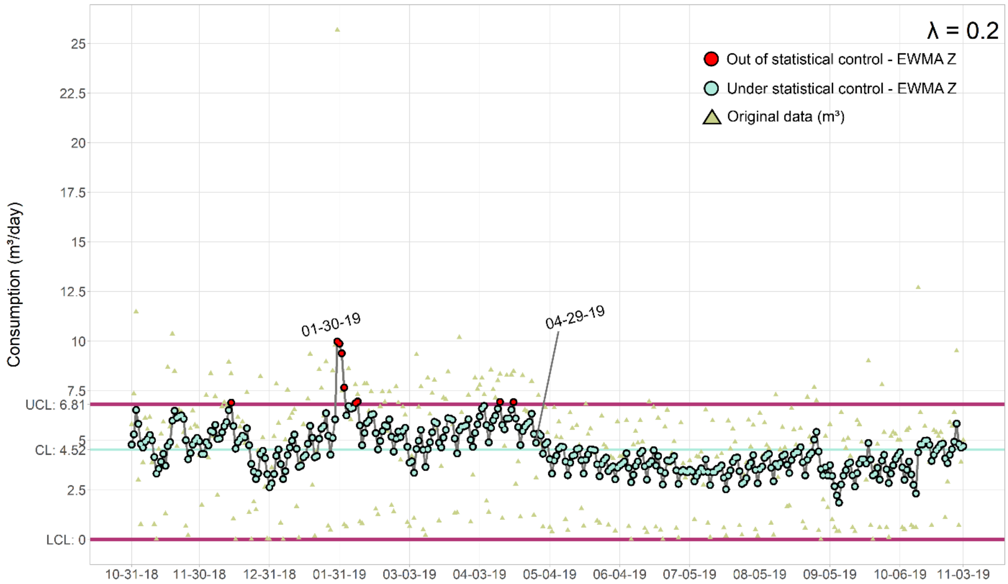


Figure 4: EWMA control chart – Daily consumption – Joinville branch.



This event can be identified in Figures 3 and 4. However, the EWMA chart (Figure 4) flagged three consecutive days (January 31, 2019, February 1, 2019, and February 2, 2019) as out of statistical control. This is due to the EWMA chart's property of assigning different weights to observations based on their age (in this case, the unusual data point on January 30, 2019). Consequently, these three days were deemed false alarms. A steady decrease in average consumption is observable from April 29, 2019, onward. This decrease is more apparent on the EWMA chart (Figure 4), due to its increased sensitivity to small, gradual changes. Two additional days were marked as out-of-control:

a. November 2, 2019 – A consumption of 11.47 m^3/day was recorded. This value was obtained just three days after the installation of the data collection system. Due to a delay in obtaining the initial dataset, acquired via the internet on November 13, 2018, the reason for this outlier could not be determined;
b. October 14, 2019 – A consumption of 12.69 m^3/day was recorded. Between 16h00 and 23h30, the branch underwent renovation, during which water was used for construction and cleaning purposes.

Figures 5 and 6 present the Shewhart and the EWMA control charts, respectively, displaying hourly data for the Joinville's branch from January 29 to 30, 2019. These figures shows that an unusual consumption began during the night of January 29 and returned to normal in the afternoon of January 30, indicating that the external faucet was closed.

Figure 5: Shewhart control chart – Joinville branch hourly consumption from January 29 to 30, 2019.

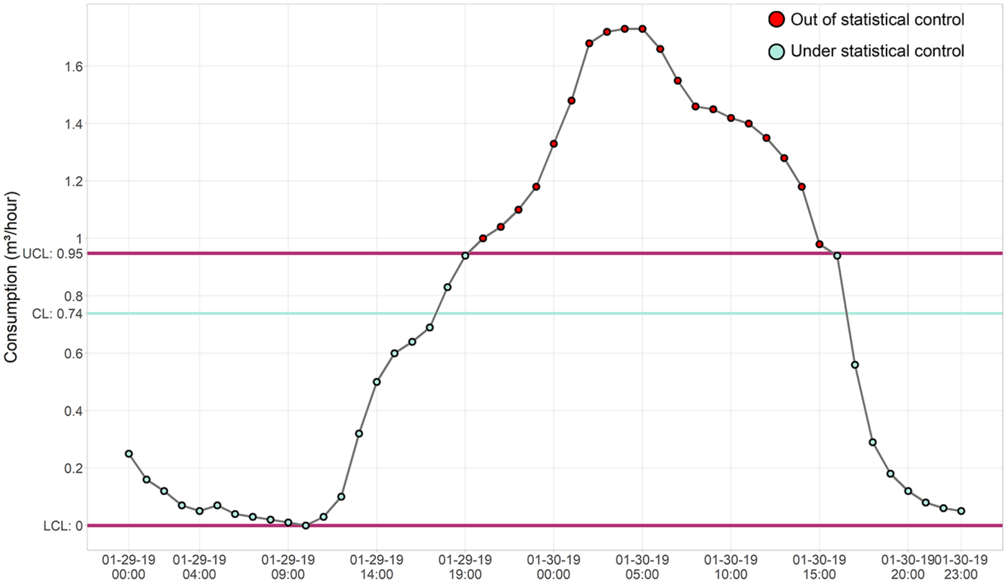
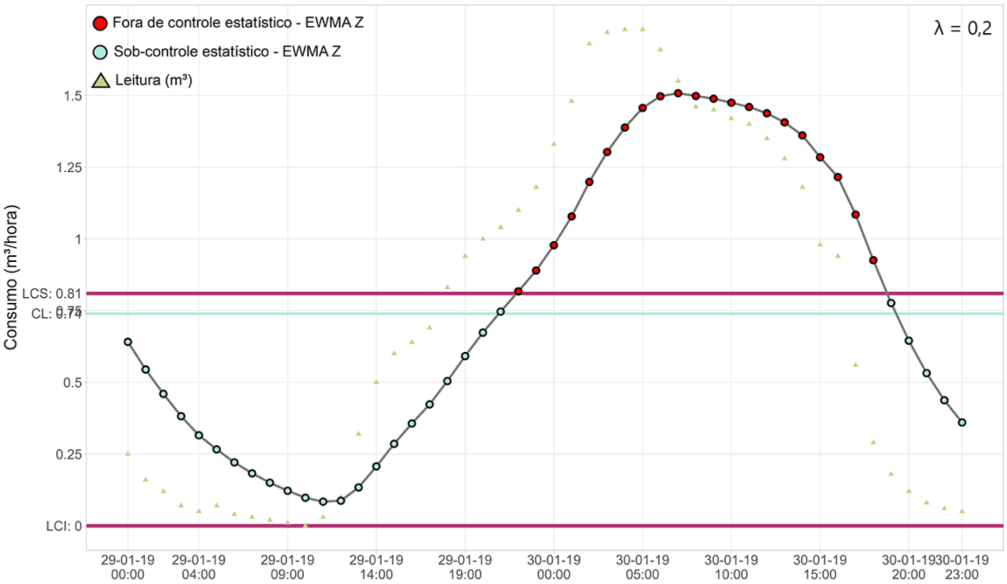


