Statistical Quality Control Charts Based on Hyper-Geometrically Distributed Data

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Abstract

In some production and administrative processes, the occurrence of certain events is best described by a hyper-geometric distribution, which in turn should be pictorially depicted by what should be called a "hyper-geometric chart (Hg-chart)" in the field of Statistical Quality Control (SQC). However, this has never been the practice, since the existence of such a chart is absent; as such, prompting administrators and process engineers to make use of already existing charts for approximately depicting hyper-geometric processes. In this article, an SQC chart for any hyper-geometric process has been developed for the total number of events in a fixed number of units. This chart has been referred to as the Hg-chart. The center line (CC), lower control limit (LCL) and the upper control limit (UCL) have been obtained for the proposed chart with a sketch of how the proposed chart should be if used for simulation. It has been recommended that simulation should be used to test the proposed chart as this could prove to be more efficient and appropriate for describing hyper-geometric data rather than using an inappropriate chart to be an approximation for solving the problem.

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1 Introduction

Indeed, like certain concepts in Statistics such as response surface methodology, statistical quality control helps to improve the quality of processes [1,2]; only that it does this with a different approach using "quality control charts" [3,2]. The need for quality control charts in quality control processes cannot be overemphasized especially because of their efficiency at monitoring processes, and their ability at helping process personnel to make valid inferences about the state of a process. This monitoring of processes usually consists of two phases: a phase 1 and a phase 2 [4,5,6]; and the inference so made by the process personnel depends on whether the monitoring approach applied is in phase 1 or phase 2 [5,6]. Phase 1 involves the collection and analysis of historical data of the process in order to: (i) understand the variation of the process overtime, (ii) evaluate the process stability, and (iii) estimate the in-control parameters [7,8,9]. However, phase 2 entails monitoring of the process in real-time in order to quickly detect shifts from the baseline established in phase 1.

But whether phase 1 or phase 2, quality control charts may be used to graph the process data, for as long as information on the distribution of such data is known. In particular, if the process data were known to be normally distributed then suitable charts such as the $\bar{x}-$, $R-$, $s-$, and s^2- charts (variable charts) may be constructed; whereas if the process data were to follow a binomial, Poisson or geometric distribution then suitable charts such as the $p-$, $np-$, $c-$, $u-$, and $g-$charts (attribute charts) may be constructed [3,7,8, 1]. Notwithstanding, when the process data does not follow any of the previously mentioned distributions, such process data are yet handled as if they actually followed one of such distributions, instead of using a chart suitable for graphing such process data; and such was the argument of [3] that gave rise to the development of the $g-$ charts.

For instance, with the continuous advancements of technology in the manufacturing industry, many processes are now characterized by a very small proportion p of nonconforming items. The sampled items in such processes often follow a Bernoulli distribution (that is, the sampled items are independently classified as conforming or nonconforming); hence, the traditional $p-$ and $np-$charts are adopted. But since the in-control value of p, that is p_0, is typically assumed to be known, but may be difficult to estimate especially because of requiring larger sample sizes than that available in practice, [1] suggested the use of a $g-$ charts (geometric chart) as a superior option to the $p-$ and $np-$charts; hence, supporting the argument of [3].

Arguably, even with this development of the $g-$charts, circumstances abound for which such a chart should not be used as the suitable control chart. A typical example is a case involving the random sampling of k items (with a particular feature) in n draws (without replacement) from a finite population of size N that contains K items with that feature, wherein each draw is either a success or a failure. This scenario is typical of a hyper-geometric process, yet handled by the $p-$, $np-$ and $g-$ charts even when they should not be used. In this article, we attempt a development and simulation of the Hg-chart for hyper-geometrically distributed data to bridge the said gap as, so far, based on thorough review of existing literature, this research direction has enjoyed little or no attention. No doubt, an attempt to solve this problem could be of benefit in statistical quality control.

