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MAKING DECISIONS IN ASSESSING PROCESS CAPABILITY INDEX C_{pk}

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SUMMARY

Process capability indices C_p, C_{pk} and C_{pm} have been used in manufacturing industries to provide a quantitative measure of process potential and performance. The formulae for these indices are easy to understand and straightforward to apply. However, since sample data must be collected in order to calculate these indices, a great degree of uncertainty may be introduced into capability assessments owing to sampling errors. Currently, most practitioners simply look at the value of the index calculated from the sample data and then make a conclusion on whether the given process meets the capability (quality) requirement. This approach is not reliable, since sampling errors are ignored. Cheng (*Qual. Engng.*, **7,** 239–259 (1994)) has developed a procedure involving estimators of C_p and C_{pm} for practitioners to use to determine whether a process meets the capability requirement or not. However, no procedure for C_{pk} was given, because difficulties were encountered in calculating the sampling distribution of the estimator of C_{pk}. In this paper we use a newly proposed estimator of C_{pk} to develop a procedure for practitioners to use so that decisions made in assessing process capability are more reliable.

KEY WORDS: process capability indices; non-central t distribution; critical values; power of the test; α risk; capability requirement

INTRODUCTION

Understanding processes and quantifying process performance are essential for any successful quality improvement initiative. The relationship between the actual process performance and the specification limits or tolerance may be quantified using appropriate process capability indices. Three capability indices commonly used in manufacturing industries are C_p, C_{pk} and C_{pm}. These indices, providing numerical measures of whether a production process meets predetermined specification limits, have been defined as

$$C_p = \frac{\text{USL} - \text{LSL}}{3\sigma}$$

$$C_{pk} = \min\left\{\frac{\text{USL} - \mu}{3\sigma}, \frac{\mu - \text{LSL}}{3\sigma}\right\}$$

$$C_{pm} = \frac{\text{USL} - \text{LSL}}{3\sqrt{\sigma^2 + (\mu - T)^2}}$$

where USL is the upper specification limit, LSL is the lower specification limit, μ is the process mean, σ is the process standard deviation (overall process variability) and T is the target value. The formulae for these indices are easy to understand and straightforward to apply. However, in order to calculate these indices, sample data must be collected. Therefore a great degree of uncertainty may be introduced into capability assessments owing to sampling errors. Currently, most practitioners simply look at the value of the estimators calculated from the sample data and then make a conclusion on whether the given process meets the capability (quality) requirement or not. This approach is highly unreliable, since sampling errors have been ignored. Chen [1] has developed a procedure (using estimators of C_p and C_{pm}) for practitioners to use to determine if a process satisfies the targeted quality condition. However, no procedure for C_{pk} was given, because difficulties were encountered in calculating the sampling distribution of the estimator of C_{pk}. In this paper we use an estimator of C_{pk} proposed by Pearn and Chen [2] to develop a simple procedure for practitioners to use so that

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decisions made in assessing process capability are more reliable.

ESTIMATION OF C_{pk}

Three estimators have been proposed to estimate the C_{pk} value, namely (a) Bissell's estimator $\hat{C}'_{pk}$ [3], (b) the natural estimator $\hat{C}_{pk}$ [4] and (c) the Bayesian-like estimator $\hat{C}''_{pk}$ [2]. Bissell's estimator assumes the knowledge of $P(\mu \geq m) = 0$ or 1, where $m = (\text{USL} + \text{LSL})/2$. If $\mu \geq m$, then $\hat{C}'_{pk} = (\text{USL} - \bar{X})/3S$; otherwise, $\hat{C}'_{pk} = (\bar{X} - \text{LSL})/3S$. Kotz *et al.* [4] investigated a different estimator of C_{pk} which is defined as $\hat{C}_{pk} = \min\{(\text{USL} - \bar{X})/3S, (\bar{X} - \text{LSL})/3S\}$, where $\bar{X} = (\sum_{i=1}^{n} X_i)/n$ and $S = \{(n-1)^{-1}\sum_{i=1}^{n}(X_i - \bar{X})^2\}^{1/2}$ are conventional estimators of μ and σ which may be obtained from a stable process. Both estimators $\hat{C}'_{pk}$ and $\hat{C}_{pk}$ are biased, but Kotz *et al.* [4] showed that the variance of $\hat{C}_{pk}$ is smaller than that of Bissell's estimator.