Figure 6: EWMA control chart – Joinville branch hourly consumption from January 29 to 30, 2019.



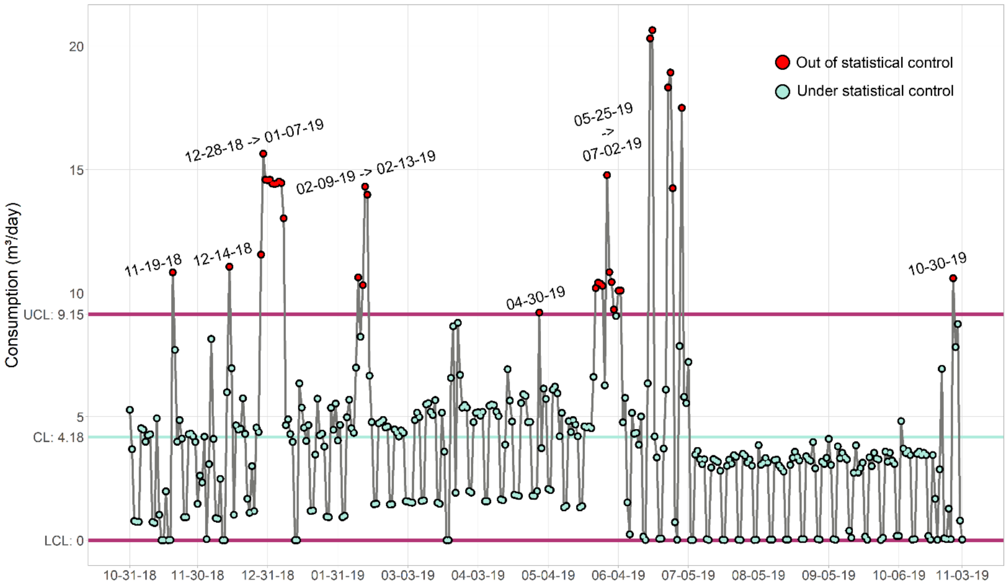
4.2 Water consumption analysis – Criciúma branch

Figures 7 and 8 present the Shewhart and the EWMA control charts, respectively, for daily water consumption at the Criciúma branch. The average consumption was 4.18 m^3/day, with a maximum of 20.65 m^3/day and a standard deviation of 3.69 m^3/day. As Figures 7 and 8 show, the control charts displayed several out-of-control periods. Their respective dates and likely causes are discussed below:

a. November 19, 2018 – A consumption of 10.84 m^3/day was recorded. The likely cause was a leak. Figure 9 displays the hourly control chart for this period;
b. December 14, 2018 – A consumption of 11.07 m^3/day was recorded. Again, the likely cause was a leak. Figure 10 displays the hourly control chart for this period;

c. December 28, 2018 to January 7, 2019 – An average consumption of 14.19 m^3/day was recorded. According to the branch's administration, this elevated consumption was due to a scheduled water tank cleanup that began on December 28, 2018.
d. February 2, 2019 to February 13, 2019 – An average consumption of 11.50 m^3/day was recorded. According to the branch's administration, there was a leak in one of the closed-couple cistern toilets. The toilet was repaired on February 2, 2019.
e. April 30, 2019 – A consumption of 9.22 m^3/day was recorded. Likely a small leak or an outlier;
f. May 25, 2019 to June 1, 2019; June 4 to 5, 2019; June 6 to 19, 2019; June 26 to 28, 2019; July 2, 2019 – On May 25, 2019, 14 closed-coupled cistern flushing systems were replaced, which may have caused the irregular consumption patterns observed at the end of May and throughout June. As Figure 7 shows, minimum consumption was rarely zero before this period, suggesting potential leaks that were addressed by the replacements; and
g. October 30, 2019 – A consumption of 10.61 m^3/day was recorded. Likely a small leak or an outlier.

Figure 7: Shewhart control chart – Daily consumption – Criciúma branch.



It's important to note that the EWMA chart (Figure 8) did not indicate any out-of-control data points on November 19, 2018, December 14, 2018, April 30, 2019, and October 30, 2019. This indicates that these observations are likely false alarms on the Shewhart chart (Figure 7). Using hourly data from November 19 to 20, 2018, Figure 8 displays an unusual consumption beginning in the morning and ending at around 22h00 on November 19, finally returning to normal on the next day, November 20.

The hourly Shewhart control chart displayed on Figure 7 shows that an out-of-control consumption was registered on December 14, 2018. However, Figure 10 indicates that this irregular consumption began on the previous day, December 13, 2018. This reinforces the idea of working with hourly and daily data combined, to accelerate the detection of unusual consumption and to obtain increased control of the process. The daily EWMA chart displayed in Figure 8 demonstrates the distinction between two periods (before and after the replacement of the flushing systems). Lower variations can be observed on the chart, with no out-of-control points detected, after the systems were replaced.

Figure 8: EWMA control chart – Daily consumption – Criciúma branch.