2 Literature Review

2.1 History of statistical quality control

The term "quality" always has been an integral part of virtually all products and services. Notwithstanding, our awareness of its importance and the introduction of formal methods for quality control and improvement

have been an evolutionary development [10]. Frederick W. Taylor introduced some principles of scientific management as mass production industries began to develop prior to 1900 [11]. He pioneered dividing work into tasks so that the product could be manufactured and assembled more easily; his work led to substantial improvements in productivity [12]. Also, because of standardized production and assembly methods, the quality of manufactured goods was positively impacted as well [13]. However, along with the standardized methods came the concept of work standards – a standard time to accomplish the work, or a specified number of units that must be produced per period [14]. Frank Gilbreth and others extended this concept to the study of motion and work design [14]. Much of this had a positive impact on productivity, but it often did not sufficiently emphasize the quality aspect of work [5]. Furthermore, if carried to extremes, work standards have the risk of halting innovation and continuous improvement, which we recognize today as being a vital aspect of all work activities [15,5].

Statistical methods and their application in quality improvement have had a long history. In 1924, Walter A. Shewart of the Bell Telephone Laboratories developed the statistical control chart concept, which is often considered the formal beginning of statistical quality control [16]. Toward the end of the 1920s, Harold F. Dodge and Harry G. Romig, both of Bell Telephone Laboratories, developed statistically based acceptance sampling as an alternative to 100 percent inspection [15]. By the middle of the 1930s, statistical quality-control methods were in wide use at Western Electric Company Inc., the manufacturing arm of the Bell System [15]. However, the value of statistical quality control was not widely recognized by industry. World War II saw a greatly expanded use and acceptance of statistical quality-control concepts in manufacturing industries.

Wartime experience made it apparent that statistical techniques were necessary to control and improve product quality. The American society for Control was formed in 1946. The organization promotes the use of quality improvement techniques for all types of products and services [9]. It offers a number of conferences, technical publications, and training programs in quality assurance. The 1950s and 1960s saw the emergence of reliability engineering, introduction of several important textbooks on statistical quality control, and the view point that quality is a way of managing the organization [2].

According to Mohibul I et al. [15], in the 1950s, designed experiments for product and process improvement were first introduced in the United States. The initial applications were in the chemical industry. These methods were widely exploited in the chemical industry, and they are often cited as one of the primary reasons that the U. S. chemical industry is one of the most competitive in the world and has lost little business to foreign companies. The spread of these methods outside the chemical industry was relatively slow until the late 1970s or early 1980s, when many Western companies discovered that their Japanese competitors had been systematically using designed experiments since the 1960s for process improvement, new process development, evaluation of new product designs, improvement of reliability and field performance of products, and many other aspects of product design, selection of component and system tolerances. The discovery sparked further interest in statistically designed experiments and resulted in extensive efforts to introduce the methodology in engineering and development organizations in industry, as well as in academic engineering curricula.

Since 1980, there has been a profound growth in the use of statistical methods for quality and overall business improvement in the United States. This has been motivated, in part, by the widespread loss of business and markets suffered by many domestic companies that began during the 1970s. For example, the U. S. automobile industry was nearly destroyed by foreign competition during this period. One domestic automobile company estimated its operating losses at nearly $1million per hour in 1980. The adoption and use of statistical methods have played a central role in the re-emergence of U. S. industry. Various management systems have also emerged as frameworks in which to implement quality improvement.

2.2 Definitions of quality control

Various definitions are available on quality control. Quality control is defined as that industrial management technique or group of techniques by means of which products of uniform acceptable quality are

manufactured [17]; it is the needed mechanism by which products are made to measure up to specification determined from customer's demand and transformed into sales, engineering and manufacturing requirements.

It was defined by Paolo CC [6] as a system of inspection, analyzing and action applied to a manufacturing process so that, by inspecting a small portion of the product currently produced an analysis of its quality can be made to determine what action is required on the operation in order to achieve and maintain the desired level of quality.

