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Full Length Research Paper

A holistic application of process capability indices

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Different capability measuring techniques have been proposed and are being used in industry today. Each one gives a certain portion of the quality picture, leaving out some equally important details about the process. There is no single index which addresses the whole quality of a production process on its own, hence the need to look at all the indices holistically. Each index has its own merits and demerits. In this paper, we consider a case study of a company which manufactures belts, and has been using only one index, C_{pk}. Its quality checks were indicating that the process was under control. On the other hand, customers have been complaining that the belts they are manufacturing are not strong and tend to breaking easily. This paper concentrates on addressing the production process of belts by looking at different capability indices and come up with a method or algorithm that addresses this problem holistically. Strengths and weaknesses of each capability index are analysed and sets of indices which address the full picture of the production process are used to check the capability of the process. Results show that customers were justified in their complaints as the new quality checks indicated that the production process of these belts was incapable of producing belts which meet customer satisfaction. Corrective measures were recommended to the company.

Key words: Holistic, capability index, control limits, production process, belts.

INTRODUCTION

Capability indices are tricky to interpret, controversial to apply and often misunderstood by many practitioners. Unless the properties of an index are clearly understood, making major capital improvements may not be the most prudent way to fix an unacceptable capability. Understanding the meaning of a particular index can have a profound impact on the cost of manufacturing. Process improvement must be driven by more than the need to improve an index number, otherwise management may be wasting time and resources.

One process capability index C_{pk}, is widely used to determine whether manufacturing processes are capable of meeting specifications or not. A company in Southern Africa is currently using one process capability index C_{pk} to determine whether their belt manufacturing process is capable of meeting specifications. Collected data indicates that the process is capable, but customers complain that the belts are not strong and tend to break easily. In this paper, we take a critical look at what C_{pk} measures together with various other indices and also investigate the inter-relationships between the indices.

Most literature would simply suggest that management must choose the 'correct' index for their application or process. A company that measures process capability using only one index such as the C_{pk} to monitor all quality characteristics of a process, may face problems since the index may be effective only in measuring a particular characteristic which does not fully define the quality of a product under consideration. We suggest a need to look at other indices to monitor other characteristics of the process under this scenario. Each

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Abbreviations: USL, Upper specifications limits; **LSL,** lower specifications limits; **T,** target value; **SPC,** statistical process control; **PCI,** process capability indices; **PPI,** process performance index; **QLF,** quadratic loss function.

index tells something different and a procedure is suggested that will harmonise all these index values and determine which indices should be used for measuring quality characteristics of a process. The procedure will be tested on data from the belt manufacturing company. Whilst C_{pk} is good at measuring certain characteristics of a manufacturing process, it is not suitable for assessing all characteristics of the process that may influence quality.

The physical processes that manufacture the part are generally subject to many sources of variation, starting from the quality of raw material to the aging and wear-out of the manufacturing equipment. Consequently, Y is a random quantity (or a random variable), whose distribution is often assumed to be Gaussian with mean, say, μ, and a variance, say σ^2. In manufacturing parlance, the variance is referred to as the "natural tolerance" of Y. When working with the process capability indices, it is common practice to assume that both μ and σ^2 does not change with time, that is, the process is stable, or is in statistical control.

The question which arises is as to whether the design engineer's compromise in going from the ideal target value (T) to the upper and lower specifications limits (USL and LSL respectively), is matched by the manufacturer's ability to meet such a compromise vis-à-vis the assumed μ and σ^2 mentioned earlier. The process capability indices were introduced to address this matter. The quantity (USL-LSL) is known as the specification interval (or tolerance); denoted by 2d, where *d* is the half length of the specification interval. The midpoint of the specification interval, which will is denoted by *M*, is equal to (USL+LSL)/2 (Figure 1).

Capability indices, similar to coefficients of variation, are dimensionless measures of relative variability. It is a ratio, or a number without units of measurement, that compares process spread to tolerance spread and results in a single number. That number is then judged acceptable or unacceptable by some arbitrary standard. An index can also be used to compare one process to another or set a minimum acceptable quality standard for processes. A capability index should be computed using data from a stable process. Typically, process stability is assessed by collecting sub-samples at regular intervals and plotting sub-sample statistics on control charts. Once the charts show a reasonable degree of stability, process capability can be assessed.

Capability analysis is used in many facets of industrial processes and is beginning to be used as well in business processes. Capability analysis and thresholds for capability indices are used in the qualification of processes, acceptance of equipment, purchase parts approval activities, continuous improvement efforts, problem solving activities and for many other purposes. It is the backbone for measuring processes ability to produce product that falls within a desired specification through the enumeration of variation. Capability indices provide a yardstick for measuring improvement. The accuracy of capability indices is dependent on proper understanding of the theory behind the indices as well as an understanding of variation.

PROCESS CONTROL AND PROCESS CAPABILITY INDICES

Statistical process control (SPC) and quality improvement methods are generally based on control charts which are used for monitoring relevant process characteristics, like process capability indices (PCI) which were developed for measuring uniformity of the process. The main goal of SPC consists of keeping small process variation around a given target value and thus guaranteeing a small number of nonconforming items produced and a large PCI-value. Process capability analysis includes substantially more than just the computation of any index. After process control has been established, capability is assessed.
The use of classical univariate PCI is based on the following assumptions:

i. There is only one quality characteristic considered.
ii. The distribution of the quality characteristic is approximately normal.

