Isolated truncated chain deferred sampling plan for Weibull product life distribution

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Abstract. In this article, an Isolated Truncated Chain deferred Sampling Plan for Weibull product life distribution is proposed when the testing is truncated at a specified time. This type of sampling plan is used to save the testing time. The optimal sample sizes, required for testing product quality to ascertain a true mean life are obtained under a given Maximum Allowable Percent Defective, test termination ratios and acceptance numbers. The operating characteristics formula of the proposed plan was developed. The operating characteristics and mean-ratio were used to assess the performance of the plan. The study revealed that: Weibull distribution have low failure rate; as mean life ratio increase, the failure rate reduces and the minimum sample size increase as the acceptance number, maximum allowable percent defective and experiment time ratio increases; The study concluded that the modified required minimum sample sizes were smaller compared to those in the literature making it a more economical plan to be adopted when time and cost of production is expensive and the testing is destructive.

1. Introduction.
Acceptance sampling is a vital field of statistical quality control used to reject or accept products submitted for inspection [1] and [2]. Acceptance sampling is the process of examining samples or fraction of lot to determine whether it meets certain minimum quality specification in order for the lot to be accepted or rejected if otherwise. Dodge and Roming summarized the procedure of Acceptance Sampling is as follows: a sample is randomly taken from a lot and the chance of the products being accepted or rejected depends on the information obtained from this sample. This process is known as acceptance sampling.

Acceptance sampling is not meant to improve the quality of a process and thus is not a suitable tool to use in process control but very important in product control. In literatures, life distributions were not studied under the same platform and the peculiarities of these life distributions were not put into
consideration. Authors like [3] and [4] studied Truncated Acceptance Sampling Plan Based on Generalized
and Marshal Olkin’s Generalized Exponential Distribution respectively assuming Binomial and Poisson
distribution only. It was also observed that the said earlier work did not discriminate effectively between
poor and good quality lots. However, from reviewed literatures, the following perceived flaws need to be
addressed: The failure rate of the life distribution was not considered in literatures; The need to further
reduce sample sizes particularly in situations when testing is costly and destructive; the consumer’s risk
was always considered while neglecting the producer’s risk [5] and [6]; and the ordinary chain sampling
plan consider only the information from the previous without looking at the information from the
succeeding inspected lot for lot disposition. A statistical Quality Control Flow Cycle is as shown in figure
1 below.

Fig. 1: Statistical Quality Control Circle

Proposed Isolated Truncated Chain Deferred Sampling Plan (ITCDSPI)

In this section, an Isolated Truncated Chain Deferred Sampling Plan (TCDSP) is developed; the Operating
Characteristics (OC) function is obtained to calculate OC values. The algorithm and the sampling
procedure are also given. Lastly, a program will be written in R to simulate operating characteristics values.
The advantage of this plan is that the tester considers information from both sides (preceding and
succeeding lots) for an unaccepted lot to be accepted or rejected.

Conditions for Using Isolated Truncated Chain Deferred Sampling Plan

The conditions for the proposed sampling scheme are as follows:

The cost of destructiveness of testing is such that a quite small sample size is necessary; the products to
be inspected consist of a series of successive lots produced by a continuing process; and usually, lots are
expected to be of essentially the same quality.

Operating Procedure of Isolated Truncated Chain Deferred Sampling Plan

The Chain Sampling Plan proposed by Dodge [7] is for costly and small sampling situations. The TCSP
later developed by many authors are only one sided or part chain. The chain sampling plan considers
the past lot in order to decide about the current lot, the differed sampling plan consider the succeeding lots in
order to decide the dispensation of the unaccepted immediate past lot.

However, Osanaiye [8] proposed a CDASP where he considered both information from the
preceding and proceeding lot, in order to accept or reject a current lot. Therefore, the proposed ITCDSPI
is also developed by taking into consideration the results of past and as well as the future lots which is an
extension of the work of [8], if the current information from the sample does not results indisposition of
the lots. If any defective (d) occurs in a lot and the lot is not accepted and information surrounding lots is
required for the acceptance or rejection of the lot, then not only the preceding lot (‘i’) should also be taken
into consideration for the decision of the current lot, the succeeding lots (‘j’) should also be put into
consideration for acceptance or rejection of lot that was not accepted.
Algorithm for Isolated Truncated Chain Deferred Sampling Plan

The operating procedure for this plan is as follows:

Select a sample of n units from each lot and test each unit for conformance to the specified attribute requirements. Count the number of defectives; Accept the current lot if the defective items (d) is zero in the n-sample units; Reject the lot, if d > 1. If d = 1, then go wait for the next lot and test for number of defectives; Accept the lot with d = 1, known as current lot if no defectives are found in the immediately preceding ‘i’ samples and succeeding ‘j’ samples from the same stable state process; Reject the current lot if the number of defectives in the succeeding lot is 1.

