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Variables Skip-Lot Sampling Plans Based On Taguchi Capability Index for High Quality Product

NABIL EL FARME[1]
[1]Emines – School Of Industrial Management/Mohammed VI Polytechnic University
Lot 660, Hay Moulay Rachid, Ben Guerir, Morocco
nabil.elfarme@emines.um6p.ma;

Abstract - Acceptance sampling is one of the most important tools in the area of quality control, which is used for inspecting incoming or receiving lots. The concept of skip lot-sampling plan (SKSP) is based on the idea of inspecting some fractions of lots. Thus, when the quality of the process is high and stable, the SKSP is an effective and economic scheme, which diminishes the cost of examination. This article aims to establish an economic and efficient sampling plan, by integrating the Taguchi capability index and the skip lot-sampling plan of type 2 (SKSP-2) using a variable single sampling plan as reference plan. A non-linear optimisation model is solved to decide the plan parameters by minimizing the average sample number with two constraints specified by the producer and the consumer. The efficiency and performance of the suggested scheme has been investigated in terms of average sample number (ASN) and the operating characteristic (OC) curves, and also compared with the existing variables single sampling plan. Furthermore, the plan parameters with particular conditions are delivered for reference as tables and an example is presented for illustration.

***Keywords*:** acceptance sampling; SKSP-2; Taguchi capability index; statistical quality control.

1. Introduction

The acceptance sampling is a statistical quality control tool, which has been used in numerous productions processes with diverse characteristics. Acceptance sampling plans emphasis on examining the product's quality by determining whether a batch is acceptable or not, in order to minimize the risks of the supplier and the customer of having batches of non-conforming parts.

There are two types of inspection: inspection by attributes (based on go or no go), and by variables (based on measurement). In comparison to the attribute inspection, the variable inspection gathers more information about the lot, resulting in a reduced sample size (Lee et al. 2016; Wu et al. 2012; Wu and Pearn 2008). Two main risks could be faced while examining a lot, the risk of rejecting a good lot (producer's risk (α)), which corresponds to the acceptable quality level (AQL) and the risk of accepting a bad lot (consumer's risk (β)) associated with the rejectable quality level (RQL).

For items that are created in successive lots and have generally consistent and excellent quality, the skip-lot sampling plan (SkSP) is an effective and economic scheme to minimize inspection costs and time by randomly selecting a subset of the lots for examination. Dodge (1955) originally expanded the idea of continuous sampling plans Type 1 (CSP-1) for single units of production, to develop a type of the SkSP, today is known as SkSP-1. Perry (1973) created a modified SkSP with a reference-sampling plan (i.e., SkSP-2) to address the limitations of SkSP-1, which may be used for sampling inspection on individual lots. In the present literature, the SkSP-2 methodology has been implemented with various modifications and applications. (more details could be found in Wu et al. (2020); Balamurali et al. (2018); Hussain et al. (2017) Balamurali et al. (2015); Aslam et al. (2015); Balamurali, Aslam, and Jun (2014); Aslam et al. (2014); Aslam et al. (2013a); Aslam et al. (2012); Balamurali et al. (2011)). Recently, Wu et al. (2021) extended the idea of SKSP-2 to variables inspection using a single sampling plan (SSP) based on the capability index C_{pk} as a reference-sampling plan.

Several process capability indices (PCIs), such as C_p and C_{pk}, have become popular in recent years as numerical indicators of process performance. However the issue of process centering is not effectively addressed by these indices. It is shown that C_{pk} is essentially a measure of process yield and can fail to distinguish between off-target and on-target processes (Boyle 1998). Taguchi proposes an alternate definition of C_p that immediately solves this problem, say C_{pm}. The idea of quality loss was used in the C_{pm} capability index; it takes into account production item variation in relation to the target value and manufacturing requirements. More details for the readers who are interested could be found in Yum and Kim (2011) Wu et al., (2009) and Kotz and Johnson (2002).

Therefore, to validate the flexibility of the SkSP-2 plan and to address the question of process centering, this article incorporate the SkSP-2, as variable-type, with the recognized Taguchi capability index (C_{pm}) using single sampling plan as reference plan, to meet the essential quality characteristic of products with bilateral specification limits, where the suggested sampling scheme are symbolised by C_{pm}-SkSP-2.