Lack of normality may provide a misleading interpretation of the result. For example, if a population distribution is uniformly distributed over the interval from 0.5 - 2.5 with LSL = 0.5, USL = 2.5, and nominal (Target) = 1.5, then the mean of a uniform distribution is $\mu = 1.5$ and $\sigma = \sqrt{\frac{1}{12}} \approx 0.29.$ Hence,

$$C_{pk} = \min\left(\frac{USL-\mu}{3\sigma}, \frac{\mu-LSL}{3\sigma}\right) = \min\left(\frac{2.5-1.5}{3(0.29)}, \frac{1.5-0.5}{3(0.29)}\right) = 1.$$

15.

We have bad parts but the C_{pk} index suggest that we are just capable.

The quality characteristics of different items are stochastically independent.

The process is under statistical control, that is, the process mean and process variability are constant.
The sample size is large enough that calculations for standard deviation are rational.

Assessment is essentially the act of comparing the distribution of data, or a model, to the engineering requirements, typically in the form of engineering specifications. If the process is deemed capable, then the process will be maintained using statistical process control methods. If, on the other hand, the process is deemed not capable that is it is producing an acceptable level of non-conforming product, then the process will undergo a process improvement stage and work toward an acceptable level of capability and control. Previous researchers (Kane, 1986; Chan et al., 1988; Choi and Owen, 1990; Pearn et al., 1992; Greenwich and Jahr-Schaffrath 1995) addressed different process capability indices for providing measures for process potential and process performance. The initially proposed PCI is C_p and it was proposed by Juran (1974).

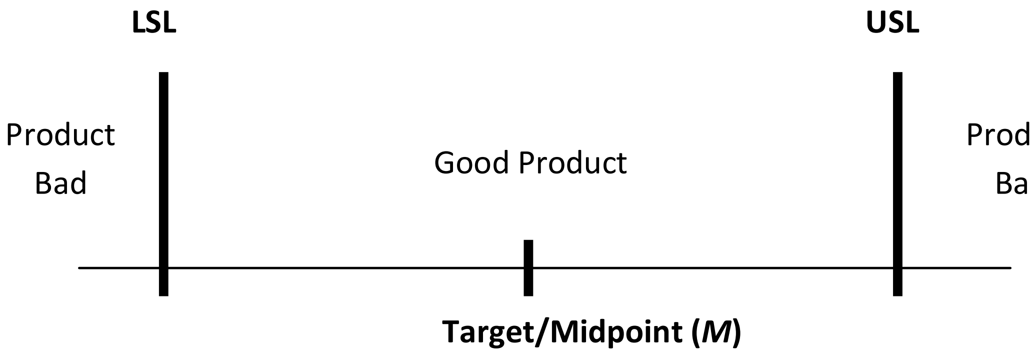

Figure 1. Upper specification limit and lower specification limit.

C_p is a powerful index that provides a quick observation to determine whether the process is capable of meeting specification. One could also say that C_p is the ratio between what you want the process to do (management's hope or allowable spread) versus what the process is actually doing (reality).

$$C_p = \frac{Hope}{\mathrm{Re}\,ality}$$

It was initially known as the capability ratio (Kotz and Johnson, 2002). It is a measure of tolerance spread to process spread (Figure 2) and is calculated as:

$$C_p = \frac{USL - LSL}{6\sigma} = \frac{d}{3\sigma} \quad (1)$$

Where, USL and LSL are the upper and lower specification limits respectively and d = (USL-LSL)/2, σ is the subgroup standard deviation.

It is often required that for acceptance we should have $C_p \le c$ with *c*=1, 1.33, 1.5 or 1.67 corresponding to USL-LSL= 6σ, 8σ, 9σ, or 10σ. Large values of C_p are desirable and small values undesirable (because a large standard deviation is undesirable).

C_p compares one process spread to another. It does not for instance evaluate where process average is or if it is centered with respect to the nominal (target) of the specifications. It is actually possible to have a process producing product that is 100% out of specification but associated with an acceptably high value of the index, as shown in Figure 2.

Therefore, C_p has its limitations, but it can serve as a powerful tool once one understands its strengths and weaknesses. Despite its common use in industry, enhancements and refinements of C_p have been proposed. Kane (1986) proposed C_{pk} as a PCI.

$$C_{pk} = \min\left(\frac{USL-\mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right) = \frac{d - |\mu - M|}{3\sigma} \quad (2)$$

where μ is the process mean and M = (USL+LSL)/2. Notice that C_{pk} is made up of two indices namely C_{pu} and C_{pl}, where

$$C_{pu} = \frac{USL - \mu}{3\sigma} \quad (3)$$

$$C_{pl} = \frac{\mu - LSL}{3\sigma} \quad (4)$$

Therefore, it can be written as $C_{pk} = \min\left(C_{pu}, C_{pl}\right)$. Negative values of C_{pk} occur when the process average is positioned outside of the specification interval. Whenever C_p is "large" and C_{pk} is "small," then μ is not centered at the middle of the tolerance.

In situations where both C_p and C_{pk} are "small," μ is centered near the middle of the tolerance but the process spread is too wide. If $C_{pk} = 1$, it can be shown that $M - d < \mu < M + d.$

In 1991, Boyles pointed out that "the C_p and C_{pk} do not say anything about the distance between process mean and target value" and "are essentially a measure of process potential only". Boyles showed that C_{pk} becomes arbitrarily large as σ approaches 0, irrespective of where the process is centered and this characteristic makes C_{pk} unsuitable as a measure of process centering. The same is true for C_p.