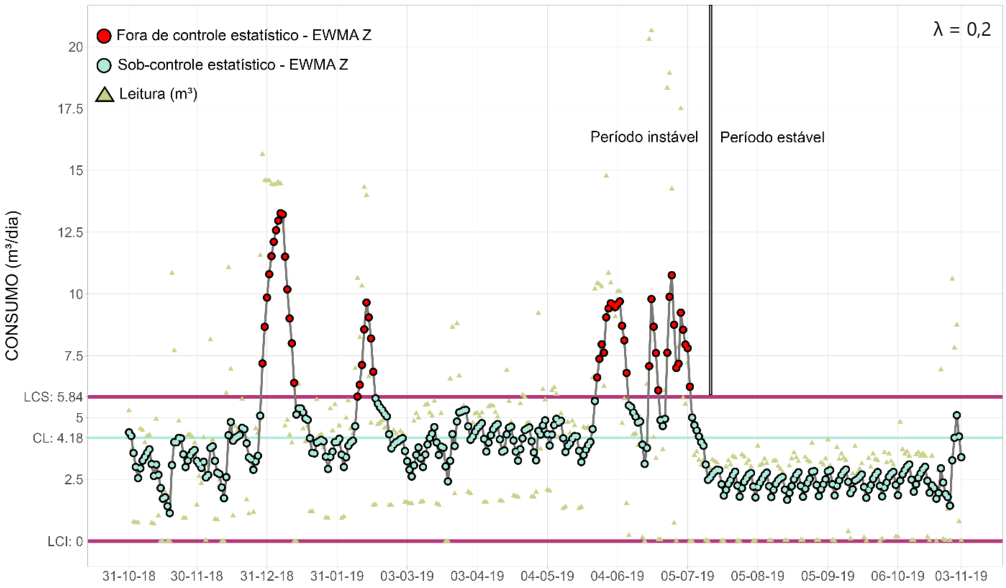


Figure 9: Shewhart control chart – Daily consumption from November 19 to 20, 2018 – Criciúma Branch.

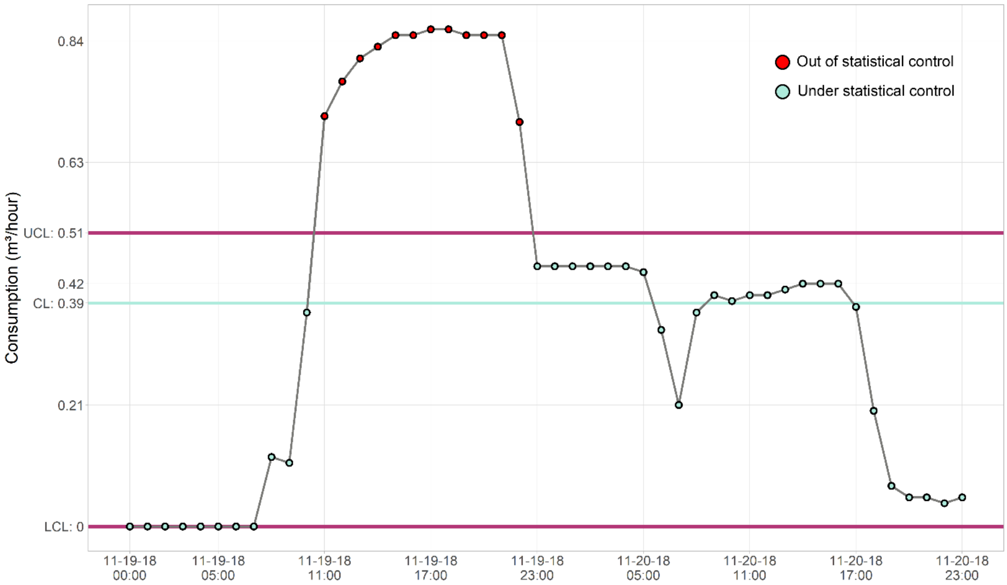
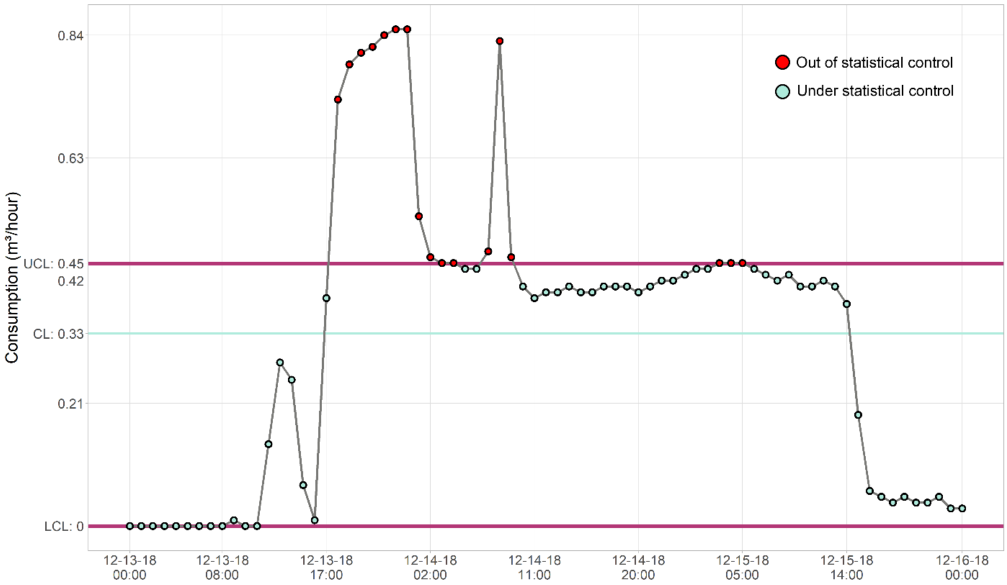


Figure 10: Shewhart control chart – Hourly consumption from December 13 to 15, 2018 – Criciúma branch.



4.3 Water consumption analysis – Curitiba branch

Figures 11 and 12 present the Shewhart and the EWMA control charts, respectively, for daily water consumption at the Curitiba branch. The average consumption was 0.61 m^3/day, with a maximum of 4.82 m^3/day and a standard deviation of 0.75 m^3/day. Compared to the Joinville and the Criciúma branches, the Curitiba Branch presented the lowest water consumption average. However, the control charts were still capable of identifying unusual consumption data. On the chart displayed on Figure 11, several days with zero consumption can be observed. This is because the Curitiba branch has two tanks with a total storage capacity of 7,000 L, and the branch's daily average consumption is 610 L. This means that the stored volume is sufficient for several days. This is noteworthy because, according to the Brazilian regulation NBR 5626 (ABNT, 2020), the total volume of water stored must ensure minimum water quality requirements, avoiding an excessive reduction in the effectiveness of the disinfecting agent, considering the average storage period.