Rohitha G et al. [18] defined quality control as a scientific management which has the objective of improving industrial efficiency by concentrating on better standard or quality and on controls to ensure that these standards are always maintained. It is not intended to show what is wrong with current technology, but rather to establish what can be achieved with existing methods when they are operated correctly. It is a systematic control by management of the variable in the manufacturing process that affects goodness of the end-product. It is used to connote all those activities which are directed for defining, controlling and maintaining quality.

Zulaikha OA [14] defined statistical quality control as the technique which uses statistical methods to control the quality of goods manufactured; it is one of the most useful and economically important tools in applications of the theory of the sampling in industrial field.

2.3 Quality control charts

Quality control charts are either variable or attribute charts. Here we have briefly discussed both groups of charts and various examples on how they find their use in real life.

2.3.1 Variable control charts

Many quality characteristics are expressed in terms of a numerical measurement. For example, the diameter of a bearing may be measured with a micrometer and expressed in millimeters. A single measurable quality characteristic, such as a dimension, weight or volume is called a variable. Control charts for variables are used extensively. Control charts are one of the primary tools used in the analyses and control steps of DMAIC. When dealing with the primary quality characteristic that is a variable, it is usually necessary to monitor both the mean value of the quality characteristic and its variability. Control of the process average or mean quality level is usually done with the control chart for means, or the control chart. Process variability can be monitored with either a control chart for the standard deviation, called the s **control chart**, or a control chart for the range, called the R **control chart**. The R chart is more widely used [2,5]. Usually, separate and R charts are maintained for each characteristic of interest. The R (or s) chart is among the most important and useful on-line statistical process monitoring and control techniques [7,8,6]. It is important to maintain control over both the process mean and process variability.

2.3.2 Attribute control charts

Many quality characteristics cannot be conveniently represented numerically. In such cases, we usually would classify each item inspected as either conforming or nonconforming to the specifications on the quality characteristics [14]. The terminology defective or non-defective is often used to identify these two classifications of product [7,8].

More recently, the terminology conforming and nonconforming has becomes popular [7]. Quality characteristics of these types are called attributes. Some examples of quality characteristics that are attributes are the proportion of warped automobile engine connecting rods in a day's production, the number of nonfunctional semiconductor chips on a wafer, the number of errors or mistakes made in completing a loan application, and the number of medical errors made in a hospital.

2.4 Previous research directions

Teuku MS et al. [10] studied quality improvement of molding machine through statistical process control in plastic industry. Alimran H et al. [19] studied quality assurance system of garments industry in Bangladesh using it as case study. Mulat AA et al. [11] implemented a statistical process control (SPC) in the sewing section of garment industry quality improvement. Safa T [17] kept track of garment production process and process improvement using quality control techniques. Maruf AR et al. [12] applied statistical process control in a production process. Ogedengbe TI et al. [13] applied statistical quality control for investigating process stability and control in an electric wire industry. Thomas DW [9] studied a variety of control charts. Zulaikha OA [14] applied statistical quality control technique in food and beverage industry using a case study of Habila Food and Beverages Nigeria LTD – Kano.

Frank CK et al. [3] developed and studied statistical control charts based on a geometric distribution. Haftu H et al. [16] applied statistical quality control (SQC) for enhancing market share. Min Z et al. [1] developed geometric charts with estimated control limits. Mohibul I et al. [15] proposed statistical quality control approach in typical garments manufacturing industry in Bangladesh. Kimberly FS [4] developed a generalized statistical control chart for over- or under- dispersed data. Rohitha G et al. [18] studied statistical quality control approaches to network intrusion detection. Muhammad MH et al. [5] studied the development and research tradition of statistical quality control. Paolo CC [6] studied process monitoring with multivariate p-control chart. James CB [8] developed and implemented a geometric-based statistical quality control charts for infrequent adverse events. James CB [7] explained the use and interpretation of statistical quality control charts.

