MATTER: International Journal of Science and Technology
ISSN 2454-5880

Olatunde A. Adeotı, 2019

Volume 5 Issue 1, pp. 99-114

Date of Publication: 16th April 2019

DOI-https://dx.doi.org/10.20319/mijst.2019.51.99114

This paper can be cited as: Adeotı, O. A. (2019). A New Control Chart for Process Monitorıng Based on the Unıfied Capabılıty Index. MATTER: International Journal of Science and Technology, 5(1), 99-114.

A NEW CONTROL CHART FOR PROCESS MONITORING BASED ON THE UNIFIED CAPABILITY INDEX

Olatunde A. ADEOTI
Department of Statistics, Federal University of Technology, Akure, Nigeria
oaadeoti@futa.edu.ng

Abstract

Control charts based on capability index for monitoring process parameters have received wide attention recently. In this paper, we proposed new control charts for online monitoring of the process mean and variability using a unified capability index approach. Control chart coefficients are given for constructing the unified capability index-based mean ($\bar{X}$) and standard deviation (S) control charts. Real life data is given to demonstrate the advantages of the proposed control charts over the standard mean ($\bar{X}$) and standard deviation (S) charts for process monitoring. The results of study showed that the proposed unified capability index-based control charts outperform the standard $\bar{X}$ and S control charts and it is efficient for simultaneous monitoring of process stability and measuring the capability of the process to meet specification.

Keywords

Process Capability Indices, Upper Control Limit (UCL), Control Chart, Lower Control Limit (LCL), Standard Deviation

1. Introduction

Process capability indices (PCIs) are dimensionless measures based on process parameters and specifications that have been widely used to determine whether a manufacturing process is capable of producing items within a given specified tolerance set by the customer or organization (Balamurali & Usha, 2018). Several capability indices have been proposed to measure process capability. Examples include the widely used capability indices, C_p and C_{pk} proposed by Kane (1986), the more advanced capability index C_{pm} developed by Chan, Cheng, & Spiring (1988) and the C_{pmk} index proposed by Pearn, Kotz, & Johnson (1992). Some other indices exist which is a modification of the four basic indices (see Boyles, 1994; Vannman & Kotz, 1995 and Castagliola, 1996).

The use of the PCIs for process capability is usually based on the assumption that the distribution of the process is normal and variation is due to random causes which is valid only when the process under investigation is free from assignable causes of variation. Montgomery (2009) stated that it is unsafe to estimate process capability when the process is affected by assignable (special) cause of variation. Therefore, to determine if random causes or a special causes of variation is inherent in a process, control charts are used (Aslam, Azam, Khan and Jun, 2015).

Control chart is an important statistical process control tool that is widely used for the study and control of repetitive processes. The Shewhart control chart introduced by Walter Shewhart in the 1920s are used to detect large shift in process parameters while the Cumulative Sum (CUSUM) control chart introduced by Page (1954) and the Exponentially Weighted Moving Average (EWMA) control chart proposed by Roberts (1959) are used to monitor small shift in the process parameters. The Shewhart variable control charts are used to monitor processes whose quality characteristics are measurable while the attribute control charts are used to monitor processes whose quality characteristics are non-measurable but can only be classified as conforming or nonconforming, good or bad e.t.c. Other control charts introduced in the literature include the nonparametric generally weighted moving average signed-rank control chart for skewed distribution (Sukparungsee, 2018) and the moving average control chart for integer-valued autoregressive process (Areepong, 2018).

Though, the R control chart is widely used to monitor the process variability, it is desirable to estimate the process standard deviation directly when the sample size is moderately large. This is because the range statistic for estimating standard deviation σ losses statistical efficiency for moderate to large sample sizes. Consequently, the use of sample standard deviation in estimating the process variability is desirable. The 3σ control limits for the

Shewhart mean and standard deviation control chart when the value of the true standard deviation is assumed known is given (see Montgomery, 2009) as

$$\begin{array}{ll} \bar{X} \text{ Chart} & \text{S chart} \\ LCL = \bar{X} - A\sigma & LCL = B_5\sigma \\ CL = \bar{X} & CL = c_4\sigma \\ UCL = \bar{X} + A\sigma & UCL = B_6\sigma \end{array} \quad (1)$$

