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Optimizing Cost-Efficient Quality Control: An Economic Statistical Design of Variable Sampling Interval CV Chart with Unknown Shifts

***Wai Kwan Lau*[1]**
lauwk@utar.edu.my[1]

***Chai Thing Tan*[1]**
tanct@utar.edu.my[1]

***Chong Heng Lim*[1]**
limch@utar.edu.my[1]

***Wai Mun Har*[2]**
harwm@utar.edu.my[2]

[1]Teh Hong Piow Faculty of Business and Finance, Universiti Tunku Abdul Rahman, Malaysia
[2]Faculty of Accountancy and Management, Universiti Tunku Abdul Rahman, Malaysia

Abstract

Defective outputs in manufacturing or service industries lead to wastage and losses. Maintaining process stability and minimizing defects are important aspects of quality control. Statistical Process Control (SPC) provides a scientific solution to monitor process performance and identify special cause variation due to uncommon errors or problems. Through its control chart method, SPC can also identify anomalies in the process and thus, able to point out unconformity. This in turn will provide a relatively higher consistency in good quality output and reduce wastages.

The control charts applied through SPC are different from the traditional version commonly being used. These traditional versions independently monitor the process mean and variability. Problem against these traditional versions is that the process mean and variability are independent. Therefore, traditional way may not be able to grab hold of the actual process behaviour when it changes concurrently in a certain dependent relationship. In contrast, the concept of coefficients of variation (CV) which measure the ratio of the standard deviation to the mean is able to capture the relative variability effectively. The relatively higher efficiency of the CV-based control charts over the traditional charts has thus gain increasing popularity and adoption in process monitoring recently.

Control charts started concentrating on the Shewhart approach due to its simplicity yet works well in detecting large variations in a process. A major disadvantage is that Shewhart approach is its inefficiency in detecting small and moderate variations. In a competitive business reality and rapid improvement and innovation in digital quality control methods, it is utmost important and regular expectation to provide conforming output. As a result, exponentially weighted moving average (EWMA) and cumulative sum (CUSUM) charts, have been innovated as better advanced control methods. The two charts can enhance detection performance and increase sensitivity to small shifts by recognizing information from past observations.

Another innovation in improving the performance process monitoring is the adaptive control methods. One example is variable sampling interval (VSI) control charts, which changes how often samples are taken based on how the process is performing. It takes samples more frequently when the process shows signs of problems and less often when the process is stable. This approach allows detect changes in the process faster while maintain efficiency when the process is stable. As a result, VSI control charts have been shown to outperform traditional fixed sampling interval (FSI) charts in terms of detection efficiency.

Despite the advancements in statistical design, many existing control charts models focus mainly on statistical performance measures such as the average run length (*ARL*) or average time to signal (*ATS*), without take into the account the costs or economic impact in the monitoring process. In practice, using control chart comes with various costs, including sampling costs, dealing with false alarms, and the costs incurred when detecting and correcting assignable causes. Ignoring these economic factors may lead to designs that are statistically efficient but economically suboptimal. This had led to the development of economic design and economic statistical design approaches. Which aim to integrate statistical performance with cost considerations.

The economic statistical design framework provides a comprehensive approach by simultaneously considering both statistical and economic objectives. In this framework, the design parameters of the control chart are optimised to minimise the expected cost per unit time, subject to constraints on statistical performance. This ensures that the control chart achieves a balance between rapid detection of process shifts and cost efficiency. Although this approach has been successful applied to various types of control charts, its application to CV-based VSI control charts remains relatively limited, especially under realistic conditions where key assumptions may not hold.

A critical limitation of most existing economic statistical designs is the assumption that the magnitude of the process shift is known in advance. Under this assumption, the average time to signal (*ATS*) is commonly used as the performance measure to evaluate the effectiveness of the control chart. In practice, the shift size is unknown and difficult to be estimated in most of the practical situations due to insufficient historical information. The occurrence of assignable causes is often random, and the magnitude of the resulting process shift is likely to vary with time and depends on some unknown stochastic model. Furthermore, limited historical data may prevent practitioners from accurately estimating the shift size. As a result, designing a control chart based on an assumed shift magnitude will results to significant performance degradation if the assumption is incorrect.