2. The Taguchi capability index

When the process is under control, indices are often calculated in order to measure the quality of the goods produced (and therefore the capability of the process); more specifically, to what extent the produced elements will fall within the allowable engineering tolerances. Most indices focus on centering the mean of the distribution around the midpoint of the tolerances ($USL + LSL/2$) but this is not always the customer target. An adaptation index, say C_{pm}, is a capability index, also known as the Taguchi capability index, that is a function of the process variability, the specification limits, the mean of the process, and a provided target, T. It is defined as (Chan et al. (1988); Hsiang and Taguchi (1985)):

$$C_{pm} = \frac{d}{3\sqrt{\sigma^2 + (\mu - T)^2}} \tag{1}$$

where $T, d = (USL - LSL)/2$ denote the target value and the half-length, respectively. A lower bound of the process yield is obtained, under the hypothesis $T = M = (LSL + USL)/2$, as $\%\,Yield \geqslant 100[2\Phi(3C_{pm}) - 1]\%$ (i.e. $\% N$onconforming $\leqslant 200\Phi(-3C_{pm})\%$) for $C_{pm} > \sqrt{3}/3$ (Ruczinski (1996)).

Let the sequence $\{X_1, X_2, \dots, X_n\}$ represent the collected samples, Boyles (1991) proposed an estimator of C_{pm}(2), by replacing the two unknown parameters μ and σ^2 by their natural estimators $\bar{X} = \sum_{i=1}^{n} X_i/n$ and $S_n^2 = \sum_{i=1}^{n}(X_i - \bar{X})^2/n$, respectively:

$$\hat{C}_{pm} = \frac{\mathrm{d}}{3\sqrt{\sum_{i=1}^{n}(X_i - T)^2/n}} = \frac{\mathrm{d}}{3\sqrt{S_n^2 + \left(\bar{X} - T\right)^2}} \tag{2}$$

The cumulative distribution function (CDF) of $\hat{C}_{pm}$ was developed by Lin and Pearn (2005) as a mixture of the normal and the chi-square distributions, using the normality assumption:

$$F_{\hat{C}_{pm}}(y) = 1 - \int_0^{b\sqrt{n}/(3y)} G\left(\frac{b^2 n}{9y^2} - w^2\right)[\phi(w + \xi) + \phi(w - \xi\sqrt{n})]dw \tag{3}$$

where $\xi = (\mu - T)/\sigma$, $b = d/\sigma$, $\phi(\cdot)$ is the probability density function of the standard normal distribution and $G(\cdot)$ is the cumulative distribution function of the chi-square distribution with degree of freedom $\mathrm{n} - 1$.

3. Developing a variables SKSP-2 plan based on the C_{pm} index

Assume that your quality criterion involves two specification bounds (LSL and USL), a targeted value T and has a normal distribution. The operational methodology for the proposed variables SKSP-2 plan based on the C_{pm} index is as follows: **Normal inspection**: If $\hat{C}_{pm} \geq k$, accept the submitted lot. Otherwise, reject the lot. If predetermined number of consecutive lots are accepted under normal inspection, then switch to skipping inspection. Otherwise, stay in normal inspection. **Skipping inspection**: Only a fraction of the submitted lots is inspected. If $\hat{C}_{pm} \geq k$, accept the submitted lots and continue skipping inspection. Otherwise, reject the lots and switch to normal inspection.

It's possible to rewrite the definition of C_{pm} index as $C_{pm} = d/\{3[\sigma^2 + (\mu - T)^2]^{1/2}\} = b/[3(1+\xi^2)^{1/2}]$, where $\xi = (\mu - T)/\sigma$. Thus, $b = d/\sigma$ can be expressed as $b = 3C_{pm}(1+\xi^2)^{1/2}$. $P_a(C_{pm})$ is the probability of accepting a lot based on the C_{pm} index, which is given as

$$P_a(C_{pm}) = \int_0^{b\sqrt{n}/(3k)} G\left(\frac{b^2 n}{9k^2} - w^2\right)[\phi(w + \xi\sqrt{n}) + \phi(w - \xi\sqrt{n})]dw \tag{4}$$

The operating characteristic (OC) function of the proposed variables SKSP-2 plan based on the C_{pm} index, according to Balamurali and Jun (2006), can be stated as follows:

$$\pi(C_{pm}) = \frac{fP_a(C_{pm}) + (1-f)[P_a(C_{pm})]^m}{f + (1-f)[P_a(C_{pm})]^m} \tag{5}$$