3 Research Methodology

3.1 The hyper-geometric distribution

Suppose a wildlife biologist is interested in the reproductive success of wolves that has been introduced into an area. Her approach could be to catch a sample, size M, and place radio collars on them. The next year, after the wolf packs had been allowed to spread, a second sample, size n, could be caught and the number of this sample that had the radio collars would be x. The hyper-geometric distribution could then be used to estimate the total number of wolves N in the area. This example illustrates an important point in the application of theory to practice – that is, the assumptions that must be made to make the application of a particular theory (distribution) reliable and valid. In the cited example it was assumed that the wolves had intermixed randomly and that the, samples were drawn randomly and independently on the successive years. Also, it was assumed that there had been minimal losses due to the activities of hunters or farmers or gains due to reproduction or encroachment from other areas.

Variate H : N, X, n
Quantile: x, number of successes
Range: $\max(0, n - N + M) \leq x \leq \min(M, n)$

Parameters N, the number of elements in the population, M, the number of successes in the population; n, sample size.

From a population of N elements of which M are successes (that is, possess a certain attribute) we draw a sample of n items without replacements. The number of successes in such a sample is a hyper-geometric variate $H : N, X, n$.

Probability function (prob. of exactly x successes) $\dbinom{M}{x}\dbinom{N-M}{n-x} \bigg/ \dbinom{N}{n}$

Mean (moments about the mean)

$$\frac{nM}{N}$$

Variance

$$\left(\frac{nM}{N}\right)\left(1-\frac{M}{N}\right)(N-n)\bigg/N-1$$

Third

$$\left(\frac{nM}{N}\right)\left(1-\frac{M}{N}\right)\left(1-\frac{2M}{N}\right)(N-n)(N-2n)\bigg/(N-1)(N-2)$$

Fourth

$$\left\{\begin{array}{c}\left[\left(\frac{nM}{N}\right)\left(1-\frac{M}{N}\right)(N-n)\bigg/(N-1)(N-2)(N-3)\right]\\\times\\\left[N(N+1)-6m(N-n)+\left(\frac{3M}{N}\right)\left(1-\frac{M}{N}\right)\left(n(N-n)(N+6)-2N^2\right)\right]\end{array}\right\}$$

Coefficient of skewness

$$(N-2M)(N-1)^{\frac{1}{2}}(N-2n)\bigg/\left[nM(N-M)(N-n)^{\frac{1}{2}}\right](N-2)$$

Coefficient of kurtosis

$$\left\{\begin{array}{c}\left[N^2(N-1)\big/n(N-2)(N-3)(N-n)\right]\\\times\\\left(N(N+1)-6n(N-n)\big/M(N-M)\right)+\left(3n(N-n)(N+6)\big/N^2\right)\end{array}\right\}$$

Coefficient of variation

$$\left[(N-M)(N-n)\big/nM(N-1)\right]^{\frac{1}{2}}$$

3.2 The mean and variance of hyper-geometric distribution

Theorem:

If a random variable X has a hyper-geometric distribution with parameters n, M, and N, then:

(a) The mean is given by:

$$\mu = np$$

(b) The variance is given by:

$$\sigma_x^2 = npq(N-n)\big/N-1$$

Proof (a):

$$\mu_x = E(x)$$

$$\Rightarrow \mu_x = \sum_{x=0}^{n} x\left\{\binom{M}{x}\binom{N-M}{n-x}\bigg/\binom{N}{n}\right\}$$

$$\Rightarrow \mu_x = \sum_{x=0}^{n} x \left\{ \frac{M}{x} \binom{M-1}{x-1} \binom{N-M}{n-x} \bigg/ \binom{N}{n} \binom{N-1}{n-1} \right\}$$

$$\Rightarrow \mu_x = \frac{nM}{N} \sum_{x=0}^{n} \left\{ \binom{M-1}{x-1} \binom{N-M}{n-x} \bigg/ \binom{N-1}{n-1} \right\}$$

$$\Rightarrow \mu_x = np$$

Since

$$p = \frac{M}{N}$$

and

$$\sum_{x=0}^{n} \left\{ \binom{M-1}{x-1} \binom{N-M}{n-x} \bigg/ \binom{N-1}{n-1} \right\} = 1$$