However, the value of standard deviation is unknown in most cases and so the need to estimate standard deviation σ from historical data. When standard deviation is unknown, Montgomery (2009) gave an unbiased process standard deviation estimator as $\hat{\sigma} = \frac{\bar{S}}{C_4}$. Therefore, the 3σ control limit of the $\bar{X}$ and S chart for unknown but estimated standard deviation is given as

$$\begin{array}{ll} \bar{X} \text{ Chart} & \text{S chart} \\ LCL = \bar{X} - A_3\bar{S} & LCL = B_3\bar{S} \\ CL = \bar{X} & CL = \bar{S} \\ UCL = \bar{X} - A_3\bar{S} & UCL = B_4\bar{S} \end{array} \quad (2)$$

Now, if a sample plots beyond the control limits given in equations (1) and (2), it is an indication that the process is out-of-control and as a result the process capability analysis cannot be instituted because the process is affected by assignable (special) cause of variation.

Monitoring and maintaining quality characteristic of interest in any production process is important for the success of any organization. In this regard, control charts are readily used that involved the collection of sample data from the production lines and determining the stability of the process. Furthermore, the capability of the process need to be ascertained (i.e. determining whether the process is capable of producing products within the given specifications). This usually involved a two stage procedure which may require considerable time for establishing control limits, frequent interruption of process, difficulty in the interpretation of the outcome of the control charts when process engineers lack the technical knowhow and delayed decision making based on the results of control charts and capability analysis taken separately (Subramani & Balamurali, 2012). Therefore, an alternative method that takes account of the benefits of control chart and capability analysis for online process monitoring simultaneously is required.

Recently, an alternative method using the PCIs have received substantial research interest in the design of control chart for process monitoring. Subramani & Balamurali (2012) proposed the $\overline{\mathrm{X}}$ and R control charts based on the capability indices $\mathrm{C_p}$ and $\mathrm{C_{pk}}$ that combines the two stage processes into a single stage for monitoring of the process mean. Ahmad, Aslam & Jun (2014) proposed $\overline{\mathrm{X}}$ control chart based on process capability index using repetitive sampling. The performance of a new repetitive sampling control chart based on process capability index for a non-normal process situation was investigated by Ahmad, Aslam and Jun (2015). However, their approaches was based on the range statistic that losses its statistical efficiency when estimating standard deviation for large sample sizes and inappropriate with non-normal distribution (Montgomery, 2009). Adeoti & Olaomi (2018) proposed a repetitive sampling PCI-based control chart using an unbiased estimator $\widehat{\sigma} = \frac{\bar{\mathrm{S}}}{\mathrm{C_4}}$ for monitoring process stability and process capability where

$$\bar{S} = \frac{\sum_{i=1}^{m} S_i}{m} \;,\quad S_i = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(X_{ij} - \bar{X}_i\right)^2} \quad \text{and} \quad C_4 = \sqrt{\frac{2}{n-1}}\;\frac{\Gamma\left(\frac{n}{2}\right)}{\Gamma\left(\frac{n-1}{2}\right)} \qquad (3)$$

The control chart using the estimated sample standard deviation statistic is shown to perform better than the PCI-based control chart using the range statistic.

Therefore, in this paper the capability index based control chart is proposed using the unified capability index approach for monitoring the process parameters. It is important to note that the proposed capability index control chart for monitoring process mean and variability is different from the standard control chart. Our main objective is to develop a new online monitoring control chart based on specified values of the unified PCIs that include the basic process capability indices which is simple, quick at detecting process shift and combines the two stages approach of monitoring online process stability and computation of the capability indices into a single procedure that helps to assess both the stability and capability of the process. The efficiency of the capability index based control chart over the standard control chart is demonstrated using a real life example. The remaining section of the paper is organised as follows: a brief review of the process capability indices is discussed in section 2. The design of the proposed unified PCI-based control chart is presented in section 3. A real life example to demonstrate the proposed chart is provided in section 4 while Section 5 gives the concluding remarks of the study

2. Brief Review of Process Capability Indices (PCIs)

The process capability indices (PCIs) are developed to provide single number assessment of ability of the process to meet specification required by the customer or organisation. In this section, the following capability indices are discussed.

