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MEASURING PROCESS CAPABILITY

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(3 EQRM 2)

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TECHNICAL REPORT

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Efficiency, Quality and Reliability
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Introduction:

The subject matter of this talk is one, it would appear, of little consequence to the statistical community. At least this could quite easily be the conclusion drawn when perusing various texts dealing with statistical process control. When it comes to process capability and process capability indices these statistics books, generally, make little more than passing mention. In fact this may well be, by the considered opinion of the statistical community, the way it should be!

However, it has been my experience, having been involved with quality management and statistical consulting with a number of companies in a variety of industries, that large sections of the manufacturing community are obsessed with capability indices. I hasten to add that use of the word 'obsessed' is no idle choice. In quality rating schemes, in production department priorities in marketing and in management meetings, capability indices often predominate. They can overshadow important features of effective quality management, important aspects of statistical control and the need for experimentation and they are often used as a goad for production staff to raise their level of performance. We can shrug our shoulders and hope the fad will pass but those working in the industrial environment haven't this luxury. They are faced daily with the problems this pre-occupation induces. Many can see the deficiencies in these indices as definitive measures of quality and yet others are knowingly blind. One has to ask then, why some close their eyes to reality?

One reason is that many companies are forced, by their corporate customers, to talk 'quality' in terms of capability indices. Even if they perceive the shallowness of this, there is an understandable reluctance to 'rock the boat'. Why then have numerous large corporations assumed this emphasis? Undoubtedly there is some belief in the justice of so doing but perhaps more important there is the issue of simplicity. I think we generally under sell the importance of simplicity. Some may like the challenge of the complex but the average manager, plagued by the pressures that he is, will gladly embrace simplicity if it is apparently in evidence in a major area of his responsibility. If the often complex issue of product quality can seemingly be summarized by reference to a simple numeric value, then why not indeed?

Beside the misleading information that can be imparted by this approach, an issue that is of prime importance to us as a group is that those who see the shallowness and inadequacies of it can assume a cynical approach to statistical methods. At a time when there is a need for Australian industry to raise its degree of sophistication in the use of statistical techniques, this is tragic indeed.

Purpose:

My aim today is to briefly outline some deficiencies in the accepted use of capability indices, highlight some reasons for these deficiencies and offer some suggestions for improvement in procedure. Nothing very statistically sophisticated is involved but I do hope that I can persuade more people to pick up the cause I've been fighting now for several years. Statistically, some of the issues I raise are trite and I guess to many with a statistical bent may seem trivial. They are, however, real stumbling blocks to meaningful use of statistical techniques for process and product improvement. Hackneyed they may be but important they are.

Qualifying Remarks:

Whilst I make some general comments on industrial processes, on process capability and on capability indices, the thrust of my comments are towards the continuous process industries. Typically, with such processes samples are small and sample values arise as the consequence of laboratory analysis. Short production runs and difficulties with maintaining stability are common.

What is Process Capability:

It would seem that there is some difference of opinion as to the meaning of the term 'process capability'. At the outset of this paper then, it is appropriate that I mention some of the definitions offered and define my own usage carefully. Lack of clarification of objectives in discussing process capability, that I allude to later, is I suspect, not unrelated to this mix of available definitions.

Some consider, I assume, that the term is self-evident, since numerous texts dealing with statistical process control tender no formal definition. An early edition of Juran's Quality Control Handbook even makes the statement ..... 'A process capability analysis is normally performed only on a process which is not regularly meeting tolerances ....'. A common definition tendered by one author defines ..... 'process capability or spread of the process as equal to six standard deviations....'. Another writes .... 'A process operating in control may or may not be operating within specifications. If the process exhibits statistical control, estimates of the process mean and standard deviation may be used to determine the capability of the process to produce within specifications....'. Under the heading of Process Capability, Wheeler and Chambers [4] write ....' can the process produce product that meets specifications? This question has been around for nearly 200 years, and the number of procedures used in the attempt to answer it is legion.

