APPLICATION OF PROCESS CAPABILITY INDICES TO MEASURE PERFORMANCE OF A MULTISTAGE MANUFACTURING PROCESS

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Abstract

A process is a unique combination of manpower, machines, methods and materials in providing a product or service. Process capability indices have been used in the manufacturing industry to provide quantitative measures of process potential and performance. High quality production provides advantages such as cost saving, reduced scrap or remanufacturing, higher yield and increased customer satisfaction and market share. Process capability indices (PCI) are extensively used in industry to evaluate the conformation of products (process yield) to their specifications. Conventional univariate process capability indices such as Cp and Cpk are applied to measure performance for single quality characteristic. In modern manufacturing when product designs are complicated and consumer's requirements are changeable day to day, multiple quality characteristics must be simultaneously evaluated to improve product's quality and also to consider correlations exist among the quality characteristics. In this paper process capability indices (both univariate and multivariate) are applied to measure performance in a multistage 'locomotive wheel' manufacturing process. The wheel manufacturing process has three stages namely press forging, rolling and heat treatment. Process capability indices are analysed for the above mentioned multistage manufacturing processes and the results are compared to identify the most accurate multivariate process capability index to evaluate multiple quality characteristics for the wheel manufacturing. The results show multivariate process capability indices (MVPCI) proposed by Taam et al. (1993) [MC_{pm} = 0.7923] gives higher capability compare to Chan et al. (1991) [C_{pm} = 0.2342] and Shahriari et al. (1995) [C_{pM} = 0.56].

Keywords:Process capability, multivariate process capability indices, multistage wheel manufacturing.

1 Introduction

Process capability indices (PCI) are extensively used in industry to evaluate the conformation of products to their specifications. Conventional univariate process capability indices such as Cpand Cpk have been developed for single quality characteristics.

A number of authors including Harrington (1983) indicated that a process which has not been studied previously of process capability is likely to be unstable. Juran (1974) first introduced the idea of capability ratios (now called indices). In the year of 1986, Kane developed Cp&Cpk. Later Chan et al.(1988) developed Cpm&Pearn et al.(1992) developed Cpmk which is a combination of Cpk&Cpm.Kotz& Johnson (2002) provide a compact survey and brief interpretations and comments on some 170 publications on process capability indices which appeared in widely scattered sources during the year 1992-2000. Ford motor company was the first American corporation to use capability indices.

Now a day when product designs are complicated and consumer's requirements are changeable, multiple quality characteristics must be simultaneously evaluated to determine product's quality. For example, strength, hardness and toughness may all be critical quality characteristics of a product, and medium or strong correlations exist among these quality characteristics. Then multivariate process capability indices (MPCI) are required to accurately evaluate process quality.

Many MPCIs have been described in the literature and studied the correlations present in the multivariate situation in many different ways. In the year 1991, Chan et al. developed Cpm, then Taam et al.(1993) developed Mcpm, Shahriari et al.(1995) developed CpM. Research on multivariate process capability indices (MPCI) started to be published in the late 1980s, but got momentum after 2005. Ray Chowdhury and Mondal (2012) compared performance of die casting and drop forging processes.

All the above mentioned process capability indices (PCI) has analysed performance in single stage manufacturing process but in this paper MPCI has been used to measure performance of a multistage manufacturing process dealing multiple quality variables.

The proposed multistage manufacturing process produces locomotive wheel (Figure 1).

Figure 1 Locomotive wheel (different views)

2 Case Study

The wheel manufacturing process has three stages namely press forging, rolling and heat treatment.

Raw material for locomotive wheel is R-34 grade of steel ingots of diameter 14 inch. The composition of R-34steel is given in Table 1.

Table 1 Composition of R-34 steel

C%	Mn%	P%	S%	Si%	Al%
0.61	0.76	0.02	0.016	0.21	0.018

Raw material in term of ingots in SMS is being stored at Wheel ingot bay. Then the‘**Band Saw’** machine cut wheel ingots vertically into specified length. Each part is called a “block”. One block is used for making a single wheel. Blocks are heated upto forging temperature into **‘Block heating furnace (Furnace-A)’**atapproximate 1280^{o}C. A mixture of Blast Furnace (BF) gas and Coke Oven gas is used as furnace gas.