2.1 C_p and C_{pk} Index

The process capability index C_p and C_{pk} was proposed by Kane (1986). It is expressed as

$$C_p = \frac{USL - LSL}{6\hat{\sigma}} \quad (4a)$$

and

$$C_{pk} = min\left\{\frac{USL-\mu}{3\hat{\sigma}}, \ \frac{\mu-LSL}{3\hat{\sigma}}\right\} \quad (4b)$$

where USL and LSL are the upper and lower specification limit and σ is the process standard deviation which is almost unknown and replaced by the estimate of $\hat{\sigma}$. Typically the standard deviation σ is estimated using an unbiased standard deviation $\hat{\sigma} = \frac{\bar{R}}{d_2}$. The C_p index relate the process variation to customer requirements. It measures the variability of the process but does not measure the deviation of process mean from target. However, the C_{pk} considers the location of the mean but does not measure the variability of the process.

2.2 C_{pm} Index

The process capability index C_{pm} proposed by Chan, Cheng, & Spiring (1988) considers specification range, process variation and variation of mean from target. It is expressed as

$$C_{pm} = \frac{USL - LSL}{6\sigma\sqrt{1+\left(\frac{\mu-T}{\sigma}\right)^2}} \quad (5)$$

The C_{pm} considers the proximity of the process mean from the target and so it is considered more sensitive to C_p and C_{pk} index

2.3 C_{pmk} Index

The process capability index C_{pmk} proposed by Pearn, Kotz, & Johnson (1992) is a modification of the numerator and denominator of the C_{pm} so as to ensure that the departure of the process mean from target value is more sensitive than the C_{pk} and C_{pm}. It is expressed as

$$C_{pmk} = min\left\{\frac{USL-\mu}{3\sigma\sqrt{1+\left(\frac{\mu-T}{\sigma}\right)^2}}, \frac{\mu-LSL}{3\sigma\sqrt{1+\left(\frac{\mu-T}{\sigma}\right)^2}}\right\} \quad (6)$$

2.4 $C_p(u, v)$ Index

Vanmann (1995) constructed a superstructure process capability index that include the four basic process capability indices C_p, C_{pk}, C_{pm} and C_{pmk} as special cases. The $C_p(u, v)$ index is defined as

$$C_p(u, v) = \frac{d-u|\mu-m|}{3\sigma\sqrt{1+\left(\frac{\mu-T}{\sigma}\right)^2}} \quad (7)$$

where μ is the process mean, σ is the unknown process standard deviation, T is the target value, $m = \frac{USL+LSL}{2}$ is the midpoint between the upper and lower specification limit and $d = \frac{USL-LSL}{2}$ is half-length of the specification interval. The basic capability indices in equations (4) to (6) are obtained by setting $(u, v) = (0,0), (1,0), (0,1)$ and $(1,1)$ into equation (7). Thus, we have $C_p(0,0) = C_p$, $C_p(1,0) = C_{pk}$, $C_p(0,1) = C_{pm}$ and $C_p(1,1) = C_{pmk}$. It must be noted that the basic indices C_p, C_{pk}, C_{pm} and C_{pmk} are inappropriate for process with non-normal distributions because of the assumption that processes follows the normal distribution and are free from assignable causes of variation. Hence, the assumption of normality is to be validated before the computation of process capability using any of the basic PCIs. A detailed discussion on process capability indices (PCIs) for different situations can be found in Vannman & Kotz (1995), Spiring (1997), Kotz & lovelace (1998), Hosseinifard & Abbasi (2012), Ebadi & Shahriari (2013), Abbasi, Aminnayeri, & Amiri (2016).

3. Design of Proposed Unified Process Capability Index-based Chart

The design of the unified process capability index based control charts using the superstructure of process capability index in equation (7) proposed by Vannman (1995) assuming that the process follows the normal distribution is presented in this section. The unified process capability index based $\bar{X}$ and S is obtained by modifying the superstructure $C_p(u, v)$ and substituting the process dispersion, σ with unbiased estimator $\hat{\sigma} = \frac{\bar{S}}{C_4}$. Therefore equation (7) becomes

$$C_p(u,v) = \frac{d-u|\mu-m|}{3\sqrt{\left(\frac{\bar{S}}{C_4}\right)^2+v(\mu-T)^2}} \quad (8)$$

So that from equation (8) we have

$$\bar{S} = C_4\left(\sqrt{\frac{\left(\frac{USL}{6}-\frac{LSL}{6}-u|\mu-m|\right)^2}{C_p^2(u,v)}} - v(\mu-T)^2\right) \quad (9)$$