Figures 11 and 12 show two out-of-control periods that happened in the Curitiba branch, discussed below:

a. December 28, 2018 to January 15, 2019 – An average consumption of 1.51 m^3/day was recorded. An inspection of the branch on January 10, 2019 revealed a leak in one of the toilets. While a representative of another outsourced monitoring system reported no anomalies, leaks or a consumption increase, the control charts were able to detect the unusual consumption. Although the control limits on the chart in Figure 11 did not indicate any anomalies, except for December 28, 2018, the minimum data values for this period were not zero, suggesting a potential recurring leak. This data inconsistency is more apparent in the EWMA chart (Figure 12).
b. February 12 to 15, 2019 – An average consumption of 1.75 m^3/day was recorded. The branch manager reported a leak in the same toilet as before, which was repaired on the morning of February 13, 2019. The EWMA chart (Figure 12) shows points above the UCL until February 15, 2019. This is because the EWMA chart assigns weights to data points based on their age. This is a recurring occurrence with EWMA charts,

where it identifies a sequence of observations as out-of-control because of its weight assigning property. An unexperienced operator might misinterpret this as a phenomenon, which otherwise would not happen with the Shewhart control chart.

Figure 11: Shewhart control chart – Daily consumption – Curitiba Branch.

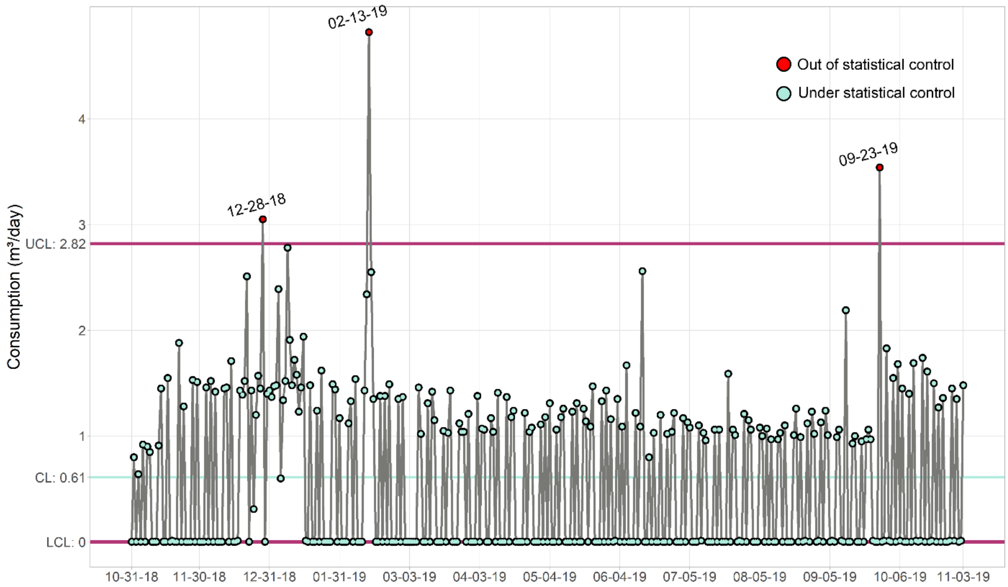
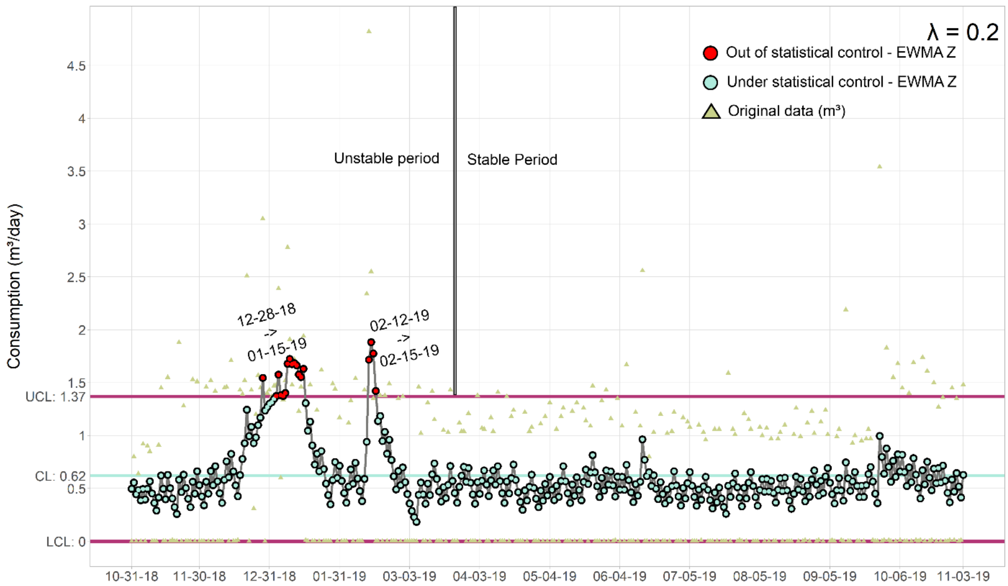


Figure 12: Gráfico EWMA control chart – Daily consumption – Curitiba branch.



4.4 Water consumption per m² of built area

The Joinville, the Criciúma and the Curitiba branches had total built areas of 3,165.40 m², 3,554.06 m², and 2,118.89 m². respectively. Table 1 provides a statistical overview of the daily consumption per m² of built area for the three branches.

Table 1: Daily consumption per m² of built area.

		Branch		
		Joinville	Criciúma	Curitiba
Built area (m^2)		3165.40	3554.06	2118.89
Consumption per area (liters/m^2/day)	Average	1.47	1.27	0.29
	Median	1.56	1.19	0.00
	Standard deviation	0.94	1.08	0.35

Figure 13 presents a box plot illustrating the daily consumption per m^2 of built area for each branch. Figure 14 shows a Shewhart chart for the combined daily consumption per built area of all three branches, during the analysis period. Similarly to the previous charts, out-of-control observations were identified by the control limits. The same happens with the consumption per customer interaction and per employee charts, suggesting that analyzing raw consumption data can be used to identify these out-of-control points, considering the context in which the control charts are used combined with an understanding of the process variables.