2. Research methods

Weibull distribution. The Weibull distribution is commonly applied in failure situations as discussed by [9] and has since then been used in many studies including survival analysis, acceptance sampling inspection and reliability studies. The Weibull distribution still remains one of the most popular distributions for analyzing lifetime data [10] and [11]. The main advantage of the Weibull analysis is its ability to provide accurate failure analysis and failure forecast with very small samples [12], [13] and [14].

The probability density function (pdf) and cumulative distribution function (cdf) of Weibull product life distribution is given as:

\[
\begin{align*}
    f(t; \mu, \alpha) &= \frac{t}{\mu^\alpha} \exp\left(-\left(\frac{t}{\mu}\right)^\alpha\right) \\
    F(t; \mu, \alpha) &= 1 - \exp\left(-\left(\frac{t}{\mu}\right)^\alpha\right)
\end{align*}
\]

{1}

where \(\mu\) is the scale parameter (quality parameter or characteristics parameter) and \(\alpha\) is the shape parameter.

Failure Rate of Weibull Products’ Distribution

Although the probability density function (pdf) describes the time till an item will fail completely, it does not directly specify either the probability of the item continuing to work for a given period of time or how the probability of failure depends on the quality of the part. Therefore, reliability is defined mathematically as:

\[
R(t) = Pr(T > t) = \int_t^\infty f(x)dx 
\]

{2}

\( = 1 - F(t)\) = probability of an item meeting specification for at least till age (time t), where F(t) is the cumulative distribution function (cdf).

Therefore, a useful function used in life time analysis is the failure rate. It is defined as:

\[
h(t) = \frac{f(t)}{1 - F(t)} 
\]

{3}
Equation (3) is the rate of failure given a testing till age \( t \), where \( f(t) \) is the pdf and \( F(t) \) is the cdf respectively. Therefore, the behaviour of failure rate \( h(t) \) as in (3) can be used to characterize product performance over time with special consideration of the fact that:

**Minimum Sample Size (n)**

Suppose the probability of accepting a poor quality lot is fixed and the lot size \( N \) is large enough, the binomial distribution can be used [2]. Thus, the acceptance and non acceptance criteria for the lot are equivalent to the decisions of accepting or rejecting the hypothesis \( \mu \geq \mu_0 \). Suppose we want to find the minimum sample size \( n \) such that:

\[
\sum_{i=0}^{c} \binom{c}{i} p^i (1 - p)^{n-i} \leq 1 - p^* \tag{4}
\]

If \( p = F(t, \mu) \) which is an increasing function of \( \frac{t}{\mu_0} \), it is always sufficient to specify this ratio.

Aslam et al. [6] assumed that if the lot is very large and \( p \) is not very small; therefore, equation (4) can be rewritten as:

\[
\sum_{i=0}^{c} e^{-\frac{\mu^i}{\mu}} \leq 1 - p^* \tag{5}
\]

where \( \mu = np = nF(t; \mu) \).

We therefore have:

\[
\sum_{i=0}^{c} e^{-\frac{\mu^i}{\mu}} = 1 - G_{c+1}(\mu, 1) \tag{6}
\]

where \( G_k(\alpha, \mu) \) denotes the cumulative distribution function of a gamma distribution with the scale and shape parameters \( \alpha \) and \( \mu \) respectively. [15] gave the minimum sample size formula as:

\[
n = \left[ \frac{\gamma_{c+1, p^*}}{p} \right] + 1 \tag{7}
\]

where \( q = \) specified probability of failure, \( \gamma_{c+1, p^*} \) is the \( P^* \) percentage point at a standardized gamma variable with shape parameter.

This approximation was later discussed in [16]. Using the relationship between Gamma and Chi-square random variable, equation (7) becomes:

\[
n = \left[ \frac{X^2_{2(c+2), p^*}}{2P} \right] + 1 \tag{8}
\]

where \( P = \) assumed failure probability, \( \beta \) is then introduced in place of \( P^* \) to take care of the consumers risk and assumed failure probability \( (P) \) with the failure probability of assumed product life distribution \( F(t; \mu) \) or consumer’s risk, that is, the cumulative life distribution function.