Balamurali and Jun (2009) point out that if the sample size required for inspection is small, a sampling plan might be beneficial. Perry (1973) introduced the average sample number (ASN) as the objective function to be minimized. We choose to minimize the average of ASN at both AQL and LQL, since ASN is a function of the index value as follows (Wu et al. (2012)):

$$ASN_{AV} = \left\{\frac{1}{2} \times \left[\frac{nf}{f + (1-f)[P_a(C_{AQL})]^m} + \frac{nf}{f + (1-f)[P_a(C_{RQL})]^m}\right]\right\} \tag{6}$$

Therefore, in accordance with Eqs. (6)–(7) and two constraints of quality-and-risk levels, the decision criteria was constructed and subjected to two constrained nonlinear equations for the C_{pm}-SkSP-2 (n, k, m, f):

$Min\{ASN_{AVR}\}$	(7)
$\pi(C_{AQL}) = \frac{fP_a(C_{AQL}) + (1-f)[P_a(C_{AQL})]^m}{f + (1-f)[P_a(C_{AQL})]^m} \geq 1 - \alpha$	
$\pi(C_{RQL}) = \frac{fP_a(C_{RQL}) + (1-f)[P_a(C_{RQL})]^m}{f + (1-f)[P_a(C_{RQL})]^m} \leq \beta$	
$n \geq 2\,; k_a > 0\,; i \geq 0\,; 0 < f < 1$	

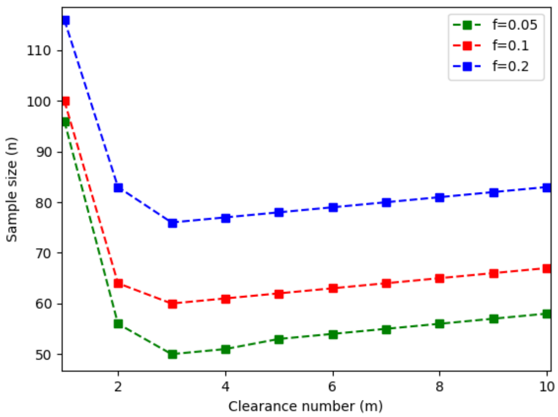
Because the process parameters μ and σ are unknown, as Pearn and Wu (2006) point out, the distribution characteristic parameter, $\xi = (\mu - T)/\sigma$ is also unknown, which must be determined in real-world situations. As a result of the estimating mistakes in determining ξ, additional sampling errors could be introduced in finding the plan parameters. They conducted comprehensive calculations to explore the behavior of sample size and critical value under various input conditions to eliminate the requirement for guessing ξ and proposed that $\xi = 0$ could be used to establish a conservative sample size for examination. As a result, to verify that the choices made are reasonable, we compute the plan parameters (n, k_a) using the condition $\xi = 0$.

4. Analysis and discussion

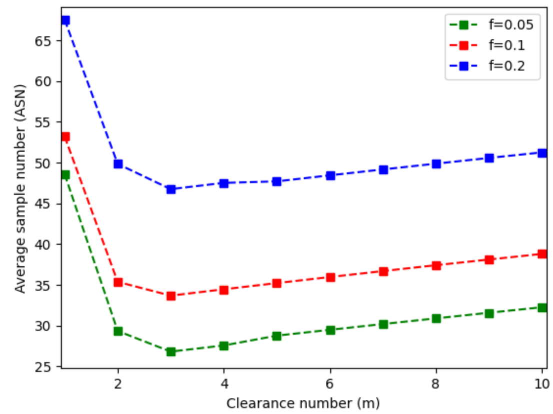
In this part, we look at the effect of clearance number i on plan parameters at different quality-and-risk levels, $(C_{AQL}, 1-\alpha)$ and (C_{RQL}, β). Second, practical designing parameters (n, k_a, m, f) for the are obtained. Third, The ASN, as well as the operating characteristic curve, are evaluated and commented.