Pearn and Chen [2] considered a Bayesian-like estimator $\hat{C}''_{pk}$ to relax Bissell's assumption on the process mean. The evaluation of the estimator $\hat{C}''_{pk}$ only requires the knowledge of $P(\mu \geq m) = p$ or $P(\mu < m) = 1 - p$, where $0 \leq p \leq 1$, which may be obtained from historical information on a stable process. Clearly, if $P(\mu \geq m) = 0$ or 1, then the estimator $\hat{C}''_{pk}$ reduces to Bissell's estimator. The estimator is defined as $\hat{C}''_{pk} = \{d - (\bar{X} - m)I_A(\mu)\}/3S$, where $I_A(\mu) = 1$ if $\mu \in A$, $I_A(\mu) = -1$ if $\mu \notin A$, and $A = \{\mu | \mu \geq m\}$.

Pearn and Chen [2] showed that under the assumption of normality the distribution of the estimator $3n^{1/2}\hat{C}''_{pk}$ is $t_{n-1}(\delta)$, a non-central t with $n-1$ degrees of freedom and non-centrality parameter $\delta = 3n^{1/2}C_{pk}$. The probability density function can be expressed as

$$f(x) = \frac{3n^{1/2}}{2^{n/2}\Gamma\left(\frac{n-1}{2}\right)(\pi(n-1))^{1/2}}\int_0^\infty y^{(n-2)/2} \times \exp\left(-\frac{y + 9n[xy^{1/2}(n-1)^{-1/2} - C_{pk}]^2}{2}\right)\,dy$$

Pearn and Chen [2] also showed that by adding the well-known correction factor b_f to the estimator $\hat{C}''_{pk}$, where $b_f = [2/(n-1)]^{1/2}\Gamma[(n-1)/2]\{\Gamma[(n-2)/2]\}^{-1}$, an unbiased estimator $\tilde{C}_{pk} = b_f\hat{C}''_{pk}$ can be obtained. They also showed that the variance of $\tilde{C}_{pk}$ is smaller than those of $\hat{C}'_{pk}$ and $\hat{C}_{pk}$. Therefore in this paper we will use the unbiased estimator $\tilde{C}_{pk}$ to develop a simple procedure, similar to those described in References [1] and [5], for the index C_{pk}.

Table 1. Quality conditions and C_{pk} values

Quality condition	C_{pk} value
Inadequate	$C_{pk} < 1.00$
Capable	$1.00 \leq C_{pk} < 1.33$
Satisfactory	$1.33 \leq C_{pk} < 1.50$
Excellent	$1.50 \leq C_{pk} < 2.00$
Super	$2.00 \leq C_{pk}$

TEST HYPOTHESIS

A process is called 'inadequate' if $C_{pk} < 1.00$: this indicates that the process is not adequate with respect to the production tolerances; either the process variation (σ^2) needs to be reduced or the process mean (μ) needs to be shifted closer to the target value. A process is called 'capable' if $1.00 \leq C_{pk} < 1.33$: this indicates that caution needs to be taken regarding the process distribution; some process control is required. A process is called 'satisfactory' if $1.33 \leq C_{pk} < 1.50$: this indicates that the process quality is satisfactory; material substitution may be allowed and no stringent quality control is required. A process is called 'excellent' if $1.50 \leq C_{pk} < 2.00$. Finally, a process is called 'super' if $C_{pk} \geq 2.00$. Table 1 summarizes the five quality conditions and the corresponding C_{pk} values.