However, important as this question is, it should not be considered alone ..... the answer tells only part of the story.' This is just a small sample of what is in print concerning process capability. In referring to operation within specifications, as one of the foregoing does, the implication is made that product requirements equate to conformance to specifications which, tacitly means satisfying customers needs, Taguchi, with his quadratic loss function, is at odds with this concept of customer satisfaction. His concept of quality and loss tends to relegate tolerances or product specifications, at the definition stage, to little more than engineering convenience. They take on more meaning in his concept of robust design (allowance design). In fact the 'buzz phrase' 'zero defects' that has been doing the rounds for some years, referring to the ideal quality objective, is in conflict with Taguchi's fundamental ideas regarding attaining a low value for the quality loss function. Taguchi emphasizes the importance of attaining product consistency to target value (for current purposes I am focusing on the assumed requirement to make the product to a certain numerical dimension or characteristic). Statistically, the ideal is to have a manufacturing process that follows a stable Gaussian distribution with mean the target value or nominal dimension and with a very small process variance. In other words a process that virtually produces products 'spot-on' the target value. Of course the statistical ideals have to be tempered by costs and a suitable compromise struck so that products are marketable from the joint perspective of 'quality' and manufacturing cost.

The definition of process capability that I choose and is the one, I am sure, was originally intended, is:-

THE POTENTIAL OF THE PROCESS TO CONSISTENTLY PRODUCE PRODUCT TO MEET EXISTING CUSTOMER REQUIREMENTS. Two aspects of this definition I draw attention to. The first, is the use of the word POTENTIAL and the second is the lack of definition of the phrase, 'customer requirements'. Hence, as defined here, process capability is immune to the vagaries of methods of defining quality or customer satisfaction. Such change occurred when Taguchi' launched' his quality loss function. It should also be noted that customer satisfaction or customer requirements, whilst not explicitly defined, would certainly include cost which would of course not be independent of competition in the market place. Customer requirements or satisfaction is a concept of considerable complexity - far more so than the average exposition would have us believe.

The method of measuring process capability may or may not change with varying definition of customer requirements bearing in mind it is process potential we are dealing with. Process potential is of much more interest to the producer than to the consumer or customer. The customer is much more interested in actual performance and consistency than in the producers' potential.

So by use of the word 'potential' we are presenting a definition of process capability that is primarily (but not exclusively) of benefit to the producer. This may seem like 'nit-picking' with semantics but bear with me.

Measuring Capability:

Having dispensed with these preliminaries consider the commonly used process capability index C_p,

$$C_p = \frac{U - L}{6\sigma} ,$$

U and L are the upper and lower product specifications respectively and σ the process standard deviation.

To have any relationship to product quality, conformance to specifications must have some direct relationship to customer satisfaction. The presence of 6σ in the denominator implies a Gaussian or near Gaussian process distribution, since under such circumstances the vast majority of process values will lie in a 6σ band symmetric about the process mean. This is reasonably robust for minor deviations from normality. Desirable values for C_p are, generally, deemed to be those in excess of 1 - the bigger the better (subject to cost). The logic is that the natural oscillation band for the process, provided it remains Gaussian and unchanged, should be narrower than the specification band, hence $C_p > 1$. Provided the two bands aren't radically out of alignment, then the process will produce products within specifications. Certain issues immediately arise that impinge on the usefulness of this measure of capability. First, is the process reasonably Gaussian and if so how long can this be retained? Second, to what degree is conformance to specifications a measure of customer satisfaction? Unless the Gaussian nature of the distribution can be maintained for a reasonable length of time and specification conformance is a major consideration in customer satisfaction, then C_p doesn't, in any real sense, measure process potential. The C_p of course doesn't make any reference to process mean but if, as Taguchi maintains, process mean is important, the C_p value represents the best possible position in relation to target for the case where the process is perfectly centred on the target dimension. The 'potential' nature of C_p is thus evident. The assumption is generally made that the target or nominal value is located at $\frac{U + L}{2}$. (which is very often the case).

A C_p value as a measure of potential is of even more value if accompanied by an indication of the length of time stability can be retained together with the process mean performance.

For any process we will of course not know σ and so this will have to be estimated from sample data. It is rare indeed, in my experience, where C_p values are calculated from sample data, to find sample estimates accompanied by an appropriate confidence interval although standard application of the chi-squared distribution provides such an interval quite readily. (again assuming the existence of a Gaussian distribution).

