APPLIED MATHEMATICS AND STATISTICS LABORATORY

STANFORD UNIVERSITY
CALIFORNIA

SAMPLING INSPECTION BY VARIABLES
WITH NO CALCULATIONS

By
HERMAN CHERNOFF AND GERALD J. LIEBERMAN

TECHNICAL REPORT NO. 22
April 22, 1955

PREPARED UNDER CONTRACT N6onr-25126
(NR-042-002)
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SAMPLING INSPECTION BY VARIABLES WITH NO CALCULATIONS

By

Herman Chernoff and Gerald J. Lieberman

1. Introduction

Most industrial applications of acceptance sampling today are by attributes, and will probably continue in this way. Nevertheless, the increase in the use of modern statistical techniques in industry has resulted in the more widespread use of sampling inspection by variables. The advantages of sampling inspection by variables are well known. For example, for a given operating characteristic curve (O.C. curve), smaller samples may be used with variables than with attributes to insure this specified protection. On the other hand, the disadvantages of sampling inspection by variables are also well known. Perhaps the two most important of these are (1) the increased clerical costs of recording the data and making relatively (compared to attributes) difficult computations, and (2) the operating characteristic curves depend heavily on the assumption that the form of the underlying frequency distribution of the quality characteristic is normal. This assumption is often difficult to evaluate.

The purpose of this paper is to present a graphical procedure for sampling inspection by variables which involves no computations and which also gives a check on the assumption of normality. This procedure will be referred to as "No Calc." in the ensuing sections. The results are only approximate and should be considered to be a "quick and dirty" technique.
and used where such procedures are tolerable. Although the approximations are good, "No Calc." is not a replacement for the usual variable procedures when a contract between two parties exists and calls for inspection by variables.


Prepare a sheet of normal probability paper in the following manner: 1/
The abscissa (horizontal axis) represents a percentage, \( p \), between 0 and 100, and the ordinate (vertical axis) represents the observation scale. 2/
Draw a sample of \( n \) items and locate their values on the ordinate scale.
Denote the smallest value by \( u_1 \), the second smallest value by \( u_2 \), \ldots, and the largest value by \( u_n \). Locate the points \((p_1, u_1), (p_2, u_2), \ldots, (p_n, u_n)\) on the graphs and visually fit a straight line to these points. The values of \( p_1, p_2, \ldots, p_n \) are found in Table I for \( n \leq 20 \). For all other \( n \), let 
\[ p_i = \frac{2i-1}{2n}. \]
The straight line can be used to estimate the percentage of observations falling outside the specification limits.

If there is only an upper specification limit, \( U \), given, locate the value of \( U \) on the ordinate scale. 3/ The fraction of values falling below this limit is estimated by finding the abscissa where the fitted line

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1/ Normal probability paper is available commercially, e.g., Keuffel & Esser Co., N.Y.
2/ The observations need not be ordered beforehand as the plotting will order them naturally.
3/ If the same sample size is to be used over and over, the \( p_i \) can be plotted on the normal probability paper beforehand.
4/ It is important to have \( L \) and/or \( U \) appear on the graph. This may entail using an enlarged piece of normal probability paper in order to get a good line.
intersects the line \( u = U \). Call this value \( 1 - \hat{P}_U \). Determine \( \hat{P}_U \), and accept the lot if \( \hat{P}_U \leq p^* \). The value of \( p^* \) is found in Table II for a given AQL and sample size code letter.

If there is only a lower specification limit, \( L \), given, locate the value of \( L \) on the ordinate scale. The fraction of values falling below this limit is estimated by finding the abscissa where the fitted line intersects the line \( u = L \). Call this value \( \hat{P}_L \). Accept the lot if \( \hat{P}_L \leq p^* \). The value of \( p^* \) is found in Table II and is the same as that for the case of an upper specification limit.

For a double specification limit, both \( \hat{P}_U \) and \( \hat{P}_L \) are found in the manner described above. The lot is accepted if \( \hat{P}_U + \hat{P}_L \leq p^* \). The value of \( p^* \) is also given in Table II.