4.1. Exploration of the influence of parameter m

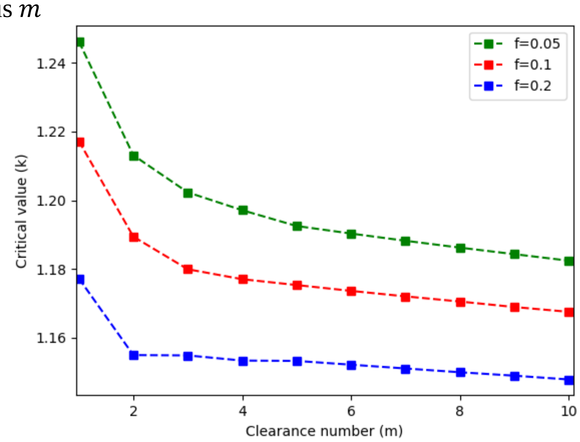
To make selecting the plan parameters (n, k_a, m, f) easier. The effect of changing parameter m from 1 to 10 on n, k, and ASN was investigated, where $(C_{AQL}, C_{RQL}) = (1.33,1.00)$ and $(\alpha, \beta) = (0.01,0.01)$. Aside from that, the values 0.05, 0.1, 0.2 was picked for the parameter f. From the Figures 1 (a), 1 (b), and 1 (c), we can observe that the higher the value of f, the higher the value of n and ASN are, on the other hand, k drops. The n and ASN form a convex function of the clearance number m in the interval [1, 10] and has a minimal value at $m = 3$, while k forms concave function of m. From a monetary standpoint, the number of consecutively accepted lots needed to adapt inspection activities is indicated to be $m = 3$ in $SkSP$-2 based on the C_{pm}.



(a) n versus m



(b) ASN versus m



(c) k versus m

Fig. 1: Plot of the ASN of the parameters (n, ASN, k) versus m for $(C_{AQL}, C_{RQL}) = (1.33, 1.0)$

4.2. Operational parameters of the C_{pm}-SkSP-2

Tables 1 and 2 provide a real-world operational parameters of the SKSP-2 based on the C_{pm} index for $f = 0.05, 0.1, 0.2$ with the risk levels of $\alpha = 0.01, 0.05, 0.10$ and $\beta = 0.01, 0.05, 0.10$, and the quality level $(C_{AQL}, C_{RQL}) = (1.33, 1.00)$ and $(1.5, 1.33)$ the clearance number m set to $m = 3$.

Table 1: C_{pm} −based SkSP-2 (n, k) values for $(C_{AQL}, C_{RQL}) = (1.33,1)$.

				$(C_{AQL}, C_{RQL}) = (1.33,1)$					
		$f = 0.05$			$f = 0.1$			$f = 0.2$	
α	β	n	k	ASN	n	k	ASN	n	k	ASN
0.01	0.01	82	1.2198	43.9079	97	1.1983	54.228	118	1.1767	71.4587
	0.05	50	1.2023	26.8194	60	1.1799	33.682	76	1.1548	46.7446
	0.1	39	1.1866	20.6972	56	1.1466	30.9494	62	1.136	37.5216
0.05	0.01	54	1.2834	31.026	63	1.2574	37.8957	82	1.2192	51.8774
	0.05	31	1.2718	17.77	38	1.2411	22.871	52	1.1953	32.9026
	0.1	23	1.2596	12.9885	28	1.2293	16.7796	34	1.1945	21.9698
0.1	0.01	46	1.3138	27.9997	53	1.2867	33.9173	71	1.2391	46.546
	0.05	29	1.2836	16.8857	38	1.2374	22.7659	38	1.2365	25.7756
	0.1	19	1.2943	11.1718	26	1.2338	15.6932	28	1.2194	18.8355

Table 2: C_{pm} −based SkSP-2 (n, k) values for $(C_{AQL}, C_{RQL}) = (1.5,1.33)$.

				$(C_{AQL}, C_{RQL}) = (1.5,1.33)$						
		$f = 0.05$			$f = 0.1$			$f = 0.2$		
α	β	n	k	ASN	n	k	ASN	n	k	ASN
0.01	0.01	421	1.4455	226.2488	493	1.4361	277.2381	568	1.4283	347.2999
	0.05	272	1.4328	145.8674	327	1.4225	183.7286	388	1.4141	237.1316
	0.1	212	1.4247	112.5623	257	1.4133	143.6032	309	1.4044	188.364
0.05	0.01	296	1.4699	167.6993	330	1.4618	198.7222	389	1.4505	253.0677
	0.05	163	1.466	93.236	198	1.4516	119.1533	243	1.4382	158.0187
	0.1	116	1.4619	65.9037	145	1.4438	86.7454	182	1.4289	117.9722
0.1	0.01	233	1.4897	142.1324	271	1.4769	174.2252	319	1.4643	220.5402
	0.05	123	1.4891	75.411	153	1.4701	98.2622	189	1.4541	130.4717
	0.1	85	1.4872	51.5625	107	1.4647	68.3139	135	1.4465	92.9894