To determine whether a given process meets the capability requirement and runs under the desired quality condition, we can consider the following statistical test hypothesis. The process meets the capability (quality) requirement if $C_{pk} > C$, and fails to meet the capability requirement if $C_{pk} \leq C$:

$$H_0: \ C_{pk} \leq C$$
$$H_1: \ C_{pk} > C$$

The critical value C_0 is determined by

$$p\{\tilde{C}_{pk} > C_0 | C_{pk} = C\} = \alpha$$
$$p\{b_f\hat{C}''_{pk} > C_0 | C_{pk} = C\} = \alpha$$
$$p\left\{\hat{C}''_{pk} > \frac{C_0}{b_f}\,\middle|\, C_{pk} = C\right\} = \alpha$$
$$p\left\{3n^{1/2}\hat{C}''_{pk} > \frac{3n^{1/2}C_0}{b_f}\,\middle|\, C_{pk} = C\right\} = \alpha$$

$$p\left\{t_{n-1}(\delta_c) > \frac{3n^{1/2}C_0}{b_f}\right\} = \alpha$$

where $\delta_c = 3n^{1/2}C$. Hence we have

$$\frac{3n^{1/2}C_0}{b_f} = t_{n-1,\alpha}(\delta_c)$$

where $t_{n-1,\alpha}(\delta_c)$ is the upper α is the upper α quantile of the $t_{n-1}(\delta_c)$ distribution, or

$$C_0 = \frac{b_f}{3n^{1/2}} t_{n-1,\alpha}(\delta_c)$$

The power of the test can be computed as

$$\begin{aligned}\pi(C_{pk}) &= p\{\tilde{C}_{pk} > C_0 | C_{pk}\}\\ &= p\{b_f \hat{C}''_{pk} > C_0 | C_{pk}\}\\ &= p\left\{\hat{C}''_{pk} > \frac{C_0}{b_f}\middle| C_{pk}\right\}\\ &= p\left\{3n^{1/2}\hat{C}''_{pk} > \frac{3n^{1/2}C_0}{b_f}\middle| C_{pk}\right\}\\ &= p\left\{t_{n-1}(\delta) > \frac{3n^{1/2}C_0}{b_f}\right\}\end{aligned}$$

where $\delta = 3n^{1/2}C_{pk}$.

MAKING DECISIONS

Tables 2(a)–2(d) display critical values C_0 for C = 1.00, 1.33, 1.50 and 2.00 respectively with sample sizes n = 10(5)250 and α risk = 0.01, 0.025 and 0.05. The computer program (using SAS) generating the tables is available from the authors. To determine if the process meets the capability (quality) requirement, we first determine C and the α risk. Then we calculate the value of the estimator $\tilde{C}_{pk}$ from the sample. From the appropriate table we find the critical value C_0 based on α risk, C and sample size n. If the estimated value $\tilde{C}_{pk}$ is greater than the critical value C_0, then we conclude that the process meets the capability (quality) requirement. Otherwise, we do not have sufficient information to conclude that the process meets the present capability requirement.

The procedure

1. Determine the value of C (normally chosen from Table 1), the desired quality condition, and the α risk (normally set to 0.01, 0.025 or 0.05), the chance of incorrectly accepting an incapable process (which does not meet the quality requirement) as a capable process (which meets the quality requirement).

Table 2(a). Critical values C_0 for C = 1.00, n = 10(5)250 and α = 0.01, 0.025, 0.05