The operating characteristic curves for the plans presented in Table II can be found in [2].

It is important to caution the user, at this time, that the points \( (p_1, u_1), (p_2, u_2), \ldots, (p_n, u_n) \) should appear to fall on a straight line. If this fails to happen, it may be an indication that the variable measured does not follow a normal distribution. In this case, existing variables techniques should not be used, and the lot should be accepted or rejected on the basis of attribute sampling.

Example: The specified minimum yield point for certain steel castings is 56500 psi. A 4% AQL plan is to be used with a sample size of 10. The yield points of the sample specimens are:

\[ \text{\textsuperscript{1/}} \text{ See \textsuperscript{1/} on page 2.} \]
58380
60440
61520
57180
58880
57800
62480
60680
59700
59350

These points are plotted on the vertical axis as shown in Figure 1. Thus \( u_1 = 57180, u_2 = 57800, \ldots, u_n = 62986 \). The values of \( p_1 \) found in Table I for \( n = 10 \) are plotted on the horizontal axis. Thus \( p_1 = 4.419\%, p_2 = 16.422\%, \ldots, p_n = 95.581\% \). The points \((p_1, u_1) = (4.419\%, 57180); (p_2, u_2) = (16.426\%, 57800), \ldots, (p_n, u_n) = (95.581, 62480)\) are located on the graph, and a straight line fitted to the data. Corresponding to \( L = 56500 \) psi, \( \hat{P}_L \) is found to be 3.0%. From Table II, the value of \( p^* \) for a 4% AQL and a sample size of 10 is 10.23%. Hence, the lot is accepted since \( \hat{P}_L < p^* \).

3. **Theory**

It is well known that it is possible to transform the cumulative-normal-distribution curve to a straight line by means of a non-linear transformation of the horizontal scale. Graph paper possessing this property is known as normal probability paper. The abscissa scale represents a percentage, \( p \), between 0 and 100, whereas the ordinate scale corresponds to the values of a normally distributed chance variable. The straight line, then, presents the percentage of values from a normal distribution falling
below a specified value. For example, a normal distribution with mean 10 and standard deviation 3, plotted on normal probability paper, is shown in Figure 2. The mean of the normal distribution can be determined by finding the ordinate where the line intersects \( p = .5 \), and the standard deviation can be determined by taking the distance between the ordinates where the line intersects \( p = .8413 \) and \( p = .5 \). The fraction of these values falling below some upper specification limit can be determined by finding the abscissa where the line intersects \( u = U \). For example, in Figure 2, 90\% of the values fall below \( U \).

If a sample of \( n \) independent observations is to be plotted on normal probability paper, it is natural to arrange them in ascending order, i.e., \( u_1 \leq u_2 \leq \ldots \leq u_n \), and to plot a point corresponding to each observation. Once the points \((p_1, u_1), (p_2, u_2), \ldots, (p_n, u_n)\) are plotted and a straight line is visually fitted to the points, the mean can be estimated as the ordinate where the line intersects \( p = \frac{1}{2} \), and the standard deviation can be estimated as the distance between the ordinates where the line intersects \( p = .8413 \) and \( p = .5 \). The fraction of the values falling below \( U \) can be estimated by finding the abscissa where the line intersects \( u = U \).

If the fraction defective is defined as the fraction falling above \( U \) (one minus the fraction falling below \( U \)), the above procedure leads to an estimate of the fraction defective. Denote this estimate by \( \hat{P}_U \). The lot is rejected if \( \hat{P}_U \) is too large. This statement can be made more

\[1/\] The plotting positions of the \( p_i \) are somewhat arbitrary. This point is discussed below when a set of values of \( p_i \) are presented.
precise if the lot is rejected when $\hat{p}_U > p^*$, where $p^*$ is a fixed constant depending upon the O.C. curve chosen. The only problems remaining is to find an "optimal" estimate of $\hat{p}_U$ and to present a set of $p^*$ corresponding to a given set of O.C. curves.