According to a report by the U.S. Energy Information Administration (EIA, 2012), the average consumption on commercial buildings was 1.63 L/m^2/day. The consumptions registered in the Joinville (1.47 L/m^2/day) and in the Criciúma (1.27 L/m^2/day) branches were comparable to that, while the Curitiba branch (0.29 L/m^2/day) was relatively lower. However, it is important to note that the Curitiba branch had a greywater reuse system.

Figure 13: Consumo Daily consumption per m² – Joinville, Criciúma, and Curitiba branches.

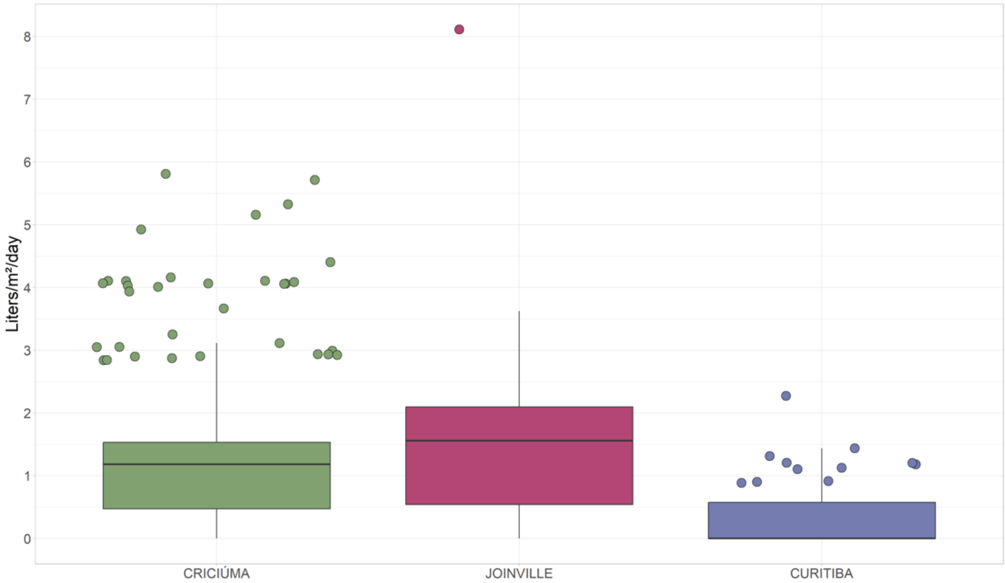
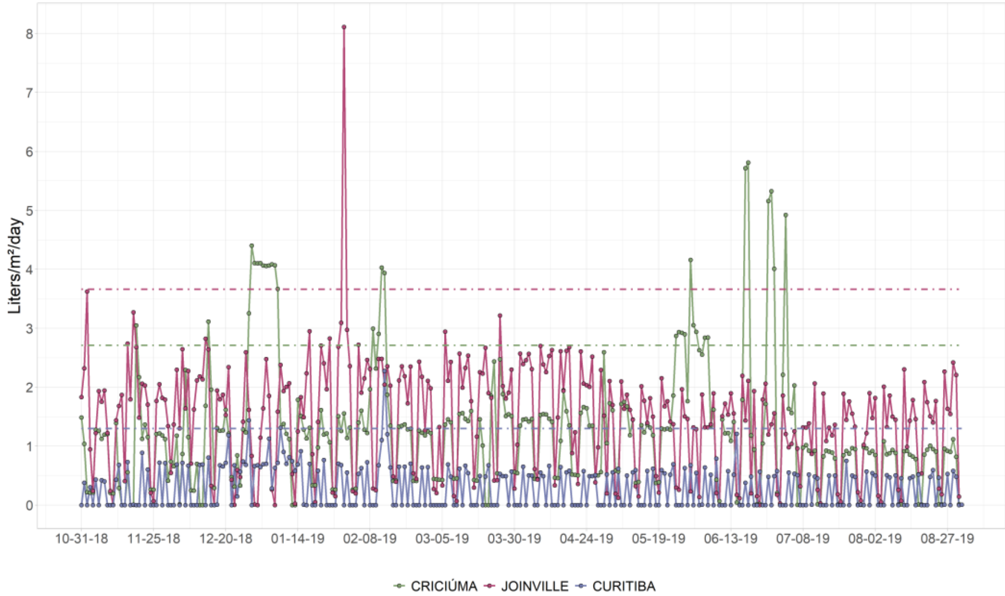


Figure 14: Shewhart control chart – Daily consumption per m^2 – Joinville, Criciúma, and Curitiba branches.



4.5 Water consumption per employee

During the analysis period, the Joinville branch had 40 employees directly related to banking activities and 17 staff members (guards, janitors and interns), totaling 57 active employees. The Criciúma branch had 120 bank-related employees and 10 extra staff members, in a total of 130 active employees. The Curitiba branch had 10 primary employees and 8 staff members, totaling 18 active workers. Table 2 provides a statistical overview of the daily consumption per employee for the three branches.

Table 2: Daily consumption per employee.

		Branch		
		Joinville	Criciúma	Curitiba
Number of employees	Bank-related	40	120	10
	Extra staff	17	10	8
Consumption per employee (L/employee/day)	Average	81.82	34.73	34.69
	Median	86.49	32.31	0.00
	Standard deviation	52.21	29.63	41.36

Figure 15 presents a box plot illustrating the daily consumption per employee, in liters per employee per day, calculated for each branch during the data analysis period. Figure 16 shows a Shewhart chart displaying the combined daily consumption per employee for all three branches. The daily consumption per employee chart on Figure 16 shows that the control limits, indicated by dashed lines, effectively identified unusual consumption patterns in all three branches. For instance, the Joinville branch experienced a significant consumption spike from January 29 to 30, 2019.