There seems to be a reluctance to accompany σ estimation (and the consequent C_p estimation) by appropriate confidence intervals. The result is often a false sense of knowing and dogmatic statements about process capability.

The standard procedure with regard to method of estimation of σ again re-enforces the fact that C_p, at its best, is an assessment of the potential capability of the process which, as mentioned earlier, is of far more concern to the producer that to the consumer.

In a discrete item manufacturing situation, being monitored by use of customary mean and range charts, it is normal procedure to estimate process standard deviation by using $\frac{\bar{R}}{d_2}$.

$\bar{R}$ is the mean range of a sequence of small samples from a Gaussian process. What goes largely unrealized in that $\frac{\bar{R}}{d_2}$ is an estimate of the within - group or within sample standard deviation not the total standard deviation experienced over the duration of sampling. It is thus an estimate of the best possible situation from the perspective of the producer and in most instances the appropriate estimate to use in control chart construction. To use this estimate in $C_p = \frac{U - L}{6\sigma}$ underlines the fact of the potential nature of C_p as a measure of process capability. The estimate of the actual standard deviation of the total production during collection of this data is:-

$$\sqrt{\frac{1}{mn - 1} \sum_{i=1}^{m} \sum_{j=1}^{n} \left(x_{ij} - x\right)^2}$$

where m is the number of samples and n the sample size. It is this that is most meaningful to the customer- a more realistic reflection of what he receives.

For continuous processes, which are common in the chemical industry, single samples are invariably taken from the process at regular intervals and submitted to chemical analysis. Process monitoring is often performed using some variant of the single value chart and standard deviation again estimated using $\frac{\overline{R}}{d_2}$ where $\overline{R} = \frac{1}{m}\ (R_1 + \ldots\ldots + R_m)$

and R_i ($i = 1, \ldots\ldots m$) are moving ranges of size 2. This is virtually equivalent to finding the average variance of moving sample value pairs and square rooting the result.

$(2,\ x_2)$

$(1,\ x_1)$ $(3,\ x_3)$ $(n,\ x_n)$

The average variance of the pairs is:-

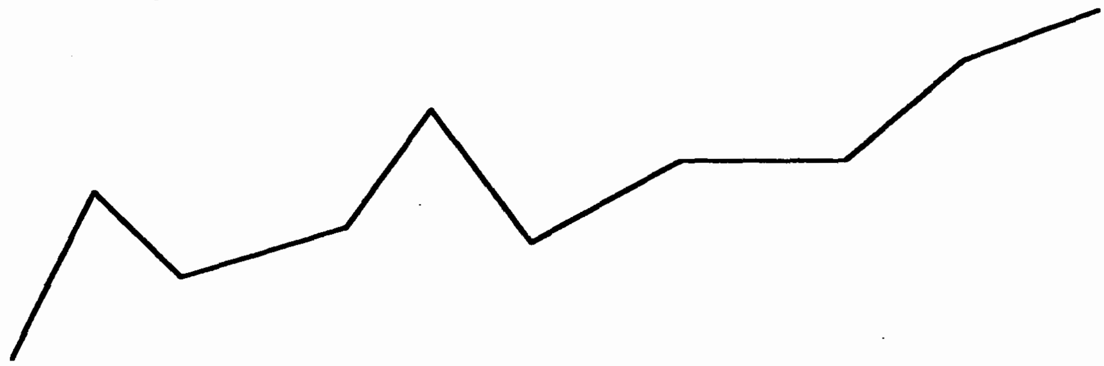
$$\frac{1}{(n-1)}\left[\begin{array}{l} \left\{x_1 - \left(\frac{x_1 + x_2}{2}\right)\right\}^2 + \left\{x_2 - \left(\frac{x_1 + x_2}{2}\right)\right\}^2 \\ + \left\{x_2 - \left(\frac{x_2 + x_3}{2}\right)\right\}^2 + \left\{x_3 - \left(\frac{x_2 + x_3}{2}\right)\right\}^2 \\ + \ldots\ldots\ldots\ldots + \left\{x_{n-1} - \left(\frac{x_{n-1} + x_n}{2}\right)\right\}^2 + \left\{x_n - \left(\frac{x_{n-1} + x_n}{2}\right)\right\}^2 \end{array}\right]$$

$$= \frac{1}{2\ (n-1)}\left[\sum_{i=1}^{n-1} \left(x_i - x_{i+1}\right)^2\right]$$

