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Monitoring Carbonation Levels in Beverage Production Using X-Bar/R-Charts and Tabular CUSUM: A Statistical Process Control Study at Seven-Up Bottling Company, Kaduna, Nigeria

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Abstract

Carbonation is a defining sensory attribute of carbonated soft drinks and a critical determinant of product quality because carbon dioxide (CO_2) volume directly influences taste, perceived freshness, mouthfeel, and consumer acceptability. Deviations from specified carbonation levels can result in under-carbonated beverages that taste flat and stale or over-carbonated products characterized by excessive foaming, premature cap ejection, and potential bottle-integrity failures. Maintaining consistent CO_2 volume is particularly challenging in high-capacity bottling operations such as Seven-Up Bottling Company, Kaduna, which produces up to 800,000 bottles daily across multiple product types and bottle sizes. Carbonation levels may fluctuate because of variations in beverage temperature, syrup concentration, filling pressure, and machine calibration across production shifts. This study aims to evaluate the statistical stability of the carbonation process and distinguish common-cause variation from assignable-cause variation in CO_2 volume. A dataset comprising 30 production subgroups, generated through the facility's 30-minute gas-volume monitoring procedure, was analyzed using Statistical Process Control techniques. The X-bar and R-chart combination was applied to assess process central tendency and dispersion, while the Cumulative Sum chart was used to detect small and persistent shifts that might not be readily identified through conventional control charts. The combined application of these methods provides a systematic framework for identifying abnormal carbonation patterns, supporting timely corrective action, and strengthening process-control decisions. This study contributes the first documented Statistical Process Control analysis of carbonation quality at the Kaduna facility and offers a practical basis for improving product consistency, reducing quality failures, and enhancing consumer acceptability in large-scale beverage production.

Keywords: Carbonation Quality; Carbon Dioxide Volume; Cumulative Sum Chart; Statistical Process Control; X-Bar and R Charts

INTRODUCTION

Statement of the Problem

A key quality concern in carbonated beverage production is whether the CO_2 level — which determines the taste and freshness of the product — remains statistically stable throughout a production run and across different bottle sizes. Unstable carbonation directly translates to product inconsistency, which undermines brand quality standards and customer satisfaction. While SBC Kaduna conducts routine gas volume checks, the absence of formal SPC chart-based monitoring means that process drift may go undetected until multiple subgroups have been produced at non-conforming CO_2 levels. This study addresses this monitoring gap.

Objectives of the Study

The specific objectives are: (i) to establish X-bar and R-chart control limits for CO_2 volume in the SBC Kaduna carbonation process; (ii) to identify out-of-control signals using X-bar and R-chart rules; (iii) to apply Tabular CUSUM analysis to detect sustained process mean shifts; and (iv) to test whether systematic variation in CO_2 levels exists across 30cl, 35cl, and 50cl bottle sizes that could manifest as taste and freshness differences.

Research Hypothesis

H_0: There are no possible causes of variation in taste and freshness identified in 30cl, 35cl, and 50cl bottles while products are properly filled as calibrated by the machines.

H_a: There are possible causes of variation in taste and freshness identified in 30cl, 35cl, and 50cl bottles while products are properly filled as calibrated by the machines.

Literature Review

X-Bar and R-Charts in Process Monitoring

The X-bar and R-chart control chart pair is the most widely deployed SPC tool for monitoring continuous quality characteristics in manufacturing (Shewhart, 1924; Montgomery, 2009). The X-bar chart monitors the process mean by plotting the mean of each subgroup against time, while the R-chart monitors process variability by plotting the range of each subgroup. Used in conjunction, they provide a comprehensive picture of process behaviour: a stable X-bar chart with an unstable R-chart indicates that the process mean is controlled but variance is expanding, while an unstable X-bar chart with a stable R-chart indicates a mean shift without a change in process spread (Wiley et al., 2007).

Control limits for the X-bar chart are derived from the process grand mean and average range: $UCL(\bar{X}) = \bar{\bar{X}} + A_2\bar{R}$ and $LCL(\bar{X}) = \bar{\bar{X}} - A_2\bar{R}$, where A_2 is a constant dependent on subgroup size n. R-chart limits are: $UCL(R) = D_4\bar{R}$ and $LCL(R) = D_3\bar{R}$, where D_4 and D_3 are tabulated constants (Montgomery, 2009). A TEST 1 violation — defined as one observation more than three standard deviations from the centre line — is the primary out-of-control signal and indicates the presence of an assignable cause requiring investigation.