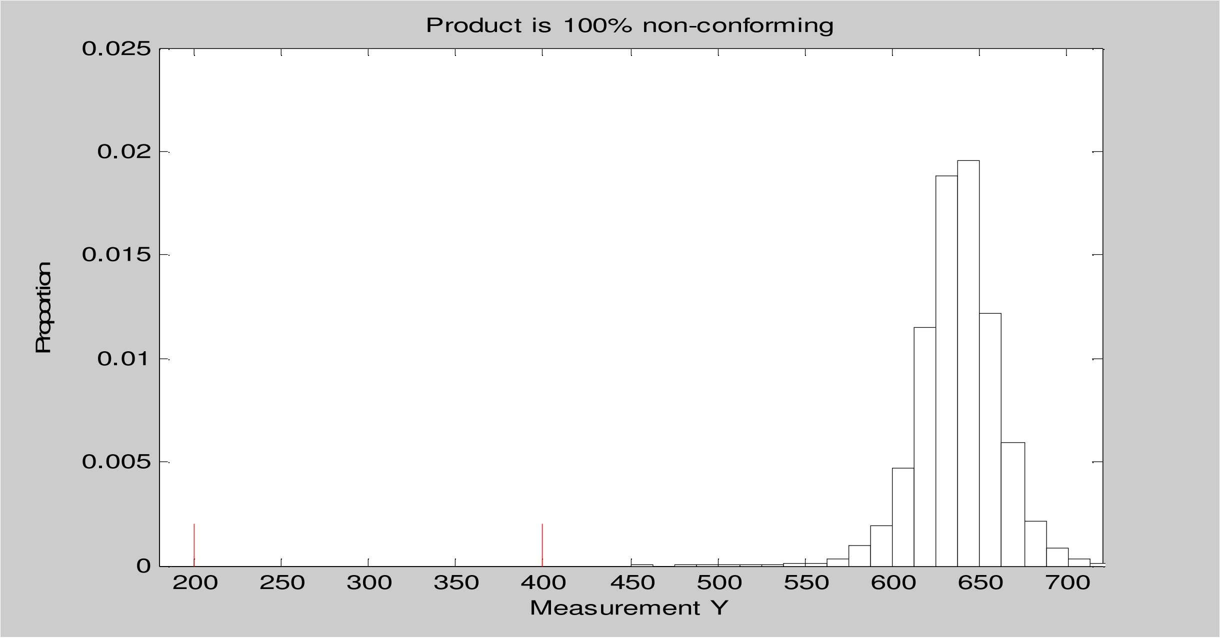

Figure 2. Production from a potentially capable process which is currently producing product that is 100% nonconforming. LSL=200 and USL=400.

Herman suggests that a different index, the 'process performance index' (PPI) , P_p might 'have more value to a customer than C_p'. The index P_p is defined as:

$$P_p = \frac{USL - LSL}{6\sigma_{total}} \tag{5}$$

An analogy to C_{pk} is:

$$P_{pk} = \min\left(\frac{USL-\mu}{3\sigma_{total}}, \frac{\mu - LSL}{3\sigma_{total}}\right) \tag{6}$$

P_{pk} is also referred to as the preliminary process capability. It is used whenever a new process is started or a major revision to an existing process is resumed. This is why some practitioners mistakenly assume P_{pk} is for short-term data and is to be used on an unstable process. Both assumptions are false. P_{pk} is an initial production run of a new process (less than 30 production days), and C_{pk} is everything thereafter.

One variation of C_{pk} is a relatively new index called C_pT , in which the T represents a target value. It allows one to select a target dimension and calculate capability from the target. C_pT calculations are the same as C_{pk} calculations, except that one substitutes a target dimension for the process average.

$$C_pT = \min\left(\frac{USL - T}{3\sigma}, \frac{T - LSL}{3\sigma}\right) = \frac{d - |T - M|}{3\sigma} \tag{7}$$

Like the C_{pk} index, both parts of the C_pT index are calculated, but only the minimum is used. The target dimension is usually the nominal of the specification, and some call it the true process centering of an index. In reality, however, the C_pT index is the same as the C_p index and has nothing to do with process centering. If the target T is set as the midpoint of the specification interval, that is T = M, C_pT yields the same ratio as C_p.

The concept of variation has undergone paradigm shift recently in industry. This shift has occurred in the interpretation of the quality of product varying within the allowable process specification. All the indices discussed so far have used the historical perspective of variation. A historical perspective of variation is that product had the same quality, that is to say that the product is equally good, regardless of where it fell within the specification limits. Product is considered bad or has less quality, only if it falls outside of the specification limits. Engineers are comfortable with this notion of variation, which is sometimes referred to as "Goal post mentality" and is displayed graphically in the following figure 3.

The problem with the goal post mentality is the step function that occurs directly at the specification limits. In regard to a process, the quality of a part falling just within the specification limit has little practical difference from the quality of a product falling just outside the specification limit. This model of quality variation has little relevance to industry. Figure 3, 4 and 5 shows a model that was proposed by statisticians. This model is more practical in that the loss in quality and thus value loss to an organization increases as the quality varies from a process target.