Then the metal block takes rough shape of a wheel in ‘**63/12 MN pressing and punching press’.**This machine is a giant hydraulic press used for press forging & punching. The metal is shaped not by means of a series of blows as in drop forging, but by means of a single continuous squeezing action. This squeezing action is obtained by means of hydraulic press. Maximum capacity is 63 MN.At last 12 MN impact load is used to make inner hole for inserting axle by punching.The temperature of the metal drops down during forging operation. Soin between 63/12 MN press and wheel mill, there is a **‘Holding furnace (Furnace B)’** to raise the temperature of the roughly shaped wheel for hot working. Temperature of holding furnace is approx 1180^{o} C.

Red hot roughly shaped wheel is taken out from holding furnace (furnace B) and mounted vertically in the ‘**wheel mill’**. Then the wheel rotates between rotating rollers like web rollers (for shaping “web” of the wheel), edge rollers (for shaping edge of the wheel), and vertical rollers (for shaping “rim” of the wheel) simultaneously for a certain time.

Rolled wheelsare placed horizontally in ‘**20 MN dish press’**which isused to make “dish shape of the web” in wheel by press forging. It is a hydraulic press of maximum capacity 20 Mega Newton. Dished wheels are placed on ‘**Hot stamping press’**to stamp manufacturer’s logo and other details. After hot stamping, wheels are taken into ‘**heat treatment furnace’**. The wheels are heated at furnace temperature of approx 540 ^{o} C for one and half hourand cooled at air temperature. After air cooling the wheel is heated again at reheating furnace for 4 hours at a temperature of 920^{o}C- 930^{o} C. Then the “rim” portion of the wheel is water sprayed in **‘Rim spraying machine’** for 5 minutes to gain extra hardness. After rim spraying tempering of wheel is done.

The heat treated wheels are then offered for metallurgical testing. Figure 2 shows the process flow diagram of a multistage wheel manufacturing plant.

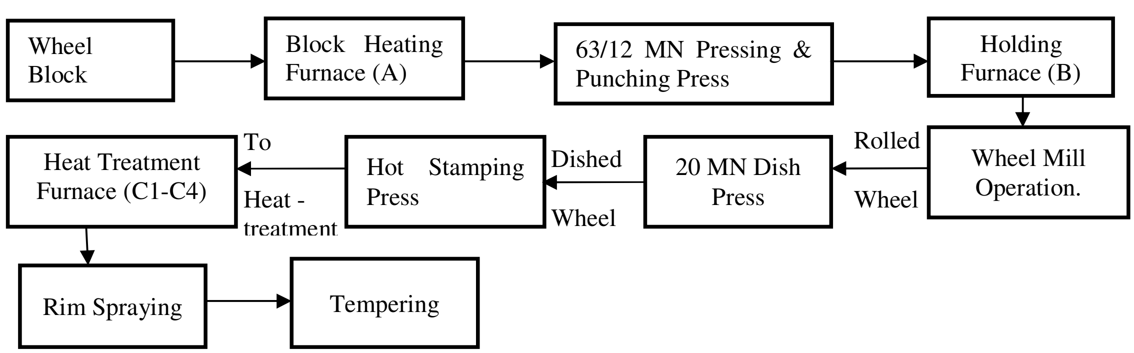

Figure 2 Process flowchart of multistage wheel manufacturing plant

3 Process Capability Indices

Capability analysis is a suitable tool when there is a need to understand the ability of a process to perform against customer's demands. Juran's definition of a process performance is "what a process actually does". Comparing it with customer's demands compares it to "what the process should do". Capability analysis was initially performed by plotting process data, e.g. using histograms, control charts or probability plots etc. and comparing these visually with the upper and lower specification limits, USL and LSL respectively. If the process performance is outside the specification limits, there is a high risk of producing poor products with spoilage and/or rework as a result.

Since the evaluation was performed visually and conclusions could differ from person to person there was a need for a more standardized way to evaluate process capability. There are some aspects of process capability indices.

i. Univariate Process Capability Indices
ii. Multivariate Process Capability indices

3.1 Univariate process capability indices

Univariate process capability indiceshave been developed for single quality characteristic of a product.In the year of 1986,**Kane**first introducedthe process capability **index Cp** which made it possible to determine whether a process is capable or not by calculating a unitless value. The index is expressed by:

$$Cp = \frac{USL-LSL}{6\sigma}, \quad (1)$$

In the equation 1 for Cp, p stands for process. σ is the process standard deviation.USL represents Upper specification limit and LSL is Lower specification limit.