The misspecification of shift size can have serious consequences for both statistical performance and economic efficiency. Control charts likely will fail to spot small yet critical deviations instantly if the expected shift size is larger than the actual change. On the other hand, if the expected shift is smaller than the actual change, the chart may become overly sensitive, causing many false alarms and unnecessary process interruptions. These issues highlight the need for a more robust design that does not rely on precise knowledge of the shift size.

To address this limitation, this study suggests a robust and cost-effective design of a variable sampling interval coefficient of variation (VSI CV) control chart when the shift size in the process is unknown. Instead of assuming the magnitude of shift as a fixed parameter, it is treated as a random variable with a certain probability distribution. This allows the design to account for uncertainty in the shift size and better suited for real-world processes.

In this study, the performance of the control chart is measured using the expected average time to signal (*EATS*). To take the shift size into consideration, *EATS* is computed by averaging *ATS* across possible magnitude of shift, with each value weighted according to its probability distribution. This change adds comprehensiveness to its measurement efficiency due to its increase ability to detect changes across different shift scenarios.

Given the lack of prior information about the shift distribution in many practical applications, a non-informative assumption is adopted by modelling the shift size as uniformly distributed over a specified interval. This assumption is extensively used in the literature because it does not prefer or fix the shift size while providing a reasonable approximation on the shift size. The *EATS* is then computed using numerical integration methods which allows an efficient evaluation of the control chart performance.

A comprehensive cost model is developed to see how economically efficient the proposed control chart is. This model calculates the expected cost per unit time by dividing the expected total cost of a production cycle by the expected length of that cycle. The cost components considered in the model include the in-control (IC) quality cost, the out-of-control (OOC) quality cost, the cost of sampling, the cost of false alarms, and the cost of identifying and eliminating assignable causes. This model also considers the stochastic character of process failures, which are assumed to follow an exponential distribution.

The objective of the proposed design is to determine the optimal set of design parameters for the VSI CV control chart. These include the sample size, control limit, warning limit and the short and long sampling intervals. These parameters are obtained by minimising the average cost per unit time, subject to the statistical constraints. Specifically, the IC performance is maintained by imposing a lower bound on the *ATS*, while the out-of-control statistical performance is controlled by imposing an upper bound on the *EATS*.

An optimisation algorithm is used to search for the best combination of design parameters that minimises the average cost per unit time while satisfies the statistical constraints. A penalty method is used to remove infeasible solutions that violate the statistical

constraints, ensuring that only practical and effective designs are considered. The optimisation process is carried out through a systematic search process, which evaluates different combinations of design parameters and identifies the optimal solution.

To evaluate the efficiency of the innovated model, various experiments are conducted using various input parameter settings. The study examines how variations in cost, rates of failure, and process conditions impact the resulting cost performance on the optimal design parameters. The results reveal that the proposed VSI CV control chart with unknown shift size achieves a lower expected cost than the traditional control charts which assume a fixed shift size. This enhancement is due to the ability of the *EATS*-based approach that capture the shift size variation and resulting in a more balanced design.

Furthermore, robustness check on the proposed model under different scenarios are performed by conducting sensitivity analysis. The results imply that the optimum design parameters are influenced by cost of sampling, rate of failure as well as false alarm signalling costs.

In generally, the findings emphasize the benefits of integrating unknown shifting of sizes when designing the VSI CV chart. By incorporating the *EATS* performance metric and cost factors, the proposed chart provides a more realistic and effective framework in monitoring processes. The ability to achieve both cost effectiveness and reliable detection performance makes the suggested approach feasible for modern industrial environments characterised by uncertainty.

In conclusion, this study fills the gap to the existing literature by introducing a more robust and cost-effective design for VSI CV control chart under unknown shift size. The use of *EATS* as a performance metric enables the model to account for variability in magnitude of shift, while economic impacts are integrated to ensure cost-effective operation. The results show that the proposed approach outperforms traditional designs that rely on known shift assumptions. This has made it a valuable tool for practical process monitoring applications. Future study might enhance on this work by exploring different shift size distributions, incorporating Bayesian methods, or applying the methodology to multivariate and non-normal processes.

Keywords:
Cost optimization; Adaptive chart; Expected average time to signal; Unknown shift size