The estimate of the fraction defective depends upon the method of plotting and the plotting positions of the observed values. The authors have shown [1] that if the method of least squares is used, an optimal method of estimating the mean, standard deviation, and the value $\xi$ such that the fraction of observations below $\xi$ is a fixed constant, determines a fixed set of abscissas ($p_i$). These abscissas lead to optimal estimates in the sense of having minimum mean square deviations from the parameters estimated. The values of $p_i$ are presented in Table II for $n \leq 20$. Optimal values of $p_i$ for $n > 20$ have not yet been computed. However, a glance at Table I reveals that an approximation is given by $p_i = \frac{2i-1}{2n}$.

Furthermore, it has been shown [1], [3] that this approximation leads to efficient estimates.

The distribution of the estimate, $\hat{p}_U$, is related to the distribution of the quantity $\frac{U\bar{u}}{\sigma}$, where $\bar{u}$ is the sample mean (obtained graphically by the method described previously), and $\hat{\sigma}$ is the estimate of the population standard deviation (also obtained graphically by the method described previously). The distribution of $\frac{U\bar{u}}{s}$, where $(n-1)s^2$ is the

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1/ In [1] the authors have shown that the optimal estimates of the mean and standard deviation lead to a fixed set of abscissas. Subsequently, they have also verified that these same abscissas will lead to a good estimate of $\xi$. 
sum of squares of the deviations of the sample values around the mean, is well known [2]. Operating characteristic curves for procedures based on \( \frac{U - \overline{u}}{s} \leq k \), where \( k \) is a fixed constant, have been tabulated and presented in [2]. These curves are referenced according to AQL and sample size code letter.

The distribution of \( \frac{U - \overline{u}}{s} \) and \( \frac{\overline{U} - \overline{u}}{\overline{\sigma}} \) are asymptotically equivalent, and hence, the asymptotic distribution of \( \frac{U - \overline{u}}{\overline{\sigma}} \) is known. For small \( n \), a constant \( C \) is found such that the distributions of \( \frac{U - \overline{u}}{s} \) and \( \frac{\overline{U} - \overline{u}}{\overline{\sigma}} \) are approximately the same. This value of \( C \) has the property that the expected value of \( C \overline{\sigma} \) is equal to the expected value of \( s \), and the variance of \( C \overline{\sigma} \) is approximately equal to the variance of \( s \). The values of \( p^* \) presented in Table II are the probabilities corresponding to normal deviates of \( kC \).

It has been indicated, in [2], that the O.C. curve of the two-sided procedure depends almost entirely on the total percent defective (as opposed to the split between limits) when the optimal estimate of the percent defective presented in [2] is used. Since the estimates presented in this paper are good, the authors conjecture that the result holds for these estimates as well.

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\( 1/ \) The fact that the variance of \( C \overline{\sigma} \) is approximately equal to the variance of \( s \) follows from the empirical results given in [1].
TABLE I.

Values of percentages ($p_i$) to be used in plotting on Normal Probability Paper for the "No Calc." Procedure

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Note: When $i > n/2$ use $p_i = 100 - p_{n-i+1}$

For $n > 20$ use $p_i = \frac{2i-1}{2n}$
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**TABLE II.**

Values of maximum estimated percentage defective allowing acceptance of the Lot (p*).
"No Calc" Procedure for Sampling Inspection by Variables

Plot of Percentage of Yield Points Falling Below a Specific Value

Figure 1.
A Cumulative Normal Distribution with Mean 10 and Standard Deviation 3

Figure 2.
BIBLIOGRAPHY


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Dayton 2, Ohio 5

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Washington, D. C. 15

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Research & Development Division
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Chief, Bureau of Ships
Dept. of the Navy
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Code 223 1

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Chief of Naval Operations
Operations Evaluation Group—OP342E
The Pentagon
Washington 25, D. C. 1

Chief of Naval Research
Office of Naval Research
Washington 25, D. C.
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