When process capability indices started to gain acceptance, a requirement for a capable process was that Cp ≥ 1 which when Cp=1 means that the length of the tolerance interval is equal to six standard deviations of the process.

The limitation of Cp is that it does not measure the process performance in terms of the target value.

Kane (1986) developed**Cpk** in order to take the process location also into consideration. However, this index does not consider whether the process location (μ), diverges from the target (T), or not.

$$Cpk = \min\left\{\frac{USL-\mu}{3\sigma}, \frac{\mu-LSL}{3\sigma}\right\}, (2)$$

For process only with the LSL, theCpkis given by:

$$Cpl = \frac{\mu-LSL}{3\sigma}, (3)$$

For processes with only USL,

$$Cpu = \frac{USL-\mu}{3\sigma}, \quad (4)$$

$$\text{therefore, } Cp = (Cpl + Cpu)/2 \quad (5)$$

When the process is perfectly centered at the specification midpoint, then Cp=Cpk.Since Cp and Cpk indices does not account for the difference between the process mean and its target value.

Chan et al. (1988) developed**Cpm index** which overcomes the problem but assumes that the target is in the middle of the specification interval.

$$Cpm = \frac{Cp}{\sqrt{1+(\frac{\mu-T}{\sigma})^2}}, \quad (6)$$

Here T represents the target value of a quality characteristic.

Pearn et al. (1992) developed**Cpmk** which is a combination of Cpk&Cpm.

$$Cpmk = \min\left\{\frac{USL-\mu}{3\sqrt{\sigma^2+(\mu-T)^2}}, \frac{\mu-LSL}{3\sqrt{\sigma^2+(\mu-T)^2}}\right\}, \quad (7)$$

Cpmk responds more rapidly than other indices (Cp, Cpk, Cpm) and decreases more rapidly when μ departs from T.

3.2 Multivariate Process capability index

Chan et al. (1991) introduced a version of the multivariate index **Cpm** which is defined by,

$$Cpm = \sqrt{\frac{nv}{\sum_{i=1}^{n}(\overline{X}-T)'A^{-1}(\overline{X}-T)}}, \quad (8)$$

They have considered measurements of a set of v characteristics x_1, x_2, x_3... x_v. Where,

$\overline{X}$ is the mean of sample data.
T is the target value
'v' is the number of quality characteristics
'n' is the number of observations
A^{-1} is the inverse of sample variance covariance matrix.

Taam et al. (1993) proposed multivariate process capability index**MCpm**.It is the ratio of two volumes called modified tolerance region (R1) and scaled 99.73% process region (R2).

Both regions are elliptical. In two dimensions they are ellipses and in higher dimensions they are ellipsoids. The modified tolerance region, R1, is the largest ellipsoid that is centered at the target and completely falls within the actual tolerance region with its major axes parallel to the sides of the rectangle tolerance region as shown in figure 3.

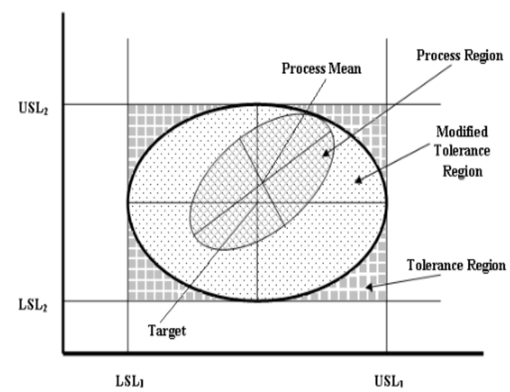

Figure 3Modified tolerance region (R1) versus estimated 99.73 % process region (R2) in a bivariate case. Raissi. (2009)

The MCpm is then defined as

$$\mathrm{MCpm} = \frac{\mathrm{Vol.}(R_1)}{\mathrm{Vol.}(R_2)} \cdot \frac{1}{D} = \frac{C_p}{D}, (9)$$

Where,

$$\mathrm{Cp} = \frac{\mathrm{Vol.}(R_1)}{\mathrm{Vol.}(R_2)} = \frac{\mathrm{Vol.}(R_1)}{|S|^{\frac{1}{2}}(\Pi\chi^2_{(v,0.0027)})^{\frac{v}{2}}[\Gamma(\frac{v}{2}+1)]^{-1}}, \quad (10)$$

Where 'v' is the number of quality characteristics. 'S' denotes sample variance-covariance matrix. |·| is a notation of determinant and Γ (.) is a Gamma function.

$$D = \sqrt{1 + \frac{n}{n-1}(\bar{X} - T)' S^{-1} (\bar{X} - T)}, \quad (11)$$

D is the correcting factor if the process mean is deviated from the target.