For an unknown standard deviation, the control limits for monitoring the process mean denoted $\bar{X}_{PCI}$ by substituting equation (9) into equation (2) is given as

$$LCL = \bar{X} - R_1^*\left(\sqrt{\frac{\left(\frac{USL}{6}-\frac{LSL}{6}-u|\mu-m|\right)^2}{C_p^2(u,v)}} - v(\mu-T)^2\right) \quad (10a)$$

$$CL = \bar{X}$$

$$UCL = \bar{X} + R_1^*\left(\sqrt{\frac{\left(\frac{USL}{6}-\frac{LSL}{6}-u|\mu-m|\right)^2}{C_p^2(u,v)}} - v(\mu-T)^2\right) \quad (10b)$$

The control chart limits for process variability denoted as S_{PCI} is given as

$$LCL = R_2^*\left(\sqrt{\frac{\left(\frac{USL}{6}-\frac{LSL}{6}-u|\mu-m|\right)^2}{C_p^2(u,v)}} - v(\mu-T)^2\right) \quad (11a)$$

$$CL = \left[C_4\left(\sqrt{\frac{\left(\frac{USL}{6}-\frac{LSL}{6}-u|\mu-m|\right)^2}{C_p^2(u,v)}} - v(\mu-T)^2\right)\right]$$

$$UCL = R_3^*\left(\sqrt{\frac{\left(\frac{USL}{6}-\frac{LSL}{6}-u|\mu-m|\right)^2}{C_p^2(u,v)}} - v(\mu-T)^2\right) \quad (11b)$$

where $R_1^* = A_3 * C_4$, $R_2^* = B_3 * C_4$ and $R_3^* = B_4 * C_4$. The values of R_1^*, R_2^*, and R_3^* have been computed for sample sizes $2 \leq n \leq 25$ and presented in Table 1. u and v takes on values 0 and 1 depending on the specified unified process capability index of interest i.e. $C_p(0,0) = C_p$, $C_p(1,0) = C_{pk}$, $C_p(0,1) = C_{pm}$ and $C_p(1,1) = C_{pmk}$. μ is the process mean, T is the target value and m is the midpoint between upper specification limit (USL) and lower specification limit (LSL) as previously stated, $\bar{S}$ and C_4 are as defined in equation (3).

The sample statistics are plotted on the proposed control chart against the sample number with control limits given in equations (10) and (11). If any sample fall outside the limits of the proposed capability index-based charts, the process is declared to be out-of-control. However, if the process fall within the control limits, it is an indication that the process is capable and meets the specifications given by customers or organisation for the specified unified PCIs values. Several control limits can be constructed for different values of specified unified PCIs. In this case, we shall consider the specified unified process capability indices C_p and C_{pk} values. An advantage of the proposed control chart is that if the process satisfies the conditions regarding the specified values of process capability indices, then it automatically means that the process is stable (i.e. in-control state) and capable of meeting the given specifications.

Table 1: *Factors for Constructing Capability Index-Based $\bar{X}$ and S chart*

n	R_1^*	R_2^*	R_3^*
2	2.1216	0	2.6067
3	1.7316	0	2.2758
4	1.4999	0	2.0877
5	1.3414	0	1.9637
6	1.2246	0.0285	1.8745
7	1.1340	0.1132	1.8056
8	1.0605	0.1785	1.7515
9	1.0003	0.2317	1.7069
10	0.9484	0.2762	1.6692
11	0.9042	0.3131	1.6377
12	0.8661	0.3461	1.6091
13	0.8325	0.3741	1.5847
14	0.8015	0.3983	1.5637
15	0.7750	0.4204	1.5442
16	0.7504	0.4406	1.5264
17	0.7275	0.4588	1.5102
18	0.7075	0.4750	1.4958
19	0.6884	0.4901	1.4823
20	0.6711	0.5033	1.4705
21	0.6548	0.5165	1.4587

22	0.6394	0.5277	1.4487
23	0.6258	0.5388	1.4386
24	0.6123	0.5490	1.4294
25	0.5997	0.5591	1.4201

4. Example

To demonstrate the application of the proposed capability index control chart, the container bursting strength data is used to monitor the stability and assess the capability of the process to meet specifications. Twenty samples of five observations each are taken from Montgomery (2009). The calculation of the means and standard deviation are summarized in Table 2.