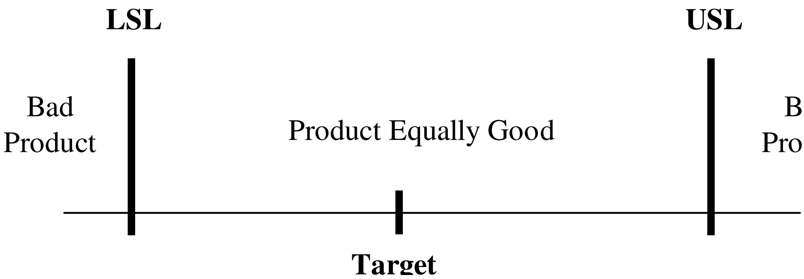

Figure 3.Goal post mentality.

Figure 4.Goal post mentality.

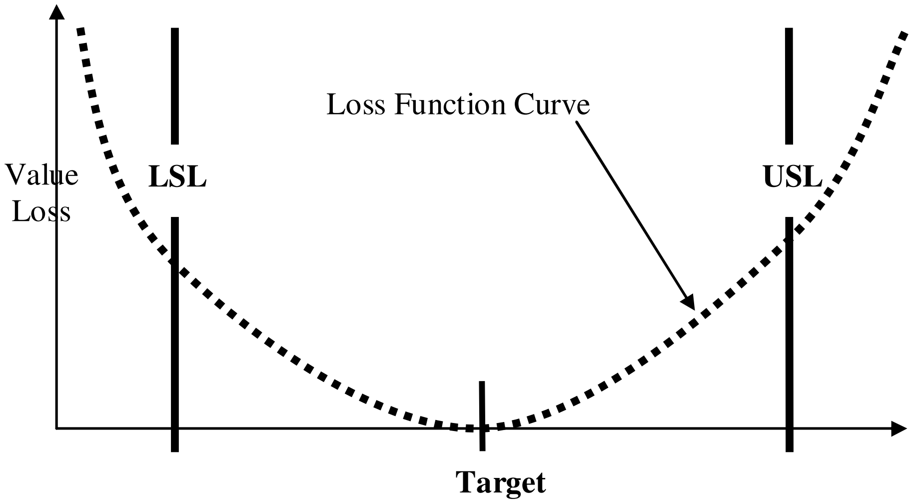

Figure 5. Loss function mentality.

This notion of variation referred to as "loss function mentality", states that there is a quadratic relationship between the loss and the distance from the target and it were proposed by Taguchi (1985). This function is called the loss function curve and it ties variation to the loss in a process. This notion is what capability is based on. Capability indices enumerate a process ability to minimize the loss function curve. Hsiang and Taguchi (1985) and also Chan et al. (1988) developed the index C_{pm} in order to take into account the process centering and defined it as follows:

$$C_{pm} = \frac{d}{3\sqrt{L(Y)}} \qquad (8)$$

where $L(Y) = E(Y - T)^2$ is the loss function. $L(Y)$ is the loss associated with a characteristic X not produced at the target. This implies the loss is zero when the process is on target and positive for any deviation from the target.

Boyles (1991) showed that for fixed μ, the index C_{pm} is bounded above when σ tends to 0 and furthermore, that $C_{pm} < \frac{d}{(3|\mu - T|)}$ and hence $|\mu - T| < \frac{d}{3C_{pm}}$.

Therefore, given a C_{pm} index of 1.00, we know that $M - \frac{d}{3} < \mu < M + \frac{d}{3}$. This interval is much smaller than the one for C_{pk} equal to 1.00 which is equal to $M - d < \mu < M + d.$

Parlar and Wesolowsky (1998) noted that if T = M, then the three basic PCIs C_{pk}, C_p, C_{pm} are connected by the relationship

$$C_{pk} = C_p - \frac{1}{3}\sqrt{\left(\frac{C_p}{C_{pm}}\right)^2 - 1} \qquad (9)$$

Whereas the index C_{pm} has the attractive features that it incorporated the parameters d, μ, T, and σ, it has an important omission, namely, the parameter M. The index C_{pmk} rectifies this deficiency. To devise an index that is more sensitive to departures of μ from T, Pearn et al. (1992) introduced another process capability index, C_{pmk}. The index takes its numerator from C_{pk} and its denominator from C_{pm}, hence it is a hybrid.

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

$$= \frac{d - |\mu - M|}{3\sqrt{\sigma^2 + (\mu - T)^2}} \qquad (10)$$

When μ is equal to M, C_{pmk} is equal to C_{pm}, when μ is equal to T, C_{pmk} is equal to C_{pk}. C_{pmk} is certainly worse than C_{pk} for being associated with a certain percentage of non-conforming product, but again, one should not choose this index if p is the main interest. C_{pmk} (and usually C_{pm}) is much more sensitive than other capability indices to movements in the process average relative to M. If μ moves away from M, however, C_{pmk} decreases more rapidly than does C_{pk} (although both are zero when μ equals one of the specification limits). Conversely, when μ is brought closer to M, C_{pmk} increases much faster than does C_{pk}. C_{pmk} reveals the most information about the location of the process average and the least about the proportion non-conforming p.

Vannam (1995) showed that among all the indices presented thus far, C_{pmk} is the most sensitive to departures of μ from T. The ranking of the following four basic indices discussed thus far in terms of sensitivity to departure of the process mean from the target value, from the most sensitive to the least sensitive are (1) C_{pmk}, (2) C_{pm}, (3) C_{pk} and (4) C_p.

