SPC Techniques for Short and Small Runs : A Review and Extensions
다품종 소량생산에서 적용되는 SPC기법의 문헌고찰 및 응용

Sungwoon Choi*
최성운

Abstract

본 연구는 다품종소량 생산시스템에서 적용되는 새로운 SPC 기법에 대한 문헌을 고찰하고 검토하는데 목적이 있다. 기존의 SPC 기법은 주로 소품종 대량생산 시스템에서 적용되어 큰 효과를 보았으나 최근의 생산시스템은 다양한 수요자의 요구를 충족시킬 수 있도록 유연성있는 다품종 소량생산체제로 이행되고 있다. 본 연구에서 사용된 분류체계는 다품종소량생산시스템의 SPC 기법을 우선 계량형과 계수형으로 크게 구분하고 계량형에서는 이를 다시 여덟 가지 차트로 계수형에서는 세 가지 차트로 재분류하여 고찰하며 향후 새롭게 적용될 수 있는 응용기법 등을 제시한다. 특히 현장의 실무진도 쉽게 접근이 가능하고 이해하기 쉽도록 기존의 SPC 기법의 대표적 분류체계인 계량형 · 계수형 구분방법을 사용하였다.

1. Introduction

Classical SPC methods such as $\overline{X}$ and R charts were developed in the era of mass production of identical parts. The current trend is short and small production runs with products tailored to the specific needs of individual customers. This environment has become much more prevalent as technological changes such as flexible manufacturing and numerically controlled processes have caused increasing trends toward build-to-order production.

Burr[3] made five general suggestions, which should help in applying statistical quality control to short runs. The following methods were presented :

(a) Fraction Defective Charts
(b) Complete Studies
(c) Measurement Charts
(d) Check of Setting
(e) X Charts

Pyzdek[36] proposed five SPC approaches for short or small runs as following :

(a) The Exact Method for Variables
(b) Code Value Charts for Variables
(c) Stabilized Control Charts for Variables
(d) Stabilized Attribute Control Charts
(e) Demerit Control Chart

* Dept. of Industrial Engineering, Kyungwon University

Al-Salti et al.[2] provided a review of the use of SPC techniques using data transformation in batch production.

Woodall et al.[53] grouped the literature in a low-volume manufacturing environment into four categories with some of the methods falling into more than one category :

(a) Pooling data from similar parts or processes in an attempt to overcome the data limitations associated with low-volume manufacturing.

(b) Adjusting the standard limits on the control chart (or equivalently transforming the data) to achieve the desired Type I error probability (probability of a false signal).

(c) Emphasizing the monitoring and controlling of the process inputs (e.g., temperature, pressure, rpms) rather than the product characteristics (e.g., diameter, thickness, number of defects).

(d) Using control charts that have greater sensitivity than the standard Shewhart charts. Examples of these charts are the CUSUM chart and the EWMA chart.

But Quesenberry[46] in response to Woodall et al.'s discussion[53] said the approach was not very effective or informative.

Several papers regarding a review and literature survey of statistically -and economically- based control charts in high volume manufacturing have been published by Gibra[18], Vance[51], Choi[6], Montgomery[31], [32], Svoboda[49], and Ho et al.[24].

The paper is structured as follows. Section 2 reviews short-and small-run variables control chart having eight classification regions. Section 3 also reviews attributes control chart having three regions. Extensions are discussed in section 4. Section 5 offers a few simple conclusions.

2. Short -and Small- Run Variables Control Chart

2.1 Two-Stage chart

Hillier[23] proposed a method for setting small-sample probability limits for the Shewhart average and range charts based on the sample mean $\overline{X}$ and average range $\overline{R}$. Thus regardless of the size of the sample, these limit provide the specified probability of a Type I error. Therefore, the charts may be used reliability with these limits as soon as after initiating the inspection of an in-control process. This method consists of two stages, first setting control limits for retrospectively testing whether the process is in control while the initial subgroups are being drawn and then, after identifying the "in-control" initial subgroups, setting control limits in control when future subgroups are drawn.