Table 2: *Container Bursting Strength Data (Montgomery, 2009)*

Sample	Data					$\bar{X}$	S
1	265	205	263	307	220	252.0	40.45986
2	268	260	234	299	215	255.2	32.29087
3	197	286	274	243	231	246.2	35.42174
4	267	281	265	214	318	269.0	37.38315
5	346	317	242	258	276	287.8	42.90921
6	300	208	187	264	271	246.0	46.8775
7	280	242	260	321	228	266.2	36.32079
8	250	299	258	267	293	273.4	21.59398
9	265	254	281	294	223	263.4	27.24518
10	260	308	235	283	277	272.6	27.17168
11	200	235	246	328	296	261.0	50.83306
12	276	264	269	235	290	266.8	20.29039
13	221	176	248	263	231	227.8	33.11646
14	334	280	265	272	283	286.8	27.30751
15	265	262	271	245	301	268.8	20.42547
16	280	274	253	287	258	270.4	14.4672
17	261	248	260	274	337	276.0	35.31997
18	250	278	254	274	275	266.2	13.1225
19	278	250	265	270	298	272.2	17.66918
20	257	210	280	269	251	253.4	26.70768
Mean						**264.06**	**30.34667**

From the above data, we have $\bar{\bar{X}} = 264.06$, $\bar{s} = 30.35$, $\hat{\sigma} = \frac{\bar{S}}{C_4} = \frac{30.35}{0.9400} = 32.28$. The standard $\bar{X}$ and S chart are computed as

$\bar{X}$	S chart
$UCL = 307.37$	$UCL = 63.40$

$$LCL = 220.75 \qquad\qquad LCL = 0$$

The standard $\bar{X}$ and S control limits are plotted in Figures 1 and 2. We observed that all sample means and sample standard deviation are within the control limits.

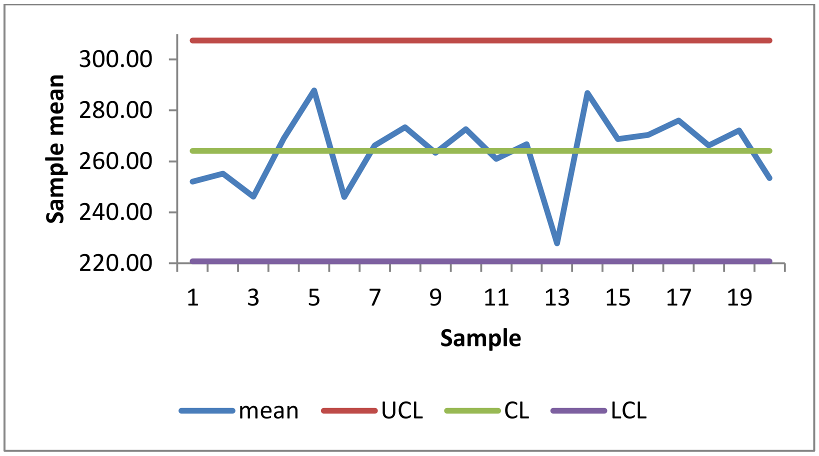

Figure 1: *Traditional Shewhart* $\bar{X}$ *Control Chart*

Now, the capability of the process is evaluated using the traditional process capability index C_p and C_{pk} because the process has been shown to be stable. Here, the upper specification limit (USL) and lower specification limit (LSL) is given as $USL = 320$, $LSL = 200$ and $\hat{\sigma} = 32.28$ So that,

$$\hat{C}_p = \frac{320-200}{6(32.28)} = 0.6195$$

$$\hat{C}_{pk} = min\left(\frac{320-264.06}{3(32.28)}, \frac{264.06-200}{3(32.28)}\right) = 0.5777$$