Unified approach

The unified approach was proposed by Kerstin Vannman (1995). Vannman constructed a superstructure class to include the four basic indices, C_p, C_{pk}, C_{pm} and C_{pmk} as special cases. By varying the parameters of this class, we can find indices with different desirable properties. The proposed, new, indices depend on two non-negative parameters, *u* and *v*, as:

$$C_p(u, v) = \frac{d - u|\mu - M|}{3\sqrt{\sigma^2 + v(\mu - T)^2}} \qquad (11)$$

It is easy to verify that:

$C_p(0,0) = C_p$; $C_p(1,0) = C_{pk}$; $C_p(0,1) = C_{pm}$; $C_p(1,1) = C_{pmk}$ From the study of $C_p(u,v)$, large values of *u* and *v* will make the index $C_p(u,v)$ more sensitive to departures from the target value. A slight modification gives the even more general index class which includes C^*_{pm} as a special case as well.

$$C_p(u_1, u_2, v) = \frac{d - u_1|\mu - M| - u_2|T - M|}{3\sqrt{\sigma^2 + v(\mu - T)^2}} \qquad (12)$$

$$C_p(0,1,1) = C^*_{pm}$$

The five C_p, C_{pk}, C_{pm}, C_{pmk} and C^*_{pm}, are equal when μ = T = M, but differ in behavior when $\mu \neq T$. By plotting the four indices as surfaces, we can get a feeling for the sensitivity with regards to departure of the process mean, μ, from the target value, T, assuming that T = M. We note that, for fixed σ, when μ moves away from T, then C_p does not change, C_{pk} changes, but slowly, C_{pm} changes somewhat more rapidly than C_{pk}, but C_{pmk} is the one that changes most rapidly (Vannman, 1993).

Normative approach

The normative approach for the control of quality is based on decision-theoretic considerations. It provides a vehicle for accomplishing both, the retroactive function of assessment and monitoring, and the proactive function of prediction and control. Furthermore, the normative approach is able to integrate the three tasks of assessment, prediction and control within an interactive and unifying framework. Here, one monitors the observable Y (rather than the unobservable μ), and make a decision to continue production, to modulate it or to stop it, based on the consequences of the deviation of the Y from T. The decision is proactive and is dictated by the predictive distribution of Y and the utilities associated with a control of the process.

According to Singpurwalla (1998) the work of Jose and Telba (1996) appears to be first to have introduced the normative approach in the context of process capability indices.

Bayes capability index

A Bayesian index is proposed to evaluate process capability which, within a decision-theoretical framework, directly assesses the proportion of future parts which may be expected to lie outside the tolerance limits.

The proposed capability index is a direct function of the data, whose value is sufficient to solve the relevant decision problem. The Bayes capability index C_B (D) (Bernardo and Irony, 1996), is given by:

$$C_B\left(D\right) = \frac{1}{v}\Phi^{-1}\left\{\Pr\left(y \in A \mid D\right)\right\} \qquad (13)$$

where v will be set equal to 3 or 6 and A is the tolerance region, Φ is the distribution function of the standard normal distribution, and D the available data.

Accept that the process is capable if and only if:

$$C_B\left(D\right) \geq c_0 \qquad (14)$$

where c_0 is a threshold value.

Mean square error

MSE embodies long-term and short-term variation around the process mean, m, as well as the deviation of the process mean from the target (that is, the process bias). In fact, the MSE can be expressed directly as:

$$MSE = \sigma^2{}_{LT} + \sigma^2{}_{ST} + \left(m - T\right)^2 \qquad (15)$$

MSE = Long-term variance component [$\sigma^2{}_{LT}$]

+ Short-term variance component [$\sigma^2{}_{ST}$]

+ The square of process bias [$\left(m-T\right)^2$]

It reflects all variation and deviation from target directly and is proportional to Taguchi's quadratic loss function (QLF), so it directly approximates the cost of quality associated with any process for which QLF is appropriate.

Incapability index

Greenwich and Jahr-Schaffreth (1995) considered a simple transformation of the index C_{pm} called C_{pp} which was defined as:

$$C_{PP} = \left(\frac{\mu - T}{D}\right)^2 + \left(\frac{\sigma}{D}\right)^2 \qquad (14)$$

where $D = \frac{d'}{3}$, $d = \frac{\left(USL - LSL\right)}{2}$, $d' = \min\left(D_L, D_U\right)$, $D_L = T - LSL$, $D_U = USL - T$

They also defined the inaccuracy index as: $C_{ia} = \left(\frac{\mu - T}{D}\right)^2$

Table 1 summarises the main indices discussed in this study.

Belt manufacturing process

Firstly the company manufactures the rubber compounds which are used for the top and bottom covers of the belt. The manufactured rubber compounds are then tested for elongation and breaking strength. The rubber compounds which pass the tests are then pressed and mixed with fabric pliers to produce the final belt. Two processes are used to produce the final belt.

In the first process, the rubber compounds and fabric pliers are heated and pressed in an oven to produce the aged belt as a final product. In the second process, the rubber compounds and fabric pliers are simply pressed without heating to produce the un-aged belt as a final product. The final belt (both aged and un-aged) is then tested for elongation, breaking strength and adhesion, these are the quality variables of interest. Belts which pass these tests are then passed on to the customers. Belts which fail the test are re-processed. Tabulating the approaches against the quality characteristics showed that the approaches can cover up for each other (Table 2). A 1 means the approach addresses the parameter and a 0, means the approach does not take into account the parameter. This is made possible by coming up with sets that contain the least number of approaches that can effectively give the total quality position of the process.

The algorithm

Step 1: Sum all the 1s and 0s for each approach

Step 2: Take the approach with the highest number to be the seed.

Step 3: For the corresponding 0s on the seed approach, choose the approach that covers most of the 0s.