In a study published by the United States Environmental Protection Agency (EPA, 2019), the expected average daily consumption per employee ranges from 75.70 L/employee/day to 132.49 L/employee/day. While the consumption registered in the Joinville branch (81.82 L/employee/day) falls within this range, the consumption in the Criciúma (32.73 L/employee/day) and in the Curitiba (34.69 L/employees/day) branches do not. In a study published by Proença and Ghisi (2010), 10 commercial buildings registered an average daily water consumption ranging from 34.9 L/user/day to 101.60 L/user/day. Again, the daily average consumption per capita in the Joinville branch is in that range, while the consumptions in the Criciúma and in the Curitiba branches are not. Kalbusch *et al.* (2018) conducted a study in 10 public buildings, using one full year worth of collected data, registering a daily consumption per employee ranging from 39.70 L/user/day to 69.30 L/user/day. Hackbarth *et al.* (2023) evaluated the consumption per capita of 53 offices in the city of Joinville, registering a daily consumption per employee ranging from 6.87 L/employee/day to 159.10 L/employee/day. The average consumption from their sample was 53.26 L/employee/day.

Figure 15: Daily consumption per employee – Joinville, Criciúma, and Curitiba branches.

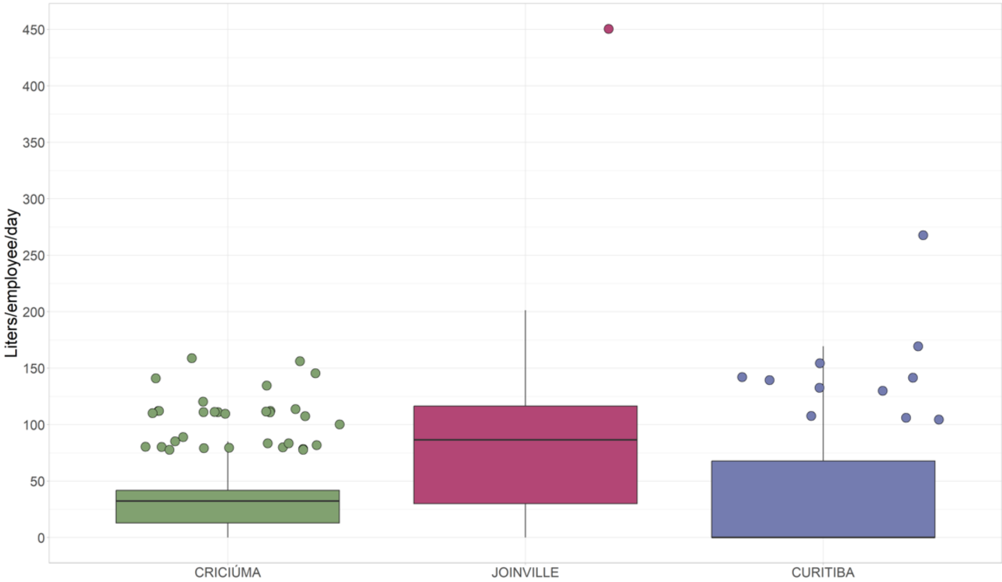
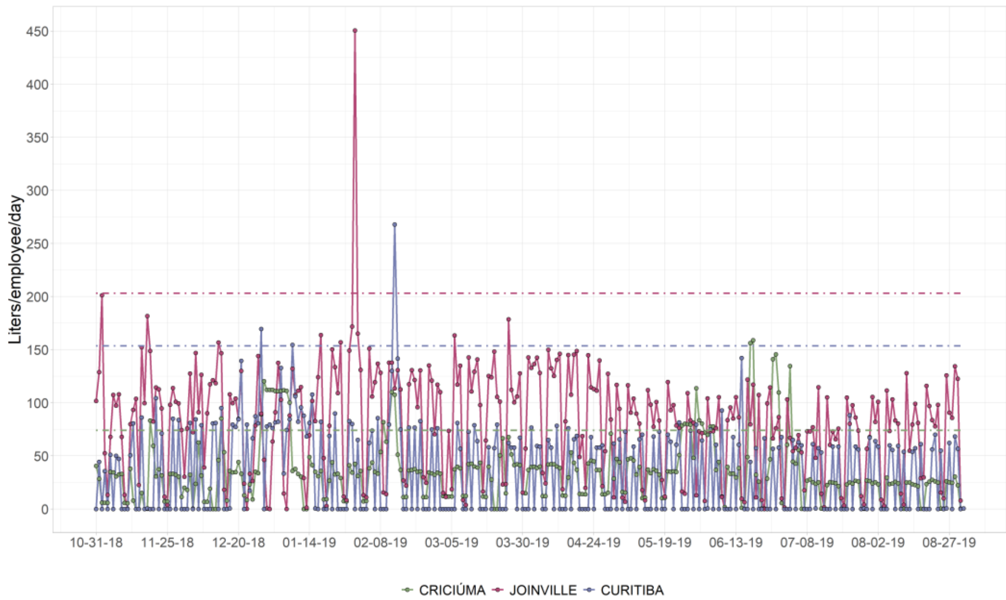


Figure 16: Shewhart Control Chart – Daily consumption per employee – Joinville, Criciúma, and Curitiba branches.