Tabular CUSUM for Mean Shift Detection

The Cumulative Sum (CUSUM) chart is specifically designed for early detection of sustained mean shifts in process output — shifts that may be too small to trigger an immediate X-bar chart out-of-control signal but that represent a progressive deterioration of process quality (Montgomery, 2009). The Tabular CUSUM procedure accumulates deviations above and below the process target using one-sided upper ($CUSUM^+$) and lower ($CUSUM^-$) statistics. The process is declared out of control when either statistic exceeds the decision interval H = hσ, typically set at H = 5σ for optimal average run length performance (Montgomery, 2009).

The reference value K = 0.5σ is calibrated to detect process shifts of approximately 1σ magnitude, making the Tabular CUSUM an effective complement to the X-bar chart for carbonation monitoring, where gradual CO_2 concentration drift due to gas line pressure changes or equipment degradation may precede acute out-of-control signals.

METHODOLOGY

Data Collection

CO_2 volume measurements (in volumes, vol) were obtained from SBC Kaduna's Quality Control records. A total of 30 subgroups were collected at 30-minute intervals during production, each subgroup comprising n = 5 bottle measurements sampled from 30cl, 35cl, and 50cl product lines of five carbonated beverage variants (Pepsi, Mirinda Orange, Teem Bitter Lemon, Mountain Dew, and 7UP). The beverage brix (%) was determined by a Densitometer/spectrophotometer and CO_2 content (g/L) by a Carbo QC CO_2 tester per manufacturer's instructions.

Control Chart Parameters

The grand mean and average range were computed as $\bar{\bar{X}}$ = 108.2/30 = 3.6067 vol and $\bar{R}$ = 8.25/30 = 0.275 vol respectively. For n = 5, the applicable control chart constants are A_2 = 0.577 (reduced to effective value from process data), D_3 = 0, D_4 = 2.281. The CUSUM parameters were set at K = 0.5σ (reference value) and H = 5σ = 0.30522 (decision interval), with σ = 0.061044548 estimated from the subgroup data.

RESULTS

X-Bar Chart Results

The X-bar chart parameters and control limits for CO_2 volume are summarised in Table 1.

Table 1: X-Bar Chart Control Limits for CO_2 Volume

Parameter	Value
Grand Mean ($\bar{\bar{X}}$)	3.6067 vol
Average Range ($\bar{R}$)	2.380

Parameter	Value
Upper Control Limit (UCL)	3.7552 vol
Centre Line (CL)	3.6067 vol
Lower Control Limit (LCL)	3.4581 vol
Out-of-Control Points (TEST 1)	Subgroup 23 ($\bar{X}$ = 3.44 vol)

The X-bar chart identified one TEST 1 violation at subgroup 23, where the sample mean of 3.44 vol fell below the LCL of 3.4581 vol. This observation indicates that an assignable cause — most plausibly a temporary pressure fluctuation in the CO_2 supply line, a temperature excursion in the product supply, or a momentary calibration deviation in the carbonation equipment — produced an anomalously low CO_2 reading at that subgroup. Investigation and corrective action at subgroup 23 are warranted.

R-Chart Results

Table 2 presents the R-chart control limits.

Table 2: R-Chart Control Limits for CO_2 Volume

Parameter	Value
Average Range ($\bar{R}$)	2.380
Upper Control Limit (UCL)	5.431
Centre Line (CL)	2.380
Lower Control Limit (LCL)	0
Out-of-Control Points (TEST 1)	Subgroup 5

The R-chart similarly identified one out-of-control subgroup at observation 5, where the sample range exceeded the UCL of 5.431. This pattern — an isolated R-chart violation at subgroup 5 accompanied by an X-bar violation at subgroup 23 — is characteristic of transient assignable cause events rather than sustained process deterioration, supporting the Tabular CUSUM findings reported below.

Tabular CUSUM Results

The Tabular CUSUM was applied with process mean μ_0 = 3.6067 vol, reference value K = 0.5σ = 0.0305 vol, decision interval H = 5σ = 0.30522 vol, and σ = 0.061044548 vol. Table 3 presents selected CUSUM statistics.

Table 3: Selected Tabular CUSUM Results for CO_2 Volume (Subgroups 1–30)

i	$\bar{X}_i$ (vol)	$CUSUM^+(i)$	N^+	$CUSUM^-(i)$	N^-
1	3.57	0	0	0.006	1
5	3.54	0	0	0.101	5
6	3.66	0.023	1	0.017	6
11	3.60	0	0	0	0
20	3.73	0.158	3	0	0
23	3.44	0	0	0.136	1
27	3.68	0.048	3	0	0
30	3.61	0	0	0	0

The maximum $CUSUM^+$ value observed across all 30 subgroups was 0.201 (at subgroup 21), and the maximum $CUSUM^-$ value was 0.137 (at subgroup 23). Neither statistic exceeds the decision interval H = 0.30522 vol. The Tabular CUSUM therefore finds no evidence of a sustained mean shift in CO_2 volume over the 30-subgroup monitoring period. The process is in a state of statistical control with respect to sustained drift, notwithstanding the isolated X-bar and R-chart violations.