Proof (b):

Recall that $\sigma_x^2 = E(x^2) - \mu_x^2$ and $E(x^2) = E\{x(x-1) + E(x)\}$

But,

$$E(x^2) = E\{x(x-1) + E(x)\} = E\{x(x-1)\} + E(x)$$

$$\Rightarrow E\{x(x-1)\} = \sum_{x=0}^{n} x(x-1) \left\{ \binom{M}{x} \binom{N-M}{n-x} \bigg/ \binom{N}{n} \right\}$$

$$\Rightarrow E\{x(x-1)\} = \sum_{x=0}^{n} x(x-1) \left\{ M(M-1) \binom{M-2}{x-2} \binom{N-M}{n-x} \bigg/ x(x-1) \frac{N(N-1)}{n(n-1)} \binom{N-2}{n-2} \right\}$$

But $\sigma_x^2 = E(x^2) - \mu_x^2$ and $E(x^2) = E\{x(x-1) + E(x)\} = E\{x(x-1)\} + E(x)$

$$\Rightarrow E\{x(x-1)\} = \sum_{x=0}^{n} \{M(M-1)n(n-1)/N(N-1)\} \left\{ \binom{M-2}{x-2} \binom{N-M}{n-x} \bigg/ \binom{N-2}{n-2} \right\}$$

$$\Rightarrow E\{x(x-1)\} = M(M-1)n(n-1)/N(N-1)$$

This is because,

$$\sum_{x=0}^{n} \left\{ \binom{M-2}{x-2} \binom{N-M}{n-x} \bigg/ \binom{N-2}{n-2} \right\} = 1$$

Therefore,

$$E(x^2) = \frac{nM(n-1)(M-1)}{N(N-1)} + \frac{nM}{N}$$

$$E\left(x^2\right) = \frac{n^2 M^2 - n^2 M - n M^2 + n M N}{N(N-1)}$$

$$\Rightarrow \sigma_x^2 = \frac{n^2 M^2 - n^2 M - n M^2 + n M N}{N(N-1)} - \frac{n^2 M^2}{N^2}$$

$$\Rightarrow \sigma_x^2 = \frac{n M (M-N)(N-n)}{N^2(N-1)}$$

$$\Rightarrow \sigma_x^2 = n \times \frac{M}{N} \times \frac{M-N}{N} \times \frac{N-n}{N-1}$$

$$\Rightarrow \sigma_x^2 = \frac{npq(N-n)}{N-1}$$

3.3 Procedure for developing the Hg-chart

In order to develop the proposed chart, the following procedure was taken:

(i) Develop the hyper-geometric distribution based on the nature of the process data
(ii) Obtain the control limits based on the hyper-geometric data
(iii) Sketch the Hg-chart

4 Implementation

4.1 The nature of a hyper-geometrically distributed data

Here, we assume that a lot contains N items, M of which are of type I and $N-M$ of which are of type II. A random variable X denoting the number of items of type I (called success) in a random sample of size n is drawn without replacement from the lot is said to have the hyper-geometric distribution with the probability function given by:

$$f(x) = \frac{\binom{M}{x}\binom{N-M}{n-x}}{\binom{N}{n}} \quad x = 1, 2, 3, \ldots, n$$

4.2 The control limits for the proposed Hg-chart

Now, If we assume that a process is generating events according to a hyper-geometric distribution, then the center line (CC), Upper Control Limit (UCL) and Lower Control Limit (LCL) are respectively summarized in the Table below, where the parameter a is the known minimum possible number of events.