n	$\alpha = 0.01$	$\alpha = 0.025$	$\alpha = 0.05$
10	1.957	1.175	1.541
15	1.686	1.529	1.411
20	1.556	1.436	1.343
25	1.477	1.377	1.299
30	1.422	1.337	1.269
35	1.383	1.306	1.246
40	1.352	1.283	1.228
45	1.327	1.264	1.213
50	1.307	1.248	1.201
55	1.290	1.235	1.190
60	1.275	1.223	1.181
65	1.262	1.213	1.174
70	1.251	1.205	1.167
75	1.241	1.197	1.161
80	1.233	1.190	1.155
85	1.225	1.184	1.150
90	1.217	1.178	1.145
95	1.211	1.173	1.141
100	1.205	1.168	1.137
105	1.199	1.163	1.134
110	1.194	1.159	1.131
115	1.189	1.155	1.127
120	1.185	1.152	1.125
125	1.181	1.148	1.122
130	1.177	1.145	1.119
135	1.173	1.142	1.117
140	1.170	1.140	1.115
145	1.166	1.137	1.113
150	1.163	1.135	1.111
155	1.160	1.132	1.109
160	1.157	1.130	1.107
165	1.155	1.128	1.105
170	1.152	1.126	1.104
175	1.150	1.124	1.102
180	1.148	1.122	1.100
185	1.145	1.120	1.099
190	1.143	1.118	1.098
195	1.141	1.117	1.096
200	1.139	1.115	1.095
205	1.138	1.114	1.094
210	1.136	1.112	1.093
215	1.134	1.111	1.092
220	1.132	1.110	1.090
225	1.131	1.108	1.098
230	1.129	1.107	1.088
235	1.128	1.106	1.087
240	1.126	1.105	1.086
245	1.125	1.103	1.086
250	1.124	1.102	1.085

Table 2(b). Critical values C_0 for $C = 1.33$, $n = 10(5)250$ and $\alpha = 0.01, 0.025, 0.05$

n	$\alpha = 0.01$	$\alpha = 0.025$	$\alpha = 0.05$
10	2.569	2.255	2.208
15	2.216	2.012	1.859
20	2.046	1.891	1.771
25	1.943	1.815	1.714
30	1.873	1.762	1.675
35	1.822	1.723	1.645
40	1.782	1.693	1.622
45	1.750	1.668	1.603
50	1.724	1.648	1.587
55	1.702	1.631	1.574
60	1.683	1.616	1.562
65	1.666	1.604	1.552
70	1.652	1.592	1.543
75	1.639	1.582	1.535
80	1.628	1.573	1.528
85	1.618	1.565	1.522
90	1.608	1.558	1.516
95	1.600	1.551	1.511
100	1.592	1.545	1.506
105	1.585	1.539	1.501
110	1.578	1.534	1.497
115	1.572	1.529	1.493
120	1.567	1.524	1.489
125	1.561	1.520	1.486
130	1.556	1.516	1.483
135	1.551	1.512	1.480
140	1.547	1.509	1.477
145	1.543	1.505	1.474
150	1.539	1.502	1.471
155	1.535	1.499	1.469
160	1.532	1.496	1.467
165	1.528	1.493	1.465
170	1.525	1.491	1.462
175	1.522	1.488	1.460
180	1.519	1.486	1.458
185	1.516	1.484	1.457
190	1.513	1.481	1.455
195	1.511	1.479	1.453
200	1.508	1.477	1.452
205	1.506	1.475	1.450
210	1.504	1.474	1.448
215	1.501	1.472	1.447
220	1.499	1.470	1.446
225	1.497	1.468	1.444
230	1.495	1.467	1.443
235	1.493	1.465	1.442
240	1.492	1.464	1.440
245	1.490	1.462	1.439
250	1.488	1.461	1.438

Table 2(c). Critical values C_0 for $C = 1.50$, $n = 10(5)250$ and $\alpha = 0.01, 0.025, 0.05$