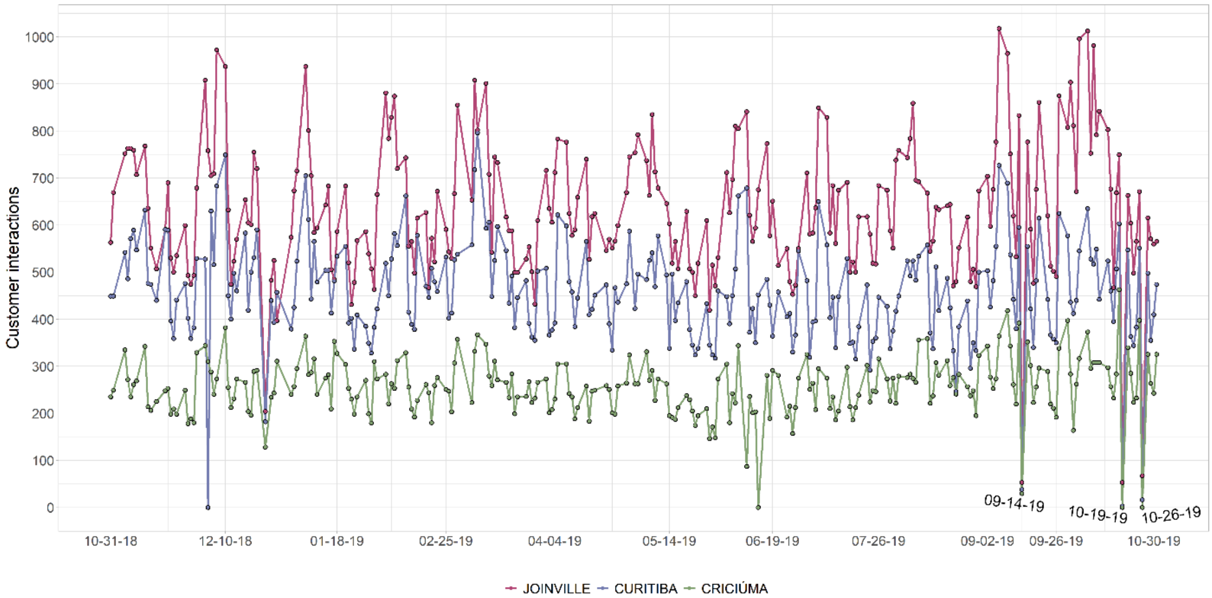
The water consumption discrepancy between the Joinville branch and the ones in Criciúma and Curitiba can be partially explained by their ages, as the Joinville branch is an older building. Another reason for this increased consumption is the water-based air-cooling system, exclusive to that branch. It is also important to note that the Curitiba branch has a greywater reuse system.

4.6 Water consumption per customer interaction

Data on the number of custom interactions was collected from October 31, 2018 to October 31, 2019, across all three branches, totaling 262 weekdays of analysis. The chart displayed in Figure 17 illustrates the variation in the number of customer interactions during the period. The chart suggests that the Joinville branch recorded the highest number of customer interactions per day, followed by the Curitiba branch, while the one in Criciúma recorded the lowest number.

Additionally, the chart displayed in Figure 17 shows a sudden decrease in the number of customer interactions that occurred on a specific day in all three branches. As the branches are typically closed on Saturdays, this sudden decrease can be attributed to the fact that on September 14, 2019, October 10, 2019, and October 26, 2019, all of which were Saturdays, the branches were exceptionally open, as the federal government allowed citizens to withdraw money from a mandatory fund called FGTS, from the Brazilian Portuguese “Fundo de Garantia por Tempo de Serviço”. Therefore, there was no significant variation in daily consumption per customer interaction for all three branches during the data gathering period. The Joinville, the Criciúma, and the Curitiba branches registered averages of 637, 257 and 460 customer interactions per day, respectively.

Figure 17: Variation in the number of customer interactions – Joinville, Criciúma, and Curitiba



A statistical overview can be found in Table 3, showing the daily consumption per customer interaction for all three branches. Figure 18 presents a box plot illustrating the daily consumption per customer interaction, in liters per service per day, for each branch during the data analysis period. Figure 19 displays a Shewhart control chart depicting the daily consumption per customer service for each branch during the same period. The control limits for each branch are indicated by a dashed line.

Table 3: Daily consumption per customer interaction.

		Branch		
		Joinville	Criciúma	Curitiba
Daily consumption per customer interaction (L/service/day)	Average	10.06	20.93	1.76
	Median	9.37	17.32	2.07
	Standard deviation	7.35	15.99	1.78

Figure 18: Daily consumption per customer interaction – Joinville, Criciúma, and Curitiba branches.

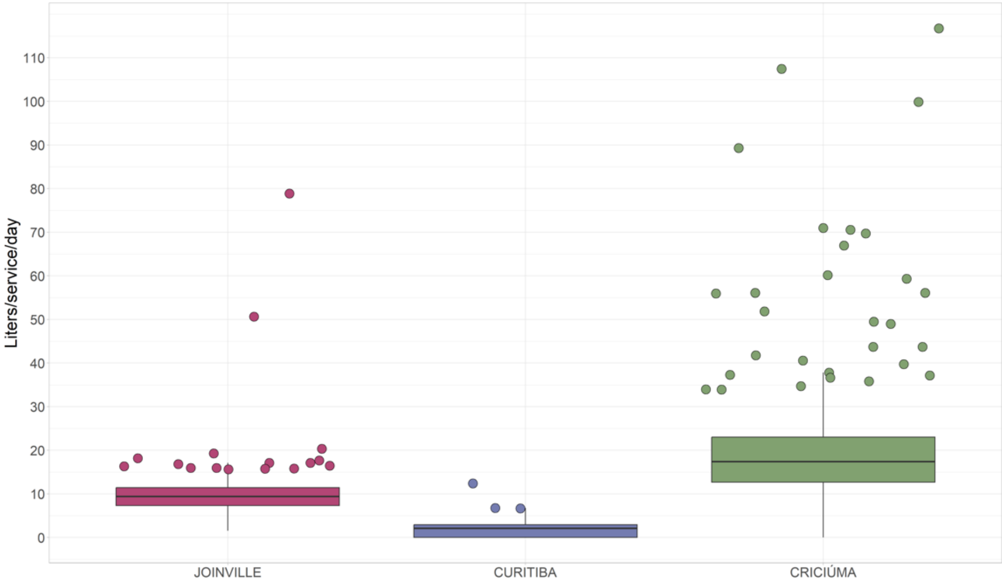
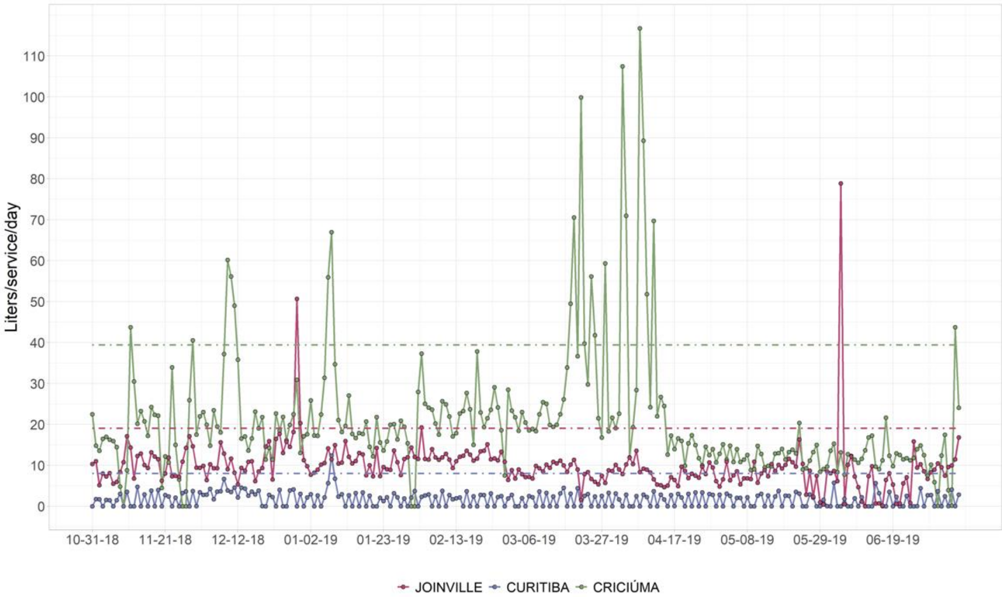