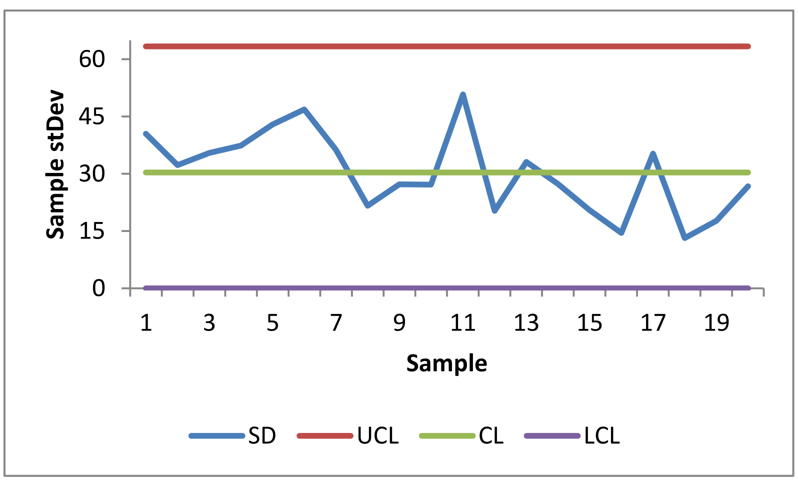

Figure 2: *Traditional Shewhart S control chart*

Suppose, the specified process capability index given by the customer or organisation is $C_p = 1.5$. We observed from the computations and Figures 1 and 2 that using separate control chart and capability index C_p, the process is in-control (stable) but operating at an unacceptable level because capability index is less than 1 (i.e. the process is producing nonconforming unit). Therefore, the production of non-conforming units from the process using the two-stage procedure may be additional cost to the manufacturer since the process personnel will need to re-work the products that are produced from the process for the quality of the product to meet the specifications given by the organisation or customer.

However, for online process monitoring based on the proposed capability index control chart where the stability and capability of the process is monitored simultaneously (i.e. a two-stage computation of process stability and capability is not required), the control limits for the proposed capability index-based $\bar{X}_{PCI}$ and S_{PCI} charts given in equations (10) and (11) for a specified value of capability index $C_p(0,0) = 1.5$ and control chart coefficient R_1^* for sample size *n* =5 in Table 1 are computed as

$\bar{X}_{PCI}$ chart	S_{PCI} chart
$UCL = 281.9451$	$UCL = 26.1756$
$LCL = 246.1749$	$LCL = 0$

The sample means and standard deviation are plotted on the proposed PCI-based control chart in Figures 3 and 4. It is evident from Figures 3 and 4 that the process is out-of-control for specified capability index $C_p(0,0) = 1.5$. Therefore, estimating the capability of the process is not permissible using the specified unified process capability indices, since the process has to be stable before assessing the capability of the process. From the foregoing analysis, it is observed that the proposed chart has eliminated the second stage of estimating the capability of the process, which the traditional control chart is unable to determine even though the process may be in- statistical control

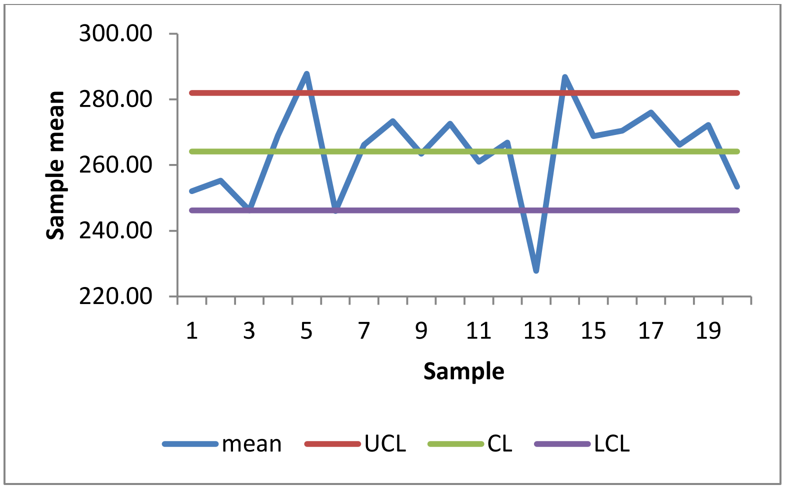

Figure 3: *Proposed $\bar{X}$-Control Chart for Specified Capability Index* $C_p(0,0) = 1.5$