Step 4: Choose the approach that covers most of the remaining 0s.

Step 5: Repeat Step 4 until all the 0s (parameters) are covered.

Step 6: The approaches chosen here make up a set.

For different set of approaches that completely address the quality parameters, go through the above algorithm with a different seed and corresponding parameters. For coming up with the sets, an algorithm was developed and it uses Table 2.

Implementation of proposed procedure

The holistic approach procedure was tested on the belting

Table 1. Summary of the main indices.

Approach	Formula
Process capability indices	$C_p = \frac{USL - LSL}{6\sigma}$
	$C_{pl} = \frac{\mu - LSL}{3\sigma}$
	$C_{pu} = \frac{USL - \mu}{3\sigma}$
	$C_{pk} = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right)$
	$C_p T = \min\left(\frac{USL - T}{3\sigma}, \frac{T - LSL}{3\sigma}\right)$
	$C_{pm} = \frac{USL - LSL}{6\sqrt{\sigma^2 + (\mu - T)^2}}$
	$C_{pmk} = \frac{\min(USL - \mu, \mu - LSL)}{3\sqrt{\sigma^2 + (\mu - T)^2}}$
	$C_{pm}^* = \frac{\min(USL - T, T - LSL)}{3\sqrt{\sigma^2 + (\mu - T)^2}}$
Unified approach	$C_p(u, v) = \frac{d - u\lvert\mu - M\rvert}{3\sqrt{\sigma^2 + v(\mu - T)^2}}$
Process performance index	$P_p = \frac{USL - LSL}{\sigma_{total}}$
	$P_{pk} = \min\left(\frac{USL - \mu}{3\sigma_{total}}, \frac{\mu - LSL}{3\sigma_{total}}\right)$

production at general beltings limited. The system has got two processes, compounding and belting. Compounding is the process of producing rubber mixtures which would form the top and bottom covers of the belt. The quality characteristics considered were the elongation at break, measured in kN/m, and break strength, measured in Mpa. Two samples of each compound are taken, one is measured without aging and the other one is first aged in the oven (high temperatures). So we had results of aged and unaged compound. The second part of the system is the formation of the belt by pressing the rubber compound to the fabric plies. The quality characteristic considered here is the elongation at break (kN/m), break strength (Mpa) and adhesion (Newtons).

The compounds are classified into two categories, PMB 68 and PMB 50/67, and therefore, the belts produced from these compounds were also considered under PMB 68 and PMB 50/67.

Verification of the set of approaches

Two of the many sets obtained, from the above mentioned algorithm, are taken. Each set gives its own quality picture of the process and verified whether it is really holistically addressing the concerns of quality engineers. After this, they are compared to each other to check whether they give the same quality of information for the same belting process.

Table 2. Approaches versus quality characteristics.

Parameters	Inherent variation	Total variation	Bias	Normal distance	Stability	Target value	Symmetric tolerance	Asymmetric tolerance	Can be average	Sensitivity variation	Proactive [predictive and control]	Retroactive [assessment and monitoring]	Potential	Sum
Cp	1	0	0	1	1	0	1	0	0	0	0	0	1	5
Cpk	1	0	0	1	1	0	1	0	0	0	0	1	0	5
Cpm	1	0	0	1	1	1	1	0	0	1	0	1	0	7
Cpmk	1	0	0	1	1	1	1	0	0	1	0	1	0	7
Pp	1	1	0	1	0	0	1	0	0	0	0	0	1	5
Ppk	1	1	0	1	0	0	1	0	0	1	0	1	0	6
MSE	1	1	1	0	0	1	0	0	1	1	1	1	0	8
Incapability	1	0	0	1	1	1	1	1	0	0	1	1	0	8
Desirability	1	1	0	0	0	1	1	1	0	0	0	1	0	6
Unified	1	0	0	1	1	1	1	0	0	1	0	1	0	7
Normative	0	1	0	0	1	0	1	1	0	0	1	1	0	6

RESULTS

The sets

Sets that came out are as a result of using the above algorithms are as follows:

Set 1: {MSE; Incapability Index; P*p*}
Set 2: {MSE; Unified Approach; Desirability Index; C*p*}
Set 3: {MSE; Normative Approach; C*pm*; C*p*}
Set 4: {MSE; Normative Approach; C*pm*; P*p*}
Set 5: {MSE; Normative Approach; C*pmk*; C*p*}
Set 6: {MSE; Normative Approach; C*pmk*; P*p*}

Note: MSE became the seed approach for its uniqueness of measuring bias of the process.

These are the sets that contain the indices that are going to be used holistically. The control charts obtained after using these sets are shown in Figures 6, 7, 8 and 9. Set 1 and Set 2 were used for the for the results that are shown in the Figures 6, 7, 8 and 9.

Process control charts

26 control charts were created and some of them are as follows; Figure 6 shows that the process is indeed out of control as several points lie outside both the upper control and lower control limits.

Figures 7, 8 and 9 also show that the production process is out of control as points are clearly lying outside either the specification limits or control limits or both. This was revealed after the holistic application of capability indices as compared to the scenario where only one index was being used. These figures are justifying the complains raised by customers that the belts are not strong and are breaking easily. Corrective measures have to be taken to address this problem, which has been identified as a result of applying more than one index to monitor the quality of a production process.