Figure 19: Shewhart control chart – Daily consumption per customer interaction – Joinville, Criciúma, and Curitiba branches.



4.7 Discussion

Considering the results, the control charts presented in this work, combined with a telemetry system, can be incorporated into water monitoring systems of bank branches, because of the control charts' versatility. To analyze water consumption, they can work with multiple time intervals, such as hourly, daily and monthly. However, working with both Shewhart and EWMA charts combined is recommended in order to make use of each chart's strengths (the Shewhart is good at detecting large consumption variations, while the EWMA is good at detecting subtle and smaller ones) and, therefore, be able to efficiently and swiftly detect leakages and other consumption irregularities. This will lower the response time and, consequently, reduce water consumption.

In this work, the sigma limits (standard deviation) were increased from 3 to 6 sigma. Using a 3-sigma limit yielded a large number of out-of-control observations, which did not correspond to any leaks found by the maintenance teams and were likely occasional increases in consumption. The 6-sigma limit was more precise to detect leaks that were effectively confirmed by the maintenance teams. Maintenance calls were, therefore, more efficient, since the alarms provided by the control charts were more reliable (generated fewer false alarms), reducing the number of trips for inspection and repair. Besides the financial costs implied, sending in a maintenance team to fix a non-existing leak is a frustrating process, which demotivates the team and increases response time when real maintenance is needed.

Another reason to increase the sigma limit from 3 to 6 was to avoid issues with autocorrelated data (Claro *et al.*, 2007). Considering the indicators water consumption per m^2, per employee, and per customer interaction used in the control charts (Figures 14, 16, and 19), a few irregularities can be seen that were also found by the daily consumption control charts. Therefore, using these indicators in combination with Shewhart control charts can improve the water consumption analysis in the branches. Furthermore, these water consumption indicators allow for a comparison between bank branches, effectively creating a benchmark.

The initial goal of this work was to analyze excessive consumption, in this case, points above the Upper Control Limit (UCL), which represent large leaks or improper water utilization. Solving such challenging issues was possible after few months of monitoring and analysis. Figure 7 illustrates that some days registered a low non-zero consumption (zero consumption is expected during the night, when the branch is empty), suggesting at least one small leak. This issue was solved after the replacement of the toilet flushing system. As a result, the daily consumption data which was previously registered above the central line shifted below it, as expected. This proves the presence of small but constant leaks that had gone undetected by users or by the monthly consumption analysis containing just one full-month reading. Only after the hourly consumption analysis implementation could this issue be detected and, then, finally fixed. A consumption reduction from 4.99 m^3/day to 2.48 m^3/day was registered, adding up to 298.69 m^3 in saved water by the end of the data analysis period.

5 Conclusion

Both types of control charts used in this work proved to be effective at monitoring water consumption in bank branches, emphasizing the advantages and disadvantages of each, such as the short response time for larger variations achieved by the Shewhart chart, and the EWMA chart's high sensitivity to smaller process variations. Such differences suggest that, for an ideal water consumption monitoring, both charts can be used concurrently. There are other types of control charts beyond the ones in this study which could also be incorporated into the monitoring system after more tests to assess their efficiency and applicability.

The control charts can be incorporated into a telemetry system, where they can be generated in different time intervals (hourly, daily, monthly etc.). The shorter the time interval, the shorter its response time in identifying and resolving the issue. The charts do not necessarily need to be visually analyzed, meaning that an algorithm can be written and incorporated into the data collection system to automatically generate an alarm whenever it detects an out-of-control data point so that the system manager could take the necessary steps to investigate and fix the potential issue.

The hourly data analysis with a 15-minute interval precision displayed an adequate performance for monitoring the water consumption in bank branches. Increasing the sigma limit from 3 to 6 resulted in higher precision for detecting existing leaks, which were effectively confirmed by the maintenance teams, thereby reducing the number of false alarms. The water consumption indicators for the Joinville (81.82 L/employee/day), the Criciúma (34.73 L/employee/day), and the Curitiba (34.69 L/employee/day) branches showed consumption values comparable to those found in other research studies conducted in offices around Brazil.

The Joinville (1.47 L/m^2/day) and the Criciúma (1.27 L/m^2/day) branches registered a consumption closer to those found in more recent studies, while the Curitiba (0.29 L/m^2/day) branch registered a lower consumption in comparison. However, it is important to note that the Curitiba branch has a greywater reuse system. No studies were found that contained the L/service/day indicator. This indicator could potentially enable comparisons between branches based on customer interactions, whether they are bank branches, postal offices or other public institutions, effectively establishing a benchmark for the sector. Further analyses of this indicator are strongly recommended for future studies.

Finally, small and constant leaks cannot be identified using a single water consumption monthly reading that is usually provided by the local water utility. Therefore, implementing hourly consumption monitoring enables the identification and prompt resolution of such issues. This was demonstrated in the Criciúma branch, where the average consumption was reduced from 4.99 m^3/day to 2.48 m^3/day after the replacement of all toilet.

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