n	$\alpha = 0.01$	$\alpha = 0.025$	$\alpha = 0.05$
10	2.887	2.535	2.281
15	2.490	2.263	2.091
20	2.300	2.126	1.992
25	2.185	2.041	1.929
30	2.106	1.983	1.885
35	2.049	1.939	1.852
40	2.004	1.905	1.826
45	1.969	1.878	1.804
50	1.939	1.855	1.787
55	1.915	1.836	1.772
60	1.894	1.819	1.759
65	1.875	1.805	1.748
70	1.859	1.793	1.738
75	1.845	1.781	1.729
80	1.832	1.771	1.721
85	1.821	1.762	1.714
90	1.811	1.754	1.707
95	1.801	1.746	1.701
100	1.792	1.740	1.696
105	1.784	1.733	1.691
110	1.777	1.727	1.686
115	1.770	1.722	1.682
120	1.764	1.717	1.678
125	1.758	1.712	1.674
130	1.752	1.707	1.670
135	1.747	1.703	1.667
140	1.742	1.699	1.664
145	1.737	1.695	1.661
150	1.733	1.692	1.658
155	1.729	1.688	1.655
160	1.725	1.685	1.652
165	1.721	1.682	1.650
170	1.717	1.679	1.648
175	1.714	1.677	1.645
180	1.711	1.674	1.643
185	1.708	1.671	1.641
190	1.705	1.669	1.639
195	1.702	1.667	1.637
200	1.699	1.664	1.635
205	1.696	1.662	1.634
210	1.694	1.660	1.632
215	1.691	1.658	1.630
220	1.689	1.656	1.629
225	1.687	1.654	1.627
230	1.684	1.653	1.626
235	1.682	1.651	1.625
240	1.680	1.649	1.623
245	1.678	1.647	1.622
250	1.676	1.646	1.621

Table 2(d). Critical values C_0 for $C = 2.00$, $n = 10(5)250$ and $\alpha = 0.01, 0.025, 0.05$

n	$\alpha = 0.01$	$\alpha = 0.025$	$\alpha = 0.05$
10	3.826	3.361	3.026
15	3.302	3.002	2.776
20	3.050	2.821	2.645
25	2.899	2.710	2.562
30	2.795	2.633	2.504
35	2.270	2.575	2.461
40	2.661	2.531	2.426
45	2.614	2.495	2.399
50	2.576	2.465	2.376
55	2.543	2.440	2.356
60	2.516	2.418	2.339
65	2.492	2.399	2.324
70	2.471	2.383	2.311
75	2.452	2.368	2.300
80	2.435	2.355	2.289
85	2.420	2.343	2.289
90	2.407	2.332	2.271
95	2.394	2.323	2.264
100	2.383	2.313	2.256
105	2.372	2.305	2.250
110	2.363	2.297	2.243
115	2.354	2.290	2.238
120	2.345	2.283	2.232
125	2.337	2.277	2.227
130	2.330	2.271	2.223
135	2.323	2.266	2.218
140	2.317	2.261	2.214
145	2.311	2.256	2.210
150	2.305	2.251	2.206
155	2.299	2.247	2.203
160	2.294	2.242	2.199
165	2.289	2.238	2.196
170	2.284	2.235	2.193
175	2.280	2.231	2.190
180	2.276	2.227	2.187
185	2.272	2.224	2.185
190	2.268	2.221	2.182
195	2.264	2.218	2.180
200	2.260	2.215	2.177
205	2.257	2.212	2.175
210	2.253	2.209	2.173
215	2.250	2.207	2.171
220	2.247	2.204	2.169
225	2.244	2.202	2.167
230	2.241	2.199	2.165
235	2.238	2.197	2.163
240	2.236	2.195	2.161
245	2.233	2.193	2.159
250	2.230	2.191	2.158

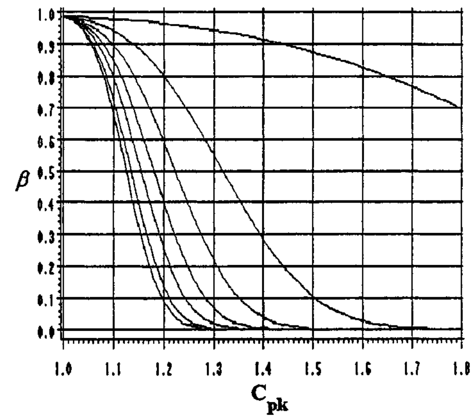

Figure 1. OC curves for $C = 1.00$, $\alpha = 0.01$ and $n = 10(40)250$ (top to bottom in plot)

2. Calculate the value of the estimator $\tilde{C}_{pk}$ from the sample.
3. Check Tables 2(a)–2(d) to find the corresponding C_0 based on α, C and sample size n
4. Conclude that the process meets the capability requirement if $\tilde{C}_{pk}$ is greater than C_0. Otherwise, we do not have enough information to conclude that the process meets the capability requirement.