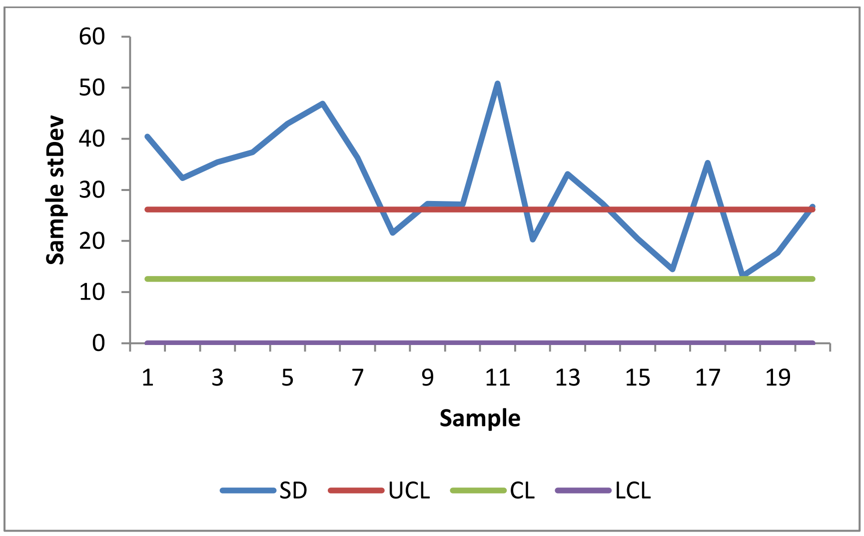

Figure 4: *Proposed S-Control Chart for Specified Capability Index* $C_p(0,0) = C_p = 1.5$

Similarly, for a specified unified capability index $C_p(1,0) = C_{pk} = 1.5$, the unified PCI-based control limits are given as

$\bar{X}_{PCI}$ chart	S_{PCI} chart
$UCL = 278.3144$	$UCL = 20.8672$
$LCL = 249.8056$	$LCL = 0$

Here, the sample means is plotted on the proposed control limits shown in Figure 5 for specified capability index $C_p(1,0) = 1.5$. Hence, the process is out-of- statistical control and not capable of meeting the specification given by the customer or organisation since sample points are beyond the control limits. So the process is not efficient for producing conforming units at the given specified value.

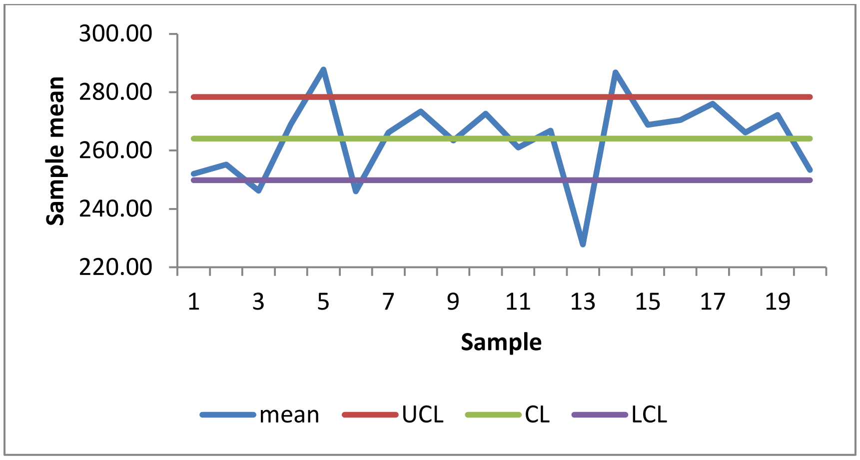

Figure 5: *Proposed* $\bar{X}$ *chart for Specified Capability Index* $C_p(1,0) = C_{pk} = 1.5$

The control limits of the proposed capability index-based $\bar{X}_{PCI}$ and S_{PCI} control charts for different specified capability indices $C_p(0,0)$ and $C_p(1,0)$ values are summarized in Tables 3 and 4. Therefore, any sample value that is plotted outside the control limits with specified unified capability index values is an indication of the process being out-of-control and it is unable to produce items that meet the specification of the customers. Hence, the process has to be adjusted so that the process is stable and the specified process capability index is achieved.

Table 3: $\bar{X}$ *Control Limits for Specified Values of Capability Indices* $C_p(0,0)$ *and* $C_p(1,0)$

Control limit	$C_p(0,0)$				$C_p(1,0)$			
	1.00	1.33	1.50	2.00	1.00	1.33	1.50	2.00
UCL	290.8876	284.2311	281.9451	277.4738	285.4416	280.1363	278.3144	274.7508
LCL	237.2324	243.8889	246.1749	250.6462	242.6784	247.9837	249.8056	253.3692

Table 4: *S Control Limits for Specified Values of Capability Indices* $C_p(0,0)$ *and* $C_p(1,0)$