Table 1. Control limit for Hg- chart with standards given

	Total number of events chart
Center line (CC)	$\frac{nM}{N} = np$
Upper Control Limit (UCL)	$n(p+a) + k\sqrt{npq(N-n)\big/N-1}$
Lower Control Limit (LCL)	$n(p+a) - k\sqrt{npq(N-n)\big/N-1}$

Let the subgroup $X_1, X_2, X_3, \ldots, X_n$ be a random sample of size n from the process (hyper-geometric in nature). The X_i for $1, 2, 3, \ldots, n$ are, therefore independent and identically distributed random variables for a hyper-geometric distribution. The two statistics of interest are the total number of events $T = X_1 + X_2 + X_3 + \cdots + X_n$ and the average number of events $\overline{X} = T/n$ in the subgroups. Then:

$$E(T) = n(p + a)$$

$$\mathrm{var}(T) = \frac{nq}{p^2}$$

$$E(\overline{X}) = \frac{q}{p} + a$$

$$\mathrm{var}(\overline{X}) = \frac{q}{np^2}$$

Using these expectations and variances, the center line and $k\sigma$ control limits are computed in the usual fashion.

4.3 Sketching of the Hg-chart

Based on the center line (CC), lower control limit (LCL), and upper control limit (UCL) obtained in the Table above, the Figure below gives a sketch of the proposed Hg-chart.
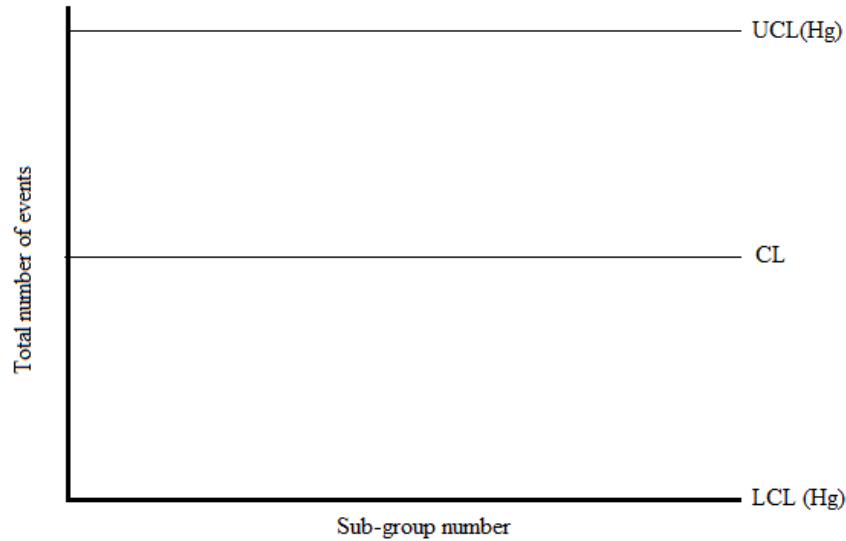

Fig. 1. Sketch of the proposed Hg-chart

The sketch above gives a description of the proposed Hg-chart for a hyper-geometrically distributed data. The chart clearly plots the total number of events against the sub-group number for any process whose information be described as being hyper-geometrically distributed.

5 Conclusion

This article exposes a common problem in quality control analysis, being that of using unsuitable charts as approximations for data that are differently distributed from the distribution based on which such charts are developed. In this article, a case is made for data which follow a hyper-geometric distribution. Based on this, a chart termed "the Hg-chart has been developed in the study to cater for data of this nature. The center line (CL), lower control limit (LCL), and the upper control limit (UCL) have all been obtained for the proposed chart (the Hg-chart) with a sketch of how the proposed chart should be if used for simulation.

The article concludes based on the development that the proposed Hg-chart, no doubt, may prove to be more efficient than other previously developed charts for meeting the demands of analyzing hyper-geometrically distributed data. More so, the article concludes that an incorporation of this chart into software which graph data could make simulation better, easier, elegant and faster; hence, making deductions and inferences from such data possible in quick time.

This article recommends, based on the study developments that simulation should be used to test the proposed chart, as tendencies abound that this could prove to be a very efficient, as well as appropriate tool for the description of process data which follow a hyper-geometrically distributed process; rather than adopt/implement charts which are unsuitable processes of this kind as approximations to solving the problem.

Competing Interests

Authors have declared that no competing interests exist.

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