To accelerate the calculations of the estimator $\tilde{C}_{pk}$, we have provided values of the correction factor b_f for various sample sizes $n = 10(5)250$ (see Table 3). Figure 1 plots the OC curves ($\beta = 1 - \pi(C_{pk})$ versus C_{pk} value) for the quality conditions with C set to 1.00, α risk $= 0.01$ and sample sizes $n = 10(40)250$.

AN EXAMPLE

Consider the following example taken from *bopro*, a manufacturer and supplier in Taiwan exporting high-end audio speaker components including rubber edge, Pulux edge, Kevlar cone, honeycomb and many others. The production specifications for a particular model of Pulux edge are the following: USL $= 5.95$, LSL $= 5.65$, $T = 5.80$. The quality requirement was defined as 'Satisfactory' ($C_{pk} > 1.33$). A total of 90 observations were collected which are displayed in Table 4.

To determine whether the process is 'Satisfactory', we first calculate $d = (\text{USL} - \text{LSL})/2 = 0.15$, $m = (\text{USL} + \text{LSL})/2 = 5.80$, sample mean $\bar{X} = 5.830$ and sample standard deviation $S = 0.023$. To calculate the value of the estimator $\tilde{C}_{pk}$, we need to determine the value of $I_A(\mu)$, which requires the knowledge of $P(\mu \geq m)$ or $P(\mu < m)$. The historical information of the process shows that $P(\mu \geq m) = 0.75$. Thus

Table 3. Values of b_f for various sample sizes n

n	b_f	n	b_f	n	b_f	n	b_f	n	b_f	n	b_f	n	b_f
10	0.914	45	0.983	80	0.990	115	0.993	150	0.995	185	0.996	220	0.997
15	0.945	50	0.985	85	0.991	120	0.994	155	0.995	190	0.996	225	0.997
20	0.960	55	0.986	90	0.992	125	0.994	160	0.995	195	0.996	230	0.997
25	0.968	60	0.987	95	0.992	130	0.994	165	0.995	200	0.996	235	0.997
30	0.974	65	0.988	100	0.992	135	0.994	170	0.996	205	0.996	240	0.997
35	0.978	70	0.989	105	0.993	140	0.995	175	0.996	210	0.996	245	0.997
40	0.981	75	0.990	110	0.993	145	0.995	180	0.996	215	0.996	250	0.997

Table 4. Collected sample data (90 observations)

5.88	5.83	5.84	5.80	5.89	5.81	5.84	5.83	5.82	5.83
5.81	5.82	5.85	5.81	5.81	5.81	5.84	5.82	5.80	5.84
5.86	5.87	5.82	5.87	5.80	5.81	5.85	5.84	5.83	5.86
5.81	5.81	5.82	5.83	5.85	5.80	5.86	5.82	5.86	5.83
5.80	5.77	5.82	5.85	5.84	5.82	5.85	5.81	5.86	5.79
5.84	5.83	5.80	5.83	5.81	5.83	5.81	5.85	5.83	5.88
5.82	5.87	5.80	5.82	5.83	5.81	5.84	5.79	5.85	5.85
5.84	5.84	5.80	5.82	5.84	5.85	5.86	5.81	5.81	5.85
5.86	5.81	5.81	5.83	5.85	5.85	5.82	5.83	5.86	5.81

we can determine the value of $I_A(\mu) = 1$ or -1 using available random number tables.

Suppose the generated two-digit random number is 65, then we have $I_A(\mu) = 1$. Checking the value of b_f from Table 3, we obtain $b_f = 0.992$. Thus $\tilde{C}_{pk} = b_f \hat{C}''_{pk} = b_f(d - \bar{X} + m)/3S = 1.890$. Assume the α risk is 0.05. We find the critical value $C_0 = 1.516$ from Table 2(b) based on $C = 1.33$, $\alpha = 0.05$ and sample size $n = 90$. Since $\tilde{C}_{pk}$ is greater than the critical value C_0, we conclude that the process is 'Satisfactory'.

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