Yang et al.[54] considered two such measures, the average subgroup variance and the sample variance, and showed for each how to obtain statistically sound control limits based on a small number of subgroups. If accuracy is of paramount importance, and computational considerations are secondary, then it may be worthwhile to use control charts based on the variance (or standard deviation) of the subgroups or the overall sample instead. The approach was quite analogous to that described by Hillier[23] for the $\overline{X}$- and R- charts.

Quesenberry[41] recommended that, whenever possible, the practice of beginning with "trial" limits should be replaced by starting with Q charts for the case when parameters are assumed unknown because of dependence in a charting program to increase the rate of false alarms after shot runs, even though the ARL is increased.

Pyzdek[36] considered the exact method adapted from the work of Hillier[23] and four-step procedure whether a setup is acceptable using a relatively small number of sample units.

2.2 DNOM Chart

Maxell[30] introduced the concept of a cell chart, in which the means and range charts are ruled-off into ten cells and sample data relating to components having different tolerances plotted. The advantage of using this chart is that the control limits are fixed as long as the sample size is constant[2].

Farnum[16] recommended the generalized DNOM(deviations from nominal) to handle models of process and measurement error variation in addition to the constan variance model currently used. Practical experience and knowledge of the particular process should suggest the appropriate models of process and measurement error variance. Given a such model, the general formula σ_i^2 = var($X_m|T_i$) = var((X+ ε)$|T_i$) = var($X|T_i$) + E(var($\varepsilon|X$)) can be used to find σ_i. Incorporating $\hat{\sigma}_i$, an appropriate DNOM chart can be developed from the requirement that the standardized subgroup statistics ($\overline{X}_i$-T_i)/($\sigma_i/\sqrt{n}$) lie between -3 and +3. Four such models are

Model Ⅰ : $E(X|T_i) = T_i$, $\mathrm{var}(X|T_i) = \sigma^2$, $E(\varepsilon|X) = 0$, and $\mathrm{var}(\varepsilon|X) = \sigma_\varepsilon^2$

Model Ⅱ : $E(X|T_i) = T_i$, $\mathrm{var}(X|T_i) = k^2T_i^2$, $E(\varepsilon|X) = 0$, and $\mathrm{var}(\varepsilon|X) = k^2x^2$

Model Ⅲ : $E(X|T_i) = T_i$, $\mathrm{var}(X|T_i) = \sigma^2$, $E(\varepsilon|X) = 0$, and $\mathrm{var}(\varepsilon|X) = k^2x^2$

Model Ⅳ : $E(X|T_i) = T_i$, $\mathrm{var}(X|T_i) = k^2T_i^2$, $E(\varepsilon|X) = 0$, and $\mathrm{var}(\varepsilon|X) = \sigma_\varepsilon^2$

Pyzdek[36] presented code value charts which multiple features can be controlled with a single control chart. The procedure consists of making a simple transformation to the data:

$$\hat{X} = \frac{X - \text{target}}{\text{Unit of measure}}$$

Al-Salti et al.[2] used data transformation technique of X_i - XN_c to measure the sensitivity of standardized control charts.

2.3 Standardized Chart

Nelson[33] considered if a process is production items with different means and/or standard deviations in short runs, and if these items respond the same to process changes, then measurements on these items can be standardized and plotted on the same chart.

Pyzdek[36] proposed stabilized control charts to overcome the unit of measure problem by converting all measurements into standard, nondimensional units. The two transformations being used here are ($\overline{X}$ - grand average)/ $\overline{R}$ and R/ $\overline{R}$.