Hypothesis Test Outcome

Based on the Tabular CUSUM results, the null hypothesis H_0 — that there are no systematic causes of variation in taste and freshness across 30cl, 35cl, and 50cl bottles — cannot be rejected. The absence of any CUSUM statistic exceeding the decision interval H = 0.30522 vol confirms that CO_2 variation across bottle sizes and product types is consistent with common-cause process noise rather than assignable-cause systematic shifts. Taste and freshness variation attributable to carbonation process instability is therefore not statistically evidenced in the data.

DISCUSSION

The combined X-bar/R-chart and CUSUM analysis presents a nuanced picture of carbonation quality at SBC Kaduna. The existence of isolated out-of-control signals at subgroups 5 and 23 — while not indicating sustained process instability — nonetheless represents events that warrant investigation and remediation. In a high-volume production environment where a single subgroup of 30-minute interval production may encompass thousands of bottles, even transient CO_2 deviations of the magnitude observed (3.44 vol against a target of 3.6067 vol) can affect consumer-perceptible quality across a significant production volume.

The Tabular CUSUM confirmation of process mean stability is reassuring but should not be interpreted as a basis for reducing monitoring frequency. Rather, the finding that the process is susceptible to transient assignable cause events — manifesting as isolated violations without sustained drift — suggests that rapid-response corrective action protocols are more critical than enhanced monitoring frequency. Operator response time from out-of-control signal detection to machine adjustment represents the key process quality lever in this context.

CONCLUSION

This study applied X-bar/R-chart and Tabular CUSUM analysis to CO_2 volume monitoring data from SBC Kaduna. The key findings are: (i) The carbonation process is broadly in statistical control, with control limits of UCL = 3.7552, CL = 3.6067, and LCL = 3.4581 vol for the X-bar chart; (ii) Two isolated out-of-control signals were detected — one on the X-bar chart at subgroup 23 and one on the R-chart at subgroup 5 — both attributable to transient assignable causes; (iii) Tabular CUSUM analysis confirms the absence of sustained mean shifts (maximum CUSUM statistic 0.201, H = 0.305); and (iv) The hypothesis of no systematic taste and freshness variation across bottle sizes cannot be rejected.

The following policy recommendations are made: (i) Management should ensure that CO_2 carbonation equipment — including gas supply lines, carbonation vessels, and pressure regulators — is maintained in a standardised, calibrated state through a formal preventive maintenance schedule; (ii) The Quality Control Manager should formalise real-time X-bar and R-chart monitoring of CO_2 volume, with automated alerts triggered at TEST 1 violations, to enable rapid corrective response; (iii) Investigation protocols for isolated out-of-control signals should be documented and implemented, with root cause analysis required for each identified violation; (iv) Future studies should extend the CUSUM analysis to brix (sugar concentration) as a complementary taste quality parameter, providing a more complete statistical characterisation of the sensory quality control system.

REFERENCES

[1] Montgomery, D. C. (2009). *Introduction to statistical quality control* (6th ed.). Wiley.

[2] Juran, J. M. (1997). Early SQC: A historical supplement. *Quality Progress, 30*(9), 73–81.

[3] Marilyn, K., & Robert, B. (2007). *Statistical process control: Principles and applications*. McGraw-Hill.

[4] Montgomery, D. C. (2009). *Introduction to statistical quality control* (6th ed.). Wiley.

[5] Reza, M., & Payam, N. (2009). Application of statistical quality control techniques in manufacturing: A process control perspective. *International Journal of Quality & Reliability Management, 26*(7), 684–701.

[6] SBC Quality Control Records. (2023). *CO_2 volume monitoring data: Gas volume check logs* [Internal quality-control documentation]. Seven-Up Bottling Company, Kaduna Plant.

[7] Shewhart, W. A. (1924). Some applications of statistical methods to the analysis of physical and engineering data. *Bell System Technical Journal, 3*(1), 43–87. https://doi.org/10.1002/j.1538-7305.1924.tb01347.x

[8] Tague, N. R. (2004). *The quality toolbox* (2nd ed.). ASQ Quality Press.

[9] Render, B., Stair, R. M., Jr., & Hanna, M. E. (2009). *Quantitative analysis for management* (10th ed.). Pearson Prentice Hall.