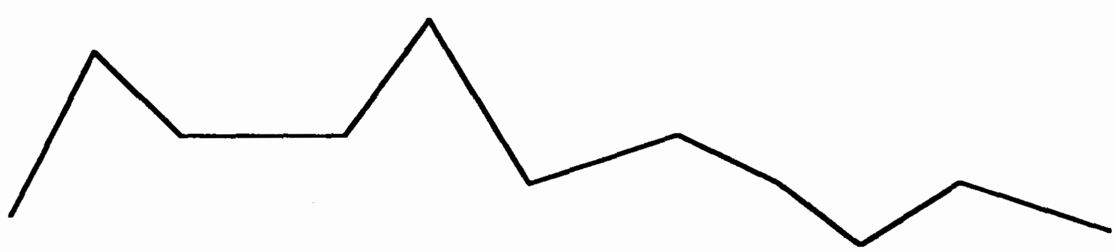
and so the standard deviation estimate

is $$\sqrt{\frac{1}{2(n-1)} \sum_{i=1}^{n=1} \left(x_i - x_{i+1}\right)^2}$$

It is possible to illustrate a physical interpretation of this calculation by taking the extreme example illustrated by the following plot.



This path is almost certainly the consequence of a climbing process mean. To find the standard deviation of these values using the root mean square method reflects rather the overall spread. With regard to process potential, however, should it be possible to arrest the movement of the mean, then the following path should be obtainable



The calculation

$$\sqrt{\frac{1}{2\,(n-1)}\left[\sum_{i=1}^{n-1}\left(x_i - x_{i+1}\right)^2\right]}$$

is more representative of this situation and as such is an estimate of the potential of the process rather than the actual performance. One can also illustrate this as a more appropriate estimate of the potential by computer simulation.

With continuous processes it is common to have the situation of a frequently moving mean as sample values have often to be obtained over a large span of time.

In summary then, C_p is a measure of the potential process capability and the usual method of standard deviation estimation re-enforces this fact. As such, its value is of more importance to the producer than to the consumer whose main focus is on the quality of the product that he actually obtains. Data collection for the estimation of σ should be done under circumstances of achieved stability and with a minimal amount of outside interference.

This contrived situation is generally called a capability trial and is an attempt to determine the natural variation of the process which common sense tells us we had best be in harmony with when considering process adjustment.

Improving on C_p?

Another index geared to coping with the inadequacy of C_p in respect of not making reference to process mean is called the C_{pk} index and is defined as:-

$$C_{pk} = \min \left\{ \frac{U - \mu}{3\sigma}, \frac{\mu - L}{3\sigma} \right\}$$

Its definition is based on the joint premises of a Gaussian distribution and a target value of $\frac{U + L}{2}$. Should the process mean be equal to $\frac{U + L}{2}$ then $C_{pk} = C_p$ else $C_{pk} < C_p$.

Now since definition of C_{pk} involves both process parameters there is the opportunity to consider this a measure of actual process capability provided the two binding premises mentioned are substantiated. Whether it is to be regarded as potential or actual depends largely on the method of estimation of σ since neither μ or σ will be known. The main use to which C_{pk} is being put is as a measure of actual quality. From samples of finished product C_{pk} values are calculated and used to describe consignment quality. It is not uncommon practice for customers to make stipulations on sample C_{pk} values to be attained. These stipulations invariably are specific numerical values with no corresponding stipulation made on the method of standard deviation estimation. Neither is it uncommon for there to be no specification of sample size. Despite all these degrees of freedom numerical sample C_{pk} values are commonly used comparatively for quality rating purposes for consignment against consignment and company against company. Not uncommonly also, low C_{pk} values are used to brow-beat production personnel.