Assuming the Chi-square(\( \chi^2 \)) random variables, equation (8) is modified as:

\[
n = \left[ \frac{X^2_{\nu, \beta}}{2F(t; \mu)} \right] + 1 \tag{9}
\]

where \( \beta \) takes care of the consumers risk, \( F(t; \mu) \) is the failure probability and can also be taken as the producer’s risk. \( \chi^2_{\nu, \beta} \) denotes the \( \beta \) consumer’s risk of a \( \chi^2 \) variable with \( \nu = 2(c + 1) \) degree of freedom. Since one of the objectives of this study is to arrive at a values of \( n \) that will results to a plan with reduced sample size needed to be selected from the lot for inspection and result to reduced inspection cost and time, the approximate value of \( n \) can then be reduce by introducing parameter \( \beta \) (shape parameter of the failure rate \( F(t; \mu) \)).

When \( p < 1.5 \), the sample size values become very large and when \( p > 2.5 \), the sample size become approximately one irrespective of the combination of the parameters.
On replacing $F(t, \mu)$ in (9) with $\rho F(t, \mu)$, the resulting equation becomes

$$n = \left[ \frac{x_{\gamma \beta}}{\rho F(t, \mu)} \right] + 1 \quad \{10\}$$

Therefore, equation (10) is the approximate of the improved sample size $n$.

**Development of the Operating Characteristics of Isolated Truncated Chain Deferred Sampling Plan**

Let $A$ be the event of having ‘0’ defectives in a sample of size ‘n’. Let $B$ be the event of having ‘1’ defectives in a sample of size ‘n’. Let $P(A)$ be the probability of having ‘0’ defectives in a lot with sample size ‘n’. Let $P(B)$ be probability of having ‘1’ defectives in a lot with sample size ‘n’.

Similarly, let $P(B)$ be probability of having ‘1’ defective in a lot with sample size ‘n’ with the condition that there are zero defectives in the immediate preceding ‘i’ lot and succeeding ‘j’ lot.

That is, $P(B) = P_{0,n} + (P_{0})^iP_{1,n}(P_{0})^j$ \quad \{11\}

Since $A$ and $B$ are mutually exclusive events, using the addition theorem of probability,

$$P(P_0 \cup P_1) = P_{0,n} + (P_{0,n})^iP_{1,n}(P_{0,n})^j \quad \{12\}$$

We therefore have the probability of acceptance of lot as:

$$P_a(P) = P_{0,n} + (P_{0,n})^iP_{1,n}(P_{0,n})^j$$

$$= P(d = 0) + \{P(d = 1)/d = 0 \text{ in the preceding k lot and succeeding j lot.}\}$$

Assuming Poisson distribution,

$$P_a(P) = \frac{e^{-np}(np)^0}{0!} + \frac{e^{-np}(np)^0 e^{-np}(np)^1}{1!} \frac{e^{-np}(np)^0}{0!}$$

$$P_a(P) = e^{-np} + \frac{e^{-np}(np)^0 e^{-np}(np)^1}{0!} e^{-np}$$

$$P_a(P) = e^{-np} + e^{-np}(np)((e^{-np}, e^{-np}), \ i = j = 1)$$

$$= e^{-np} + np e^{-(i+j)np}$$

$$= e^{-np} + np e^{2np}, \text{ since } i = j = 1$$

On factorising, we have:

$$= e^{-np}(1 + np e^2)$$

Now assuming a Binomial distribution,

$$P_a(P) = \binom{n}{0}P^0(1 - P)^n + \binom{n}{1}P^1(1 - P)^{n-1}\binom{n}{0}P^0(1 - P)^n \quad \{18\}$$

$$= \binom{n}{0}P^0(1 - P)^n + \binom{n}{1}P^1(1 - P)^{n-1}\binom{n}{0}P^0(1 - P)^n \quad \{19\}$$

Considering $i = j = 1$, we also have:

$$P_a(P) = \binom{n}{0}P^0(1 - P)^n + \binom{n}{1}P^1(1 - P)^{n-1}\binom{n}{0}P^0(1 - P)^n$$

\quad \{20\}
Product Mean Life Ratio ($\frac{\mu}{\mu_0}$)

The product life ratio is the ratio of the true unknown life of a product to the specified mean life by the producer when designing his product [18]. These values enable the producer to design his products so that it can be accepted at a high probability. In order to calculate the product life ratio values, the producer’s risk is being considered.