4.3. Performance comparisons of SSP and SkSP-2

In this part, C_{pm}-SkSP-2 was compared to C_{pm}-SSP in terms of the operating characteristic curve (OC-curves) and the average sample number curve (ASN-curves). The OC curves quantify the risk of the producer and the consumer. It's a graph that shows the proportion defective of a lot vs the likelihood that the sampling strategy will accept that lot. If a product has a bad t quality, then its chances of being accepted should be low, but if it has a high quality, its probability of acceptance should be high. The Figure 2 display a comparison between C_{pm}-SSP and C_{pm}-SkSP-2 in term of the OC-curve, when compared to the C_{pm}-SSP, the C_{pm}-SkSP-2 has a stronger discriminating capacity and sensitivity to distinguish between excellent and poor lots, and that because The C_{pm}-SkSP-2 slopes with various f were all steeper than the C_{pm}-SSP slopes. Particularly, when the fraction of skipping lots f has smallest value the OC curve converges to the ideal.

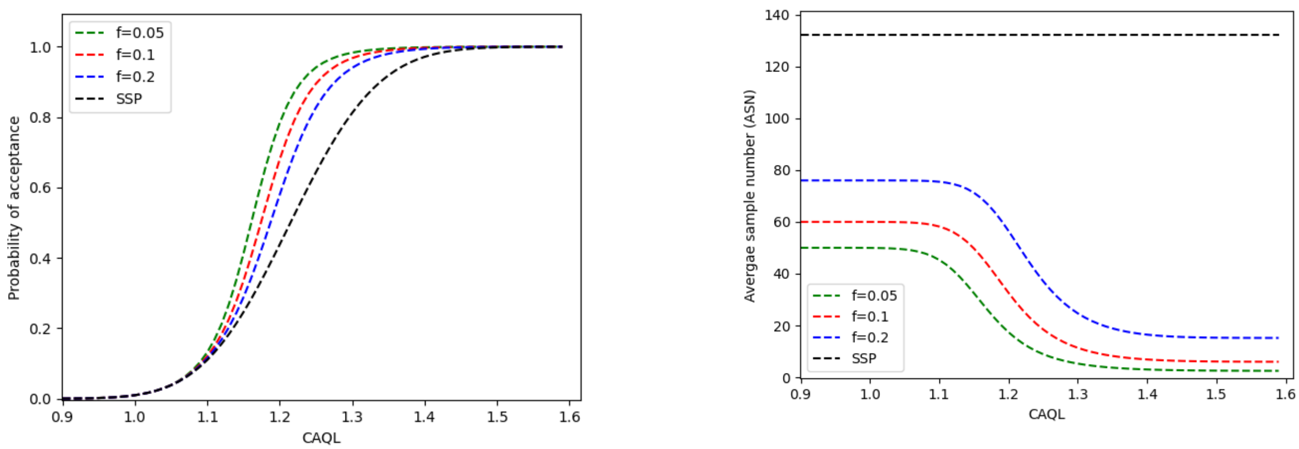


Fig. 2: Caption for figure goes at the bottom.

Furthermore, by comparing the ASN-curves of C_{pm} -SSP and C_{pm}-SkSP-2 in Figure 13, The ASN of C_{pm}-SkSP-2 with various f values was found to be less than that of C_{pm}-SSP, implying that the suggested C_{pm}-SkSP-2 is capable of properly assessing the submitted lot's quality with a reduced sample size. This lowers inspection expenses, especially at higher quality levels. (i.e., for large values of C_{pm}).

5. An industrial application

To show how the specified sampling strategy may be used in real-world situations, we take the case of producing types of adjustable precision shunt regulators used in Wu (2012). The firm focuses on the output voltage as a crucial feature that has a major influence on product quality. Under temperature condition of 25 degree Celsius, the output voltage requirements for a typical type are as follows: (LSL, T, USL) = (2.475 volt, 2.500 volt, 2.525 volt).

In a buying contract, assume that $m = 3$, $f = 0.05$, the C_{AQL} and C_{LQL} values are 1.33 and 1.00, respectively, and the risks are set to $\beta = 0.05$ and $\alpha = 0.05$. This means that the constructed sampling plan would provide a probability of no more than 0.05 of accepting the lot if the quality level of the submitted lot is at $C_{LQL} = 1.00$, and if the quality level of the submitted lot is at C_{AQL} = 1.33 based on the Cpm index, the probability of acceptance would be at least 0.95.