There appears little realization that such C_{pk} values are merely point estimates and that choice of method of standard deviation estimation is largely dependent on the purpose to which the C_{pk} values are to be put. Producers providing C_{pk} values from consignment test results for their customers, realizing that $\frac{\overline{R}}{d_2}$ estimation provides more favourable C_{pk} values, commonly use this in assessment of consignment C_{pk}'s. So fixed has 'quality' become focussed on C_{pk} values that the importance of the Gaussian assumption, if realized, is often over looked. At the consignment stage, because of natural sorting, filtering or mix of production lots sample data can evidence lack of normality even though not in evidence at the production stage.

In a paper [1] shortly to appear in print I have discussed issues involved in attempting to find confidence intervals for consignment C_{pk}'s.

The bulk of published material on statistical process control is presented from a discrete item manufacturing process perspective. Because of the path that quality improvement (with its stated dependence on statistical techniques) has trodden, companies involved in continuous process production are using techniques and approaches found to have been useful in discrete item manufacturing. This has largely stemmed from the automotive industry passing the quality buck along the supplier network. In so doing there has been a lack of sensitivity to the needs and unique features of the continuous process industries.

Successive samples taken from continuous processes are often correlated, this is a feature rarely of significance in discrete manufacturing. The generation of large amounts of data routinely, or when necessitated, is often not a major difficulty in discrete item manufacturing either. For continuous processes data not uncommonly originates with a single grab sample that may be difficult and time consuming to collect, even more time consuming to test and in addition susceptible to considerable experimental error.

Sample sizes for production runs are typically small. Production grade changes are made 'in motion' with the resulting production during changes typically non-Gaussian. During these grade changes it is not uncommon to sample and test move intensively to obtain early warning of new on-grade production or for confirmation of previously observed on-grade production. For short production runs these 'marginal' sample values can extremely deflate calculated C_{pk} values. Much more could be said on this score but would require getting company specific.

C_{pk}, Taguchi's Loss Function and Expected Loss:

Having dealt at some length with sampling deficiencies let's return briefly to the underlying concept of the C_{pk}. It might seem that consideration of C_{pk} in its conceptual form,

$$C_{pk} = \min \left\{ \frac{U - \mu}{3\sigma} , \frac{\mu - L}{3\sigma} \right\}$$

is consistent with Taguchi's notion of quality and loss in that it involves reference to both mean conformance to target and process standard deviation. If we define Taguchi's loss function as $l = kx^2$ where x is the distance of the product characteristic from target, T. Then the expected loss $E(l)$ for a process with p.d.f. f(x) (which need not be Gaussian)

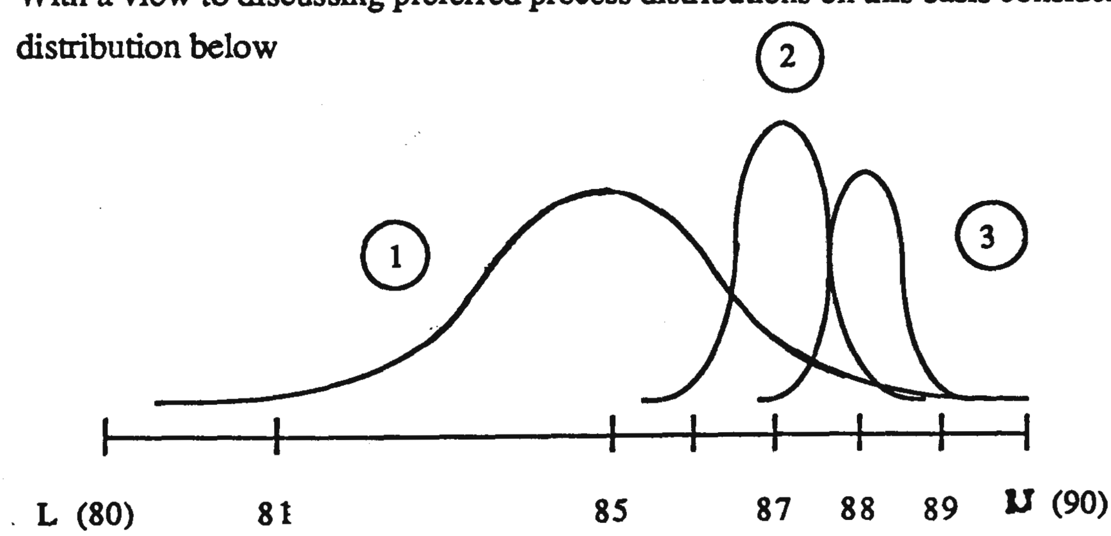
$$\text{is} \int_{\infty}^{\infty} k\,(x - T)^2 f(x)\,dx$$