The Multivariate Capability Vector **(CpM, PV, LI)**was proposed by**Shahriari et al. (1995)**,based on the original work of Hubele, Shahriari, and Cheng (1991).The vector contains three components.

CpMis the first component of the vector**.**It is a ratio of volumes. The numerator is the volume defined by the 'engineering tolerance region' andthe denominator is the area or volume of a 'modified process region', defined as the smallest region similar in shape of the engineering tolerance region, circumscribed about a specified probability contour. CpM is defined by the following equation.

$$C_{pM} = \left[\frac{\text{Volume of engineering tolerance region}}{\text{Volume of modified process region}}\right]^{\frac{1}{v}}$$

$$C_{pM} = \left[\frac{\prod_{i=1}^{v}(USL_i - LSL_i)}{\prod_{i=1}^{v}(UPL_i - LPL_i)}\right]^{\frac{1}{v}}, (12)$$

Their proposedmethod forms the modified process region by drawing the smallest rectangle around the elliptical process region. The edges of the modified process region are defined as the lower and upper process limits (LPLi and UPLi, respectively, where i=1,2,…v) as shown in the figure 4.

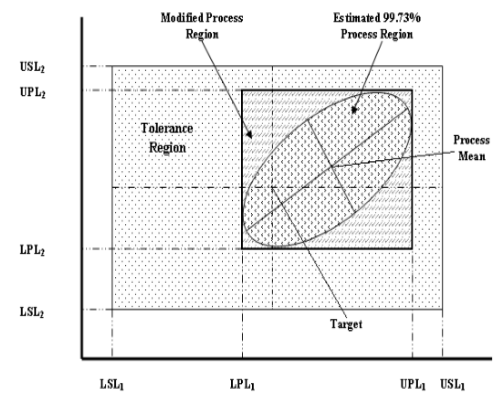

Figure 4 Rectangular Tolerance Region Versus Modified Process Region. Raissi.(2009)

Where

USLi is the upper specification limit for the ith quality characteristic

LSLi is the lower specification limit for the ith quality characteristic

'v' is the number of quality characteristics.

$$UPL_i = \mu_i + \sqrt{\frac{\chi^2_{(v,\alpha)} \det(\Sigma_i^{-1})}{\det(\Sigma^{-1})}}, \quad (13)$$

$$LPL_i = \mu_i - \sqrt{\frac{\chi^2_{(v,\alpha)} \det(\Sigma_i^{-1})}{\det(\Sigma^{-1})}}, \quad (14)$$

Therefore,

$$UPL_i - LPL_i = 2\sqrt{\frac{\chi^2_{(v,\alpha)} \det(\Sigma_i^{-1})}{\det(\Sigma^{-1})}}, \quad (15)$$

Where,$\sum^{-1}$ is the inverse of sample variance covariance matrix. det ($\sum_i^{-1}$) is the determinant of a matrix obtained from $\sum^{-1}$ by deleting ith row and column

The second component PV capability vector, measures the closeness of the process mean to the target.

The third component of the capability vector LI indicates whether the modified process region falls outside the engineering tolerance region or not. When the entire modified process region falls entirely within the engineering tolerance region, LI is equal to 1.Otherwise 0 is assigned to LI.

4 DataCollection

The data collection is done for 5 quality characteristics of 55 test wheelsin a period of six months (July-December, 2013). The quality variables and their specification limits are shown in table 2.