Summary of results

Table 3 and 4 shows the summary of all the calculations of the different indices on all the quality characteristics considered in the study. The results of the formulars previously of this holistic approach has to be implemented. The strength and weakness of a process

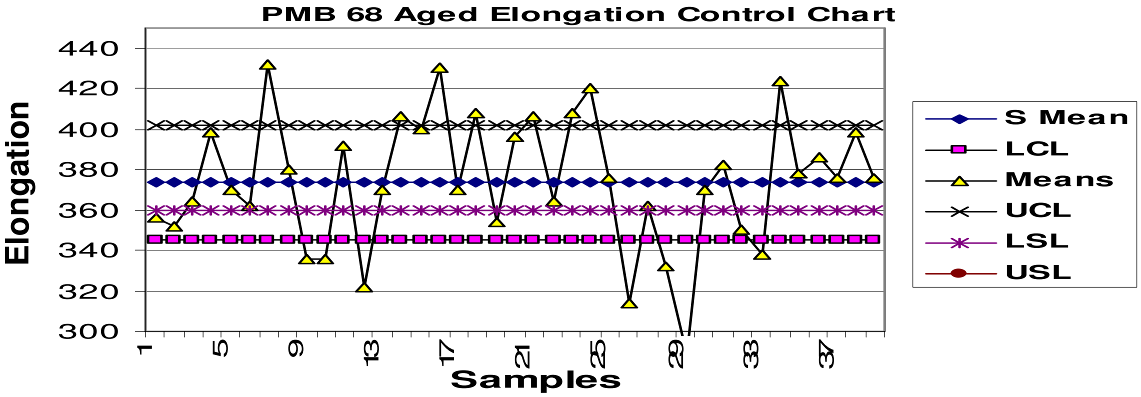

Figure 7. Control chart for PMB 68 aged at elongation.

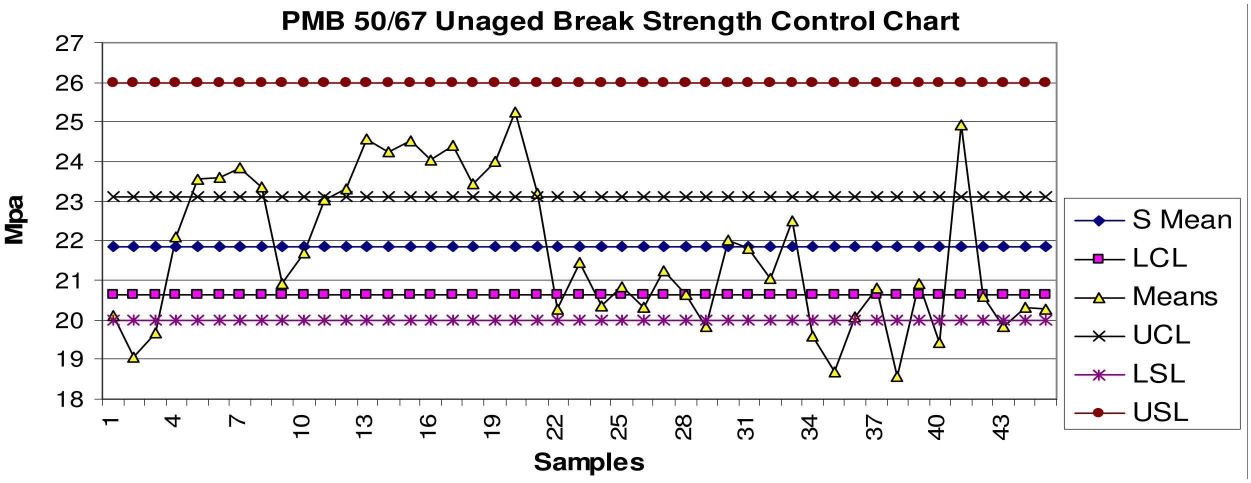

Figure 8. Control chart for PMB 50/67 unaged at break strength.

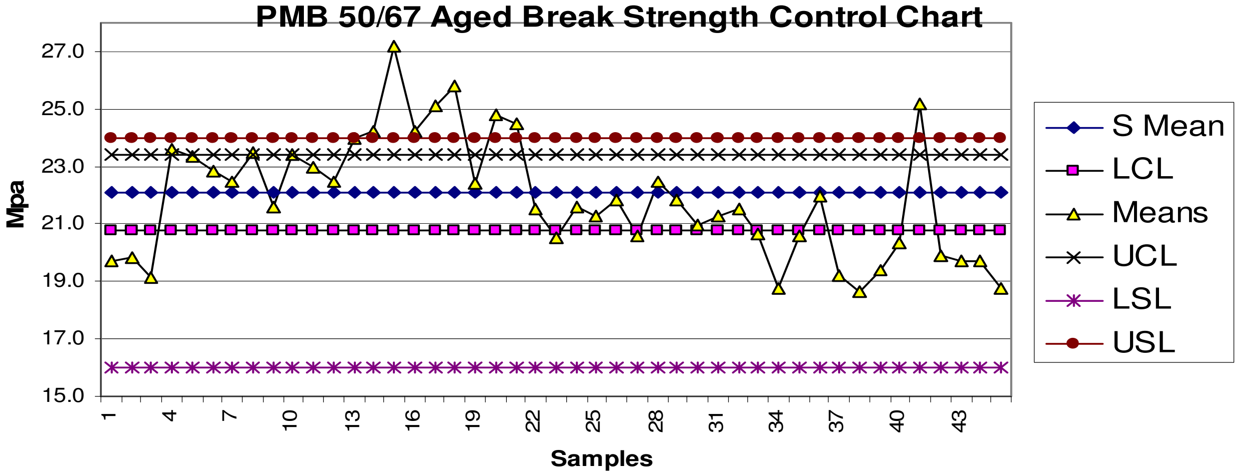

Figure 9. Control chart for PMB 50/67 aged at break strength.