$$= k\left[(\mu - T)^2 + \sigma^2 \right] .$$

and if $T = \dfrac{U + L}{2}$ this is:-

$$k\left[\left\{ \mu - \left(\frac{U + L}{2} \right) \right\}^2 + \sigma^2 \right] .$$

With a view to discussing preferred process distributions on this basis consider the three distribution below



All are Gaussian and $\mu_1 = 85$, $\sigma_1 = \frac{4}{3}$,

$\mu_2 = 87$, $\sigma_2 = \frac{2}{3}$,

$\mu_3 = 88$, $\sigma_3 = \frac{1}{3}$.

Assuming L =80, U = 90 then 1 is perfectly centred giving $E(l_1) = \frac{16}{9} k$

and 1 and 2 give $E(l_2) = \frac{40}{9} k$

and $E(l_3) = \frac{82}{9} k$ respectively.

So in order of preference, based on expected loss, we would have 1 , 2 , 3 .

Examining these now on the basis of C_{pk} values $C_{pk}(1) = 1.25$,

$C_{pk}(2) = 1.5$,

and $C_{pk}(3) = 2$.

So bearing in mind it is large values of C_{pk} that are to be preferred then the order of preference on a C_{pk} basis is 3 , 2 , 1 , the reverse order to that on the basis of expected loss!

If, however, we consider the potential for improvement brought about by what may well be an inexpensive appropriate adjustment of the mean,

2 has the potential to provide $E(l_2) = \frac{4}{9} k$

and $C_{pk}(2) = 2.5$

and 3 $E(l_3) = \frac{k}{9}$ and $C_{pk}(3) = 5$.

Provided the cost of this mean shift is negligible, the order of preference now given by the two criteria may well line up (adding into the expected loss the cost of shifting the mean). To achieve this we need to regard the potential rather than the current performance and as soon as we do, C_{pk} ceases to be distinct from C_p.

Separating Process Potential and Quality Checks:

Returning then to C_p, as we have, it would seem a suitable mechanism for assessing the producer's potential on the basis that the process can be maintained Gaussian for a reasonable length of time and that measuring error doesn't dominate. A controlled capability run with suitable estimation of process standard deviation provides, in addition, the mechanism via a control chart to monitor the process. Constant monitoring of production means and standard deviations should feature.

Successful, prompt process adjustment when necessitated should then ensure customer quality. (assuming estimates of sample C_p's indicate process C_p is considerably in excess of 1.

It would be nice to think human integrity was such that producers would maintain such a scheme and that customers would accept this 'assurance' of quality - some what of the close, confident working relationship between customer and supplier spoken of by Deming. Reality however, dictates that we don't live in this type of world and so corporate customers will inevitably want their own 'guarantee' of quality. There is a nievety in believing that we can check up on our customers by using their data. If customers will not rely on the integrity of their suppliers then it will involve them in sampling consigned product themselves (with the associated costs) and common sense dictates that any statistical appraisal of the quality should make few assumptions - certainly not that the process from which the products have emanated is Gaussian. If the product concerned is a continuous flowing product (liquid, gas or fine granular material) then assuming independence of sample values may also be 'unsafe'. Checks may take a number of forms, they might be simply to establish that all tested values are within specifications. They might, in addition, be to check the mean and or standard deviation of consignments. The way checks are currently done they invariably involve C_{pk} estimation ignoring the inevitable sampling fluctuations. Customers need to appraise what is most important to them - average performance or distribution standard deviation. C_{pk} estimation tangles the two together in a way that doesn't really aid in manufacturing terms (supposing that the product purchased is further used in manufacturing). Neither does looking at expected loss using a quadratic loss function provide the relative importance of mean and standard deviation. Separate consideration of the two parameters seems to make more general sense.