Table 2 Quality variables and their specification

Item	Mean value of Hardness (in B.H.N)	Yield Strength (N/mm2)	Ultimate Tensile Strength (N/mm2)	Percentage of elongation (%)	Charpy Value (in Jule)
USL	341				
LSL	340	620 (min)	980 (min)	8 (min)	9 (min)
Sample mean (μ)	321.50	694.04	1076.16	12.19	19.597
Std. deviation(σ)	6.22	21.612	37.078	.684	1.895
Target(T)	320.5	620	980	8	9

5 Results & Discussions

Table 3Univariate and multivariate Process capability indices

Sl. No.	Proposed by	Index	Hardness (in B.H.N)	Y.S. (N/mm2)	U.T.S (N/mm2)	Percentage of elongation (%)	Charpy Value (Jule)
Univariate Index							
1	Kane (1986)	Cp	1.098	1.142	0.864	2.042	1.865
2	Kane (1986)	Cpk	1.04	1.142	0.864	2.042	1.865
3	Chan et al.(1988)	Cpm	1.08	0.32	0.311	0.329	0.328
4	Pearn et al.(1992)	Cpmk	1.03	0.32	0.311	0.329	0.328
MultivariateIndex							
1	Chan et al.(1991)	Cpm	0.2342				
2	Taam et al.(1993)	MCpm	0.7923				
3	Shahriari et al.(1995)	CpM	0.56				

From table 3 it has been observed that process capability index p, proposed by Kane (1986) takes into account the actual process spread. It does not consider the actual process location (mean of the process). When Cp≥1, then it is considered as a capable process and 99.73% process region is within tolerance limit. It gives an inaccurate indication of actual process performance. It does not reflect the impact of the shift of the process mean on the process ability to produce product within specification limits. Process capability index Cpk, proposed by Kane (1986) overcomes the limitation of Cp and considers process mean location into account. However, this index does not consider whether the process location μ, diverges from the target value T, or not. Cpl and Cpu indices are developed from Cpk, when there is only one sided specification limit.

Chen et al. (1988) developed Cpm index which overcomes the problem and assumed that the target(T) is in the middle of the specification interval. When mean (μ) shifts from the target value (T), the value of Cpm decreases. From the results it is observed that μ is close to T for Hardness and farthest from T for ultimate tensile strength (U.T.S). Except Hardness, for other quality characteristics where USL is not specified, LSL has been considered as Target value (T). Therefore for safe and capable process, divergence of T from μ is an essential requirement for those quality characteristics.

Pearn et al.(1992) developed Cpmk which is a unique combination of Cpk and Cpm. Cpmk responds more rapidly thanother indices (Cp,Cpk,Cpm) and decreases more rapidly when μ departs from T. Cpmk most accurately reflects univariate process capability among others.

Chan et al. (1991) proposed multivariate process capability index Cpm. When process mean (X^-) diverges from target (T) then value of Cpm decreases. Except hardness for all other quality characteristics process mean is diverging from target value (their LSL). So the value of Cpm is lower [$C_{pm} = 0.2342$].

Taam et al.(1993) proposed multivariate process capability index MCpm , which is estimated by the ratio (Cp/D). Where Cp> 1 implies that the process has a smaller variation regarding it is allowed by the specification limit. The value of Cp calculated is 7.4. Therefore the variation is negligible against specification limit and process performance is excellent. The larger value of (1/D) implies that the mean is close to the target. It must satisfy the criteria 0< (1/D) <1. The value of 1/D is 0.106, which satisfy the criteria. The value of Mcpm is 0.7923.The value of multivariate process capability index C_{PM}, proposed by Shahriari et al.(1995) is 0.56**.**

6 Conclusions

The locomotive wheel manufacturing process is best represented by MCpm proposed by Taam et al.(1993). Two or more batches of wheel could be compared by a single multivariate process capability index MCpm. The batch with highest value of MCpm indicates that the qualities of end products of that batch are more accurate than other batches. The variation of the value of MCpm could be observed by changing the chemical composition of input raw material, process parameters of multistage manufacturing process to get the best result.

The quality of the end products depends on the quality of the input raw materials, multistage manufacturing and heat treatment processes. Qualities of the end product are being assessed by different capability indices. So to improve the quality of the output product, the quality of the input raw materials and the selection of parameters of the manufacturing and heat treatment processes have to be improved.

During this study some limitations has come across. The data which are collected has to be normally distributed. The process has to be statistically controlled.

In work can be extended by developing and analyzing a new multivariate capability index in the same manufacturing process.

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