The value of $\frac{\mu}{\mu_0}$ is the smallest positive number for which the following inequality holds:

$$\sum_{i=c+1}^{n}(\binom{n}{i})p^i (1-p)^{n-i} \geq 0.95$$  \hspace{1cm} \text{(21)}$$

For a given value of the producer’s risk, for example 0.05, one may be interested in knowing what value of $\frac{\mu}{\mu_0}$ that will ensure a producer’s risk less than or equal to 0.05 if a sampling plan is adopted. For a given sampling plan $(n, c, \frac{t}{\mu_0})$ and specified confidence level $P^*$ the minimum values of $\frac{t}{\mu_0}$ is said to satisfy the equation below.

$$\sum_{i=c+1}^{n}(\binom{n}{i})p^i (1-p)^{n-i} \leq 0.95$$  \hspace{1cm} \text{(22)}$$

3. Results and Discussion

Product Failure Rate Analysis

The failure rate $h(t)$ was used to obtain the failure rate of products that assume these distributions. This function can be used to characterize the performance of an item with time. The result for this analysis is shown in table 1 and figure 3 and 4 below.

Table 1. Failure Rates of Life Distributions at specified $\frac{t}{\mu_0}$

| $\frac{t}{\mu_0}$ | Failure Rate |
|------------------|--------------|
| 0.628            | 0.5540       |
| 0.942            | 0.9429       |
| 1.571            | 1.0000       |
| 2.356            | 0.9200       |
| 3.141            | 0.1818       |
| 3.972            | 6X10^{-7}    |
| 4.713            | 1.1X10^{-9}  |

![Failure Rate Plot](image)

Figure 3. Failure Rate Plot for the Underlined Distribution for Specified $\frac{t}{\mu_0}$

From table 1 and figure 3, Weibull has a distinct failure rate pattern, such that the failure rate initially increases as the testing time increases and later reduce as the testing time increase.
Effect of Increasing Mean Ratio \( \frac{\mu}{\mu_0} \) on Failure Rate of Life Distribution

Since the failure rate of the life distributions is known, how do we now reduce the failure rate of products that assume these distributions? Table 2 and figure 4 shows the effect of product’s mean life on failure rate of the distribution.

**Table 2.** Effect of \( \frac{\mu}{\mu_0} \) on Failure Rate for the Studied Life Distributions

| \( \frac{\mu}{\mu_0} \) | Weibull |
|------------------------|---------|
| 2                      | 0.3140  |
| 4                      | 0.1570  |
| 6                      | 0.1047  |
| 8                      | 0.0078  |
| 10                     | 0.0063  |
| 12                     | 0.0052  |

**Figure 4.** Effect of Mean Life on Failure Rate Plot for Studied Distributions

From the table 2 and figure 4, as the products’ life ratio increases, the failure rate reduces. Weibull distribution had a sharp decrease in failure rate as the mean life increases.

**Improved Minimum Sample Size**

From existing literature [1], [5], [4], [6] and [17], the acceptance number, acceptance maximum allowable percent defectives and test ratio are conventionally set as follows: acceptance number \( (c = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 \text{ and } 10) \), \( (\beta = 0.75, 0.90, 0.95 \text{ and } 0.990) \) and \( (t/\mu_0 = 0.68, 0.942, 1.257, 1.571, 2.358, 3.141 \text{ and } 3.972) \). A programme written in R is used to generate the results.

**Simulations for the Study**

The minimum (optimal) sample size is obtained by first calculating the failure probability which is the probability that an item is classified as defective using the product life cumulative distribution function \( (p) \) and then after substituting it into our modified minimum sample size formula with other parameters. A programme was written in R to accomplish this task.

Tables 3 display the simulated values of the developed and modified sample sizes for the studied product life distribution under single truncated acceptance sampling plan.
## Table 3. Minimum sample size for Weibull distribution