Al-Salti et. al.[2] proposed six data transformation techniques such as $X_i - \overline{\overline{X}}_c$, $X_i/\overline{\overline{X}}_c$, $(X_i - \overline{\overline{X}}_c)/\overline{\overline{X}}_c$, $(X_i - \overline{\overline{X}}_c)/2T_c$, $(X_i - \overline{\overline{X}}_c)/\sigma_c$, and $(X_i - \overline{\overline{X}}_c)/\overline{R}_c$. Aspects of data transformation were dealt with especially with regard to explaining the mechanism of data transformation and selecting as well as evaluating several transformation techniques. In addition, a method of sensitivity analysis for standardized control charts was also included.

2.4 Short -and Long- Term Chart

Cooper[7] proposed a simple step-by step procedure to carry out SPC machine set-up. The control limits were applied to a set-up control chart. This guarantees all parts are within specification when the batch is run.

Koons et al.[27], [28] recommended SPC procedure monitoring for short -and long- term chart. The logic for this dual monitoring approach is shown in Figure 1 which is a flow chart of the procedure. For analysis of subgroup variance s^2 chart discussed by Duncan[15] was used.

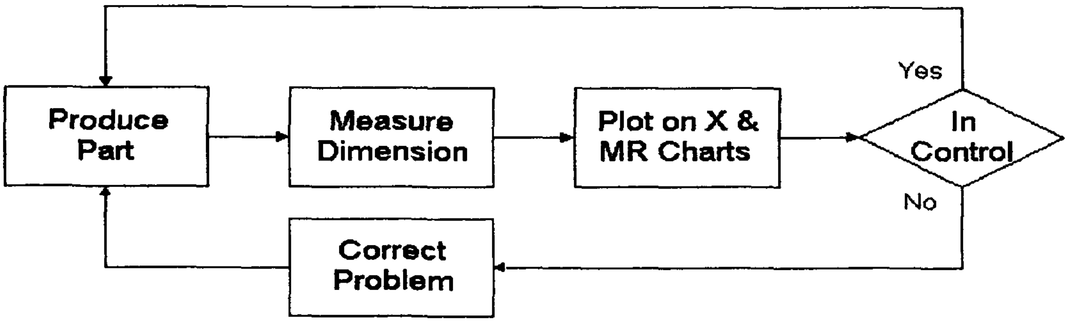

FIGURE 1a. SPC Procedure, Monitoring for Short-Term Control

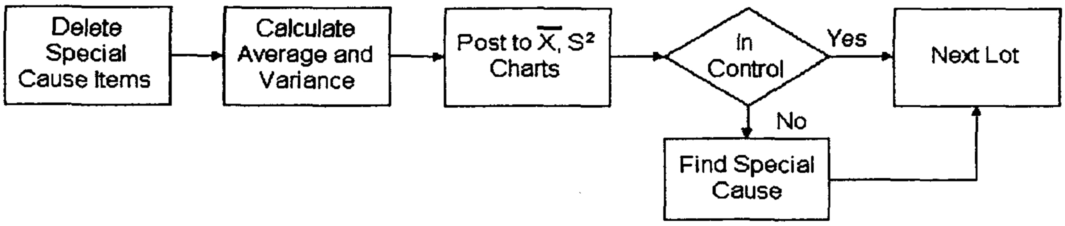

FIGURE 1b. SPC Procedure, Monitoring for Long-Term Control

Lill et al.[29] and [26] proposed statistical methods to estimate, starting with the first piece produced, the most probably correct adjustment to make in a machine setup to produce pieces as close to the desired dimension as possible. Methods were also presented to minimize the effects of a known trend such as abrasive tool wear.

Pillet[35] developed new control charts to permit the application of statistical reasoning even in batches as small as 10. These control charts resemble traditional ones. Both mean and range charts are used, although the principles for calculating control limits for the charts are a little different.

2.5 Pre-Control Chart

Tang et al.[50] provided a rationale for making a statistical comparison between the techniques of 'pre-control' and traditional $\overline{X}$ and R charts. Special attention was drawn to the application of both techniques to the short run manufacturing environment where, for the use of $\overline{X}$ and R charts, parameter estimation is a problem. When sampling effort is important, a comparison that fairly compares the two techniques when the sampling effort is the same, revealed that for capable processes. $\overline{X}$ and R charts are superior to 'pre-control'.