The plan parameters (n, k) may be determined using Table 3 as follows $(n, k) = (31, 1.2718)$. Therefore, the normal inspection starts by randomly selecting 31 samples from submitted lot for examination. Since the industrial example has collected 37 samples, in this study we use 31 sample to estimate C_{pm} index, Table 3 lists the measurements of the 37 samples. The Anderson–Darling normality test also shows that these samples are pretty near to the normal distribution. Figure 3 shows a normal probability plot of the gathered data with a p-value of 0.46 for evaluating the normality assumption. For a sample size of 37, the power of different normality tests is just modest. With previous process data, the voltage distribution was likewise confirmed to be normal.

Table 3: measurements.

2.5072	2.5064	2.5057	2.5121	2.5011	2.4969	2.5023	2.5037	2.4998	2.5092
2.5068	2.5100	2.5056	2.4979	2.4974	2.5059	2.4975	2.5091	2.4986	2.4953
2.5111	2.5026	2.5114	2.5052	2.5020	2.5088	2.5034	2.5016	2.5011	2.5051
2.5094	2.5063	2.4997	2.5084	2.5007	2.5000	2.5072			

The sample mean and sample standard deviation are computed using 31 measurements, $\bar{X} = 2.5042, S_n = 0.00474$ volt. As a result, because the estimated $\hat{C}_{pm} = 1.3158$ is greater than the critical value for acceptance $k = 1.2718$, the customer would take the entire lot in this situation. If three consecutive lots are accepted (m = 3) using normal inspection, the process transitioned to skip-lot inspection. Skipping will continue as long as there is acceptance, otherwise (if lot is rejected) normal inspection will return. If the variable single sampling plan based on the C_{pm} index is used in this situation, it is important to notice that under the same conditions, a sample size of 95 is required for examination. As a result, the suggested variables SKSP-2 plan can give a more efficient and cost-effective system for determining product acceptability.

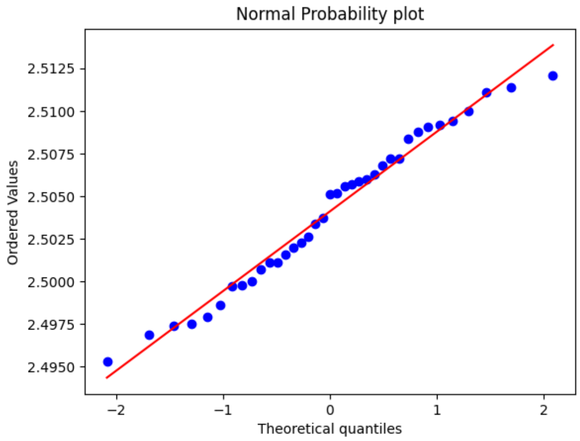


Fig. 3: Normal probability plot of the gathered data.

5. Conclusion

Many suppliers and customers consider that sample programs involving lot-by-lot (normal) inspection are too costly for selling high-quality items. When suppliers provide generally consistent and high-quality items, skip-lot sampling might be employed. The sample size can be reduced using the skipping inspection, and lots that pass the skipping inspection can be rapidly sent to the next workstation, ensuring a smooth production process and significantly reducing inspection time and cost. As a result, this research combined the concepts of skip-lot sampling and Taguchi capability index, and suggested SkSP-2 as a variable with a C_{pm}-based SSP as the reference plan. With a normally distributed quality characteristic within bilateral specification limitations, the SkSP-2 is appropriate for today's high-yield process settings and products. The suggested SkSP2's operating characteristic (OC) function was constructed, as well as a mathematical model for selecting plan parameters, which minimizes the average sample number (ASN) while meeting the producer's and consumer's quality and risk standards. In terms of the OC and ASN curves, the suggested SkSP-2's performance and efficiency were compared to those of the standard SSP.

In comparison to the C_{pm}-SSP, the suggested SkSP-2 is more effective and cost-efficient than the traditional SSP since it needs less sample and has greater discriminating power and sensitivity to distinguish between good and poor goods. This lowers inspection costs, especially at higher quality levels (i.e., for large values of C_{pm}), where the ASN of C_{pm}-SkSP-2 is significantly lower than that of C_{pm}-SSP. Furthermore, the plan parameters were computed and solved for future reference under a variety of quality and risk situations, and a practical application was illustrated using an example from the industry. Finally, SkSPs are a good acceptance-sampling technique that may also be used as a reduced-inspection system. When the quality of the submitted lots is excellent, their performance is partially good. However, SkSPs should only be used in circumstances when there is a sufficient history of supplier quality to assure that the submitted batches are of outstanding quality.

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