Table 3. Results of the process of producing the compound used for the covers of the belts.

			Cp	Cpk	Cpm	Cpmk	Pp	Ppk	MS	ML	MB	MSE	C”ia	Cip	C”pp	P(U,V)	Norm	EDU
PMB 68	Unaged	Elongation	1.00	1.58	0.51	0.27	0.42	0.57	465	1115	2074	3654	8	6	13	0.39	0.14	0.00
PMB 68	Unaged	Break strength	2.36	5.19	0.25	-0.08	1.19	2.65	1	1	46	48	17	0	17	0.15	0.00	0.00
PMB 68	Aged	Elongation	1.74	2.30	0.46	0.15	0.79	0.73	487	965	6799	8251	8	1	9	0.28	0.04	0.00
PMB 68	Aged	Break strength	1.88	1.19	0.67	0.38	0.93	0.58	1	2	9	13	4	3	7	0.55	0.18	0.16
PMB 50/67	Unaged	Elongation	1.9	1.2	0.83	0.57	0.6	0.4	551	2193	2270	5013	2	3	5	0.58	0.19	0.01
PMB 50/67	Unaged	Break strength	1.5	1.4	0.67	0.391	0.5	0.4	1	4	5	9	5	4	9	0.46	0.16	0.13
PMB 50/67	Aged	Elongation	1.6	1.2	0.91	0.677	0.7	0.5	436	982	1379	2797	2	2	4	0.68	0.26	0.01
PMB 50/67	Aged	Break strength	1.7	1.7	0.75	0.494	0.6	0.6	5	5	8	13	4	3	7	0.55	0.18	0.16

Table 4. Results of the process of putting rubber to the plies.

		Cp	Cpk	Cpm	Cpmk	Pp	Ppk	MS	ML	MB	MSE	C”ia	Cip	C”pp	Vp(U,V)	Norm	EDU
PMB 68	Break strength	0.31	0.24	0.22	0.04	0.12	0.19	201	24	63	287	22	71	93	0.17	0.07	0.06
PMB 68	Elong @ ref load	0.25	0.33	0.18	-0.02	0.14	0.31	3362	459	2274	6131	32	51	83	0.14	0.06	0.01
PMB 68	Elong @ break	0.79	0.17	0.67	0.53	0.54	0.38	9	3	4	16	1	3	5	0.58	0.25	0.14
PMB 68	L-Tc/P	0.38	0.24	0.32	0.17	0.31	0.21	10	1	3	13	3	10	13	0.27	0.12	0.13
PMB 68	L-P/P	0.55	0.34	0.43	0.29	0.46	0.31	5	0	1	6	1	5	6	0.37	0.15	0.13
PMB 68	L-Bc/P	0.49	0.33	0.38	0.22	0.39	0.27	6	1	3	10	3	6	10	0.31	0.13	0.14
PMB 68	L-Tc/P	0.47	0.35	0.33	0.15	0.39	0.29	7	0	4	11	4	7	11	0.26	0.11	0.14
PMB 68	L-P/P	0.67	0.46	0.37	0.15	0.50	0.36	4	0	4	8	4	4	8	0.27	0.10	0.15
PMB 68	L-Bc/P	0.60	0.82	0.29	0.03	0.13	0.18	4	1	10	14	10	56	65	0.20	0.06	0.08
PMB 50/67	Break strength	0.58	0.43	0.33	0.10	0.33	0.29	241	47	198	486	7	8	16	0.24	0.09	0.03
PMB 50/67	Elong @ ref load	0.20	0.17	0.17	0.04	0.16	0.24	5124	163	566	1863	14	38	52	0.15	0.07	0.01
PMB 50/67	Elong @ break	0.95	0.28	0.70	0.51	0.67	0.46	4	1	3	8	1	2	3	0.55	0.24	0.17
PMB 50/67	L-Tc/P	0.36	0.26	0.30	0.15	0.29	0.23	11	1	4	16	4	2	16	0.25	0.11	0.11
PMB 50/67	L-P/P	0.56	0.25	0.37	0.20	0.36	0.23	7	1	2	10	2	8	10	0.30	0.12	0.13
PMB 50/67	L-Bc/P	0.39	0.33	0.32	0.18	0.32	0.27	9	1	3	13	3	10	13	0.27	0.12	0.12

Table 4. Cont'd.

PMB 50/67	L-Tc/P	0.62	0.30	0.39	0.18	0.44	0.23	5	0	4	9	4	5	9	0.29	0.11	0.16
PMB 50/67	L-P/P	0.86	0.68	0.38	0.15	0.46	0.37	4	1	5	9	5	5	9	0.27	0.08	0.09
PMB 50/67	L-Bc/P	0.59	0.92	0.27	0.00	0.46	0.65	4	1	11	16	11	5	16	0.18	0.06	0.10

are only exposed by a complete quality study of that process, even when it is producing products that meet the specifications. All the characteristics of a paper were used to come up with the data on these two tables.

CONCLUSION

If the quality of a product is to be guaranteed, the production process and their corresponding set of capability index have to be identified first. The sets brought out more information about the process than individual indices. The holistic approach found out that the belting process was incapable. Investigations have to be done to find out the possible causes of variation and necessary adjustments to the process have to be done urgently.

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