2.6 Q Chart

Quesenberry[39], standardized SPC charts, called Q charts, were proposed for monitoring a process mean or variance for a normally distributed quality variable. Formulas were given for computing the Q statistics for the classical case when the parameters are known and for the case when the process parameters, i.e., mean and variance, are not known, but it is desired to plot $\overline{X}$ and S charts in real time from the start-up point of the operating process, especially for short runs.

Quesenberry[37], [38] proposed methods for screening outliers in univariate normal data or normal regression process data using uniform residuals obtained from conditional probability integral transformations(CPITs). Quesenberry[42] studied the sensitivity of four tests on Shewhart type Q charts and of specially designed EWMA and CUSUM Q charts to detect one-step permanent shifts of either a normal mean or standard deviation.

Farnum[17] discussed since the DNOM chart can be considered a special case of the Q chart (by assuming that μ equals the nominal, or target, value of the process), Q charts should be of value.

Hawkins[21] defined 'self-starting' CUSUMS for normal data with both μ and σ unknown, giving a transformation to a stream of independent $N(0,1)$ quantities and suggesting this stream in Shewhart and CUSUM charts. Hawkins[22] discussed his schemes are different from Quesenberry[39] largely in using an easily-computed approximate transformation rather than the exact transformation to turn the standardized residuals into $N(0,1)$ quantities

Del Castillo et al.[10], [11], [12], [13] presented an analysis of the ARL properties of Q charts. Modifications and alternative methods for different case classified according to the prior knowledge of the process were also presented. Case III, where the process average is known and the process variance unknown, was shown to be easy to deal with by using either an EWMA approach or an adaptive kalman filtering method. Both methods exhibited better ARL performance than Q charts. The case when both parameters are unknown was more challenging, particularly if assignable causes were assumed to produce sudden shifts in the mean level of the quality characteristic. An adaptive kalman filtering method, coupled with a tracking signal, provided a resonable performance since its ARL properties improve as the prior estimates of the process average and variance improve

But Quesenberry[47] showed that ARL and SRL are not useful criteria for comparing control procedures for the situations considered in Del Castillo et al.'s papers [10], [11], [12], [13].

2.7 Kalman Chart

Del Castillo et al.[11] presented a Kalman filter control chart for monitoring stable short-run production processes where the process variance is unknown prior to the start-up of production. It was shown that for the proposed scheme the run length properties are independent of the unknown process variance and that these properties are appropriate for monitoring a stable process during start-up. An economic model for the optimal design of proposed chart was introduced.

2.8 Adjustment-Cost Chart

Crowder[8] presented an algorithm for implementing a finite-horizon or short-production-run version of an economic-process-control model. The control or adjustment limits for this model depend on the break-even points between quadratic cost for being off-target and fixed adjustment cost. The short-run limit were computed using dynamic programming to develop the numerical algorithm. It was shown that the length of the production run can greatly influence the control or adjustment strategy.

3. Short -and Small- Run Attributes Control Charts

Harrison[19] introduced an approach based on running a percentage defective chart on the process. It assumes that the average percentage defective is the same for all components and lacks the ability to defect drift and variability in the process[2].

Caplan[4] described a system for process control in a job shop. An important idea in the system was the fact that it did not matter what quality characteristic was being checked. What mattered was whether or not such a characteristic had been achieved. The cumulative number of the quality characteristics checked and the cumulative number of defects found were calculated. Despite a considerable time lag before information is fed back, the system can help highlight problem areas[2].