| $\beta$ | $c$  | 0.628 | 0.942 | 1.257 | 1.571 | 2.356 | 3.141 | 3.972 | 4.713 |
|---------|------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.01    | 0    | 2     | 2     | 2     | 2     | 2     | 1     | 1     |       |
|         | 1    | 3     | 3     | 3     | 2     | 2     | 2     | 2     | 2     |
|         | 2    | 4     | 4     | 3     | 3     | 3     | 3     | 3     | 2     |
|         | 3    | 5     | 5     | 4     | 4     | 3     | 3     | 3     | 3     |
|         | 4    | 6     | 6     | 4     | 4     | 4     | 4     | 4     | 4     |
| 0.05    | 0    | 3     | 3     | 3     | 2     | 2     | 2     | 2     |       |
|         | 1    | 5     | 5     | 5     | 4     | 4     | 4     | 4     | 3     |
|         | 2    | 5     | 5     | 5     | 5     | 5     | 4     | 4     | 4     |
|         | 3    | 7     | 7     | 6     | 6     | 6     | 6     | 6     | 4     |
|         | 4    | 7     | 7     | 6     | 6     | 6     | 6     | 6     | 4     |
| 0.10    | 0    | 3     | 3     | 3     | 2     | 2     | 2     | 2     |       |
|         | 1    | 5     | 5     | 5     | 4     | 4     | 4     | 4     | 3     |
|         | 2    | 5     | 5     | 5     | 5     | 5     | 5     | 4     | 4     |
|         | 3    | 7     | 7     | 6     | 6     | 6     | 6     | 6     | 4     |
|         | 4    | 7     | 7     | 6     | 6     | 6     | 6     | 6     | 4     |
| 0.25    | 0    | 3     | 3     | 3     | 2     | 2     | 2     | 2     |       |
|         | 1    | 5     | 5     | 5     | 4     | 4     | 4     | 4     | 3     |
|         | 2    | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 4     |
|         | 3    | 7     | 7     | 6     | 6     | 6     | 6     | 6     | 4     |
|         | 4    | 7     | 7     | 6     | 6     | 6     | 6     | 6     | 4     |

From table 3 above, the behaviour of choice parameters from the sample size is as follows: The minimum sample sizes are smaller for lower acceptance number compared to a higher acceptance number for any combination of consumers’ risk and experiment time ratio ($\frac{L}{\mu_0}$).
Operating Characteristics for Isolated Truncated Chain Deferred Sampling Plan

The generated design parameters for the proposed sampling plan are presented in table 4.

Table 4. Operating characteristics for ITDCSP for Weibull distribution

| $\beta$ | $t$ | $n$ | $\mu_o$ | $\mu_o$ | $\mu_o$ | $\mu_o$ |
|--------|-----|-----|--------|--------|--------|--------|
|        | 2   | 4   | 6      | 8      | 10     | 12     |
| 0.628  | 3   | 0.60947 | 0.62952 | 0.73319 | 0.79180 | 0.82937 | 0.85548 |
| 0.912  | 3   | 0.52934 | 0.66502 | 0.78750 | 0.77510 | 0.80673 | 0.83058 |
| 1.257  | 3   | 0.41389 | 0.60932 | 0.67911 | 0.72584 | 0.76051 | 0.78738 |
| 1.571  | 3   | 0.29034 | 0.56522 | 0.64156 | 0.68978 | 0.72587 | 0.75432 |
| 2.356  | 3   | 0.07694 | 0.44303 | 0.56262 | 0.62103 | 0.65951 | 0.68982 |
| 3.141  | 3   | 0.01762 | 0.29053 | 0.48782 | 0.56529 | 0.60941 | 0.64162 |
| 0.628  | 3   | 0.60949 | 0.62952 | 0.73319 | 0.79180 | 0.82937 | 0.85548 |
| 0.912  | 3   | 0.52934 | 0.66502 | 0.78750 | 0.77510 | 0.80673 | 0.83058 |
| 1.257  | 3   | 0.41389 | 0.60932 | 0.67911 | 0.72584 | 0.76051 | 0.78738 |
| 1.571  | 3   | 0.29034 | 0.56522 | 0.64156 | 0.68978 | 0.72587 | 0.75432 |
| 2.356  | 3   | 0.07694 | 0.44303 | 0.56262 | 0.62103 | 0.65951 | 0.68982 |
| 3.141  | 3   | 0.01762 | 0.29053 | 0.48782 | 0.56529 | 0.60941 | 0.64162 |

From table 4 above, the operating characteristics increases as the mean life ratio increases, which indicate that items with increased mean life will be accepted with higher probability compared with items with lower mean life ratio.

Product Mean Life Ratio

The product mean ratio values guide the producer at improving on product quality for acceptability with high probability and minimized producer’s risk. For any given sampling plan and producer's risk, say $\alpha = 0.05$, the minimum value of $\left( \frac{\mu}{\mu_o} \right)$ is obtained. This is done by combining values of the sample size, acceptance number, Maximum Allowable Percent Defective and experimental ratio in the simulation using developed programme in R software.
From table 5, as the experimental time ratio increases, the minimum ratio of true mean life to specified mean life increases. It decreases as the acceptance number increases with decrease in consumers' risk.
4. Conclusion

This article has given an insight about the failure rate pattern and effect of mean life on the studied product life distributions, thereby enriching producers and users of these distributions on information that will enhance decision making when using these distributions. The developed sample sizes were smaller and will be economically preferred when the test is destructive, thereby saving both cost and time of testing.

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