Provided sample values are independent and the value of the consignment mean is important there is some worth, for a continuous process in calculating

$$\Pr\left[T - \varepsilon < \mu < T + \varepsilon \right]$$

utilizing, for sufficiently large samples, the Central Limit Theorem. T is the target characteristic and ε a closeness parameter to it. With the likelihood of sample values being correlated this may need to be refined. In [3] Saunders, Robinson, Lwin and Holmes obtain an expression for the error variance of the mean of a correlated stream of values. For this result the variogram,

$$v(u) = \frac{1}{2} E\left[\left\{ X(t) - X(t+u) \right\}^2 \right]$$

for u less than the sampling interval, needs to be linear. Provided sample results support the assumption of linearity a simple expression for the error variance of the mean can be obtained in the common case of fixed time sampling. I have had numerous occasions to test this assumption in practice and in every instance have found it a good approximation to reality.

In order to obtain a result that would make this expression more useful I have developed a Central Limit Theorem [2] that again would permit even in the correlated case the calculation of

$$\Pr\left[T - \varepsilon < \mu < T + \varepsilon\right] .$$

The result given in [3] is also shown to be of some relevance in the non-stationary case.

Conclusions:

In introducing this last section I mentioned the lack of confidence that might prompt customer testing. Should the process not be stable there is little recourse but to take this tack anyway.

For one particular company that I work with I have made a submission to Corporate Management in an effort to have them de-emphasize C_{pk} calculation and evaluation. It had got to a stage in their operation that both for internal production purposes and for customer evaluation of delivered product, sample C_{pk}'s were the bench mark. With regard to evaluating internal production I have had a degree of success in bringing about change in at least one Plant but having them take the case of external evaluation to their Corporate customers is another matter! In my submitted document I made the following summary.

Summary of Objections

Sample C_{pk}'s are inappropriate as a gauge of quality because:

i) C_{pk} is conceptually lacking when consignments are non-normal - comparison of sample C_{pk}'s between normal and non-normal consignments is thus meaningless.

ii) Chasing high C_{pk} values muddies the issue of customer priorities.

iii) Sample C_{pk}'s are merely point estimates that can oscillate widely, especially with sample sizes typically in use.

iv) Although confidence intervals for consignment C_{pk}'s are desirable they are not easily obtained. The varying nature of sample C_{pk}'s for a given consignment quality can be illustrated by simulation.

v) Estimated C_{pk}'s give no useful feedback for the production department on quality performance.

vi) Estimated C_{pk}'s do not provide the customer with usable information of quality for production purposes.

vii) Hopper samples can often exhibit auto-correlation, this impinges further on the reliability of sample C_{pk}'s as a gauge of consignment quality.

<u>An Alternative Approach:</u>

Any alternatives to C_{pk} as a gauge of product quality:-

i) Should ideally be expressible as a confidence interval and be, therefore, sample size sensitive.

ii) Should not be based on any distributional assumption of the consignment that cannot be verified.

iii) Should be able to accommodate the possibility of sample values being auto-correlated.

iv) Should emphasise consistency to target since this is a major concern to customers.

v) Should give both customer and production department useful feedback on consignment to consignment quality.

vi) Should be usable to assess continual improvement over time.

In the continuous process industries there are pressing problems that often need to be tackled. Gaining and retaining stability is an important one as is the issue of data quality from both the aspect of collection and analysis. Short production runs, problems of plant maintenance, frequent product changes demand much attention. Pre-occupation with sample C_{pk} values only detracts from these issues and whilst giving management a simple yardstick for evaluation frustrates those who have to deal with the real problems of production on a day to day basis. So my plea to the statistical community is, please do what you can when the opportunity arises to move industry away from this C_{pk} obsession. Statistically, there are some exciting practical problems to be solved, a focus on these will, I'm sure prove a real benefit to Australian industry.

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