3.1 Standardized Chart

Nelson[33] and Pyzdek[36] proposed four standardized attributed control charts based on corresponding classical attribute control chart methods. Four types of control chart were involved :

1. Standardized p charts for the proportion of defective items per sample.
2. Standardized np charts for the number of defection items per unit.
3. Standardized c charts for the number of defects per unit.
4. Standardized u charts for the average number of defects per unit.

These charts are based on the transformation :

$$Z = \frac{\text{Sample statistic} - \text{process average}}{\text{Process standard deviation}}$$

3.2 Demerit Chart

Pyzdek[36] proposed demerit control charts not to lose the information for using attribute data. These were ways, however, to extract additional information from attribute data :

1. Make the attribute data less discrete by adding more classification categories.
2. Assign weights to the categories to accentuate different levels of quality.

3.3 Q Chart

Quesenberry[39], [40] proposed approximatively normalized control charts for charting binomial and poisson random variables.

Quesenberry[43], [44] studied the sensitivity of four tests on Shewhart Q charts and of specially designed EWMA and CUSUM Q charts to detect one-step permananent shifts of binomial and poisson parameters. Quesenberry[45] defined Q statistics for geometric distribution based on the inverse binomial method of sampling when the process fallout p is known and when it is not known in advance of sampling. The effectiveness to detect shifts in p of four tests made on Shewhart Q charts of these statistics as well as both EWMA and CUSUM Q charts computed from these statistics was studied.

4. Extensions

4.1 GT-based Chart

Hubele et al.[25] emphasized the need for introducing new SPC techniques that will take advantage of flexible automation and the availability of sophisticated data acquisition system. They suggested the application of the GT(group technology) concept to SPC, i.e., classifying components into families having similar features and using historical data on such components to setup a quality control plan. The GT concept has also been considered by Dovich[14].

Cheng[5] addressed the issues of small lot sizes and manufacturing complexity in the implementation of SPC in a small-batch, flexible manufacturing environment. The efforts of this research are divided into two major phase. In the first phase, a general approach for implementing SPC in a small-batch, flexible manufacturing environment was proposed to overcome the difficulties encountered in this type of manufacturing, The proposed methodology combined ANOVA with GT part family concepts. In the second phase, an automatic process deviation reasoning system is proposed as an alternative to the traditional human -directed problem- solving approach. The proposed system consists of a deviation recognition algorithm and a knowledge-based expert system. The functions of this system include recognition of process deviation, pointing out the sources of variation, and suggesting the direction of action.

Al-Salti et al.[2] outlined a method for estimation process dispersion parameters based on the GT concept. Koons et al.[27] and Hart et al.[20] proposed detection techniques of the lack of within-subgroup homogeneity.

4.2 Grouped-Data CUSUM Chart

Steiner et al.[48] proposed methodology for the design of sequential methods when data are obtained by gaging articles into groups. They showed how to derive false -alarm rates, power, ASN, and ARL of grouped- data SPRT's[52] and CUSUM procedures. Step-by-step design algorithms were provided to assist the practitioner.

4.3. MPCA Chart

Nomikos et al.[34] considered the problem of using time-varying trajectory data measured on many process variable over the finite duration of a batch process. MPCA(multiway principal-component analysis) is used to compress the information contained in the data trajectories into low-dimensional spaces that describe the operation of past batches. This approach facilitated the analysis of operational and quality-control problems in past batches and allowed for the development of multivariate statistical process control charts for on-line monitoring of the progress of now batches. Control limits for the proposed charts were developed using information from the historical reference distribution of past successful batches.

5. Conclusion

This paper has reviewed some of the very early and most recent development in the SPC charts for short and small runs. Short and small production runs have become a way of life that will become even more common in the future. But today, manufacturing in small batches is carried out without any formalized method. Inevitably, truly competitive industry requires the introduction of more formal methods of SPC. The improvements, both in quality and productivity, that can be gained from this paper, are considerable.

It is also hoped that this paper helps to encourage and speed up the use of proposed techniques as well as to emphasize that SPC charts can be applied ever in short and small production runs.

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