Control limit	$C_p(0,0)$				$C_p(1,0)$			
	1.00	1.33	1.50	2.00	1.00	1.33	1.50	2.00
UCL	39.2732	29.5287	26.1756	19.6366	31.3007	23.5343	20.8672	15.6504
LCL	0	0	0	0	0	0	0	0

5. Conclusion

Control charts are used to monitor processes for assignable causes of variation. In this paper, we proposed a unified capability index-based control chart for monitoring process mean and variability and assessing the capability of the process to meet the customer specification using the superstructure process capability index proposed by Vannman (1995). An example that follows the normal distribution has been used to demonstrate the standard $\bar{X}$ and S control chart and the proposed capability index-based $\bar{X}$ and S control chart which shows the advantage of the proposed unified capability index-based control chart over the standard control chart in the quality control literature. It is clear from the result of study that the width of the proposed control chart limits is reduced when compared to the standard $\bar{X}$ and S control chart. Also, the result of study show that specifying values of process capability index in the proposed capability index-based control chart for process monitoring can help organisation to detect if the process is stable as well as capable of meeting requirements simultaneously for online process monitoring. Therefore, the proposed control charts is recommended for use by manufacturing organisations for online monitoring of process stability and capability simultaneously in the real sense. However, this research study considers only the case when the process is assumed to follow the normal distribution. The performance of the chart when the process follow non-normal distribution can be investigated in future research

Acknowledgement

The author would like to express his gratitude to the editor and anonymous referee for the useful comment that help to improve the quality of the paper

References

Abbasi Charkhi, M.R, Aminnayeri, M., & Amiri, A (2016). Process capability indices for logistic regression profile. Quality and Reliability Engineering International 32(5), 1655-1661. https://doi.org/10.1002/qre.1897

Adeoti, O.A. & Olaomi, J.O (2018) Capability index-based control chart for monitoring process mean using repetitive sampling, Communications in Statistics – Theory and Methods, 47(2), 493-507. https://doi.org/10.1080/03610926.2017.1307401

Ahmad, L., Aslam, M., & Jun, C-H (2014) Designing of X-bar control charts based on process capability index using repetitive sampling. Transactions of the Institute of Measurement and Control, 36(3), 367–374. https://doi.org/10.1177/0142331213502070

Ahmad, L., Aslam, M. & Jun, C-H (2015). The design of a new repetitive sampling control chart based on process capability index. Transactions of the Institute of Measurement and Control, 38(8), 971-980. https://doi.org/10.1177/0142331215571120

Areepong, Y. (2018), Movıng Average Control Chart for Monıtorıng Process Mean ın Inar (1) Process wıth Zero Inflated Poısson. MATTER: International Journal of Science and Technology, 4(3), 138-149. https://dx.doi.org/10.20319/mijst.2018.43.138149

Aslam, M., Azam, M., Khan, N., & Chi-Hyuck Jun, J-C (2015): A mixed control chart to monitor the process, International Journal of Production Research. https://doi.org/10.1080/00207543.2015.1031354

Balamurali, S., & Usha, M. (2018). A new mixed repetitive group sampling plan based on process capability index for product acceptance. International Journal of Quality and Reliability Management 35 (2):463–80. https://doi.org/10.1108/IJQRM-11-2016-0213

Boyles, R.A (1994). Process capability with asymmetric tolerances. Communications in Statistics-Simulation and Computation, 23(3), 615-643. https://doi.org/10.1080/03610919408813190

Castagliola, P (1996). Evaluation of non-normal process capability indices using Burr's Distributions. Quality Engineering 8, 587–593. https://doi.org/10.1080/08982119608904669

Chan, L. K., Cheng, S. W., & Spiring, F. A. (1988). A new measure of process capability: *C*pm'. Journal of Quality Technology, 20, 162–175. https://doi.org/10.1080/00224065.1988.11979102

Ebadi, M., & Shahriari, H (2013) A process capability index for simple linear profile. *The* International of Advanced Manufacturing Technology 64 (5-8), 857-865. https://doi.org/10.1007/s00170-012-4066-7

Hosseinifard, S.Z., & Abbasi, B. (2012). Evaluation of process capability indices of linear profiles. International Journal of Quality and Reliability Management, 29(2), 162-176. https://doi.org/10.1108/02656711211199892

Kane, V.E. (1986). Process capability indices. Journal of Quality Technology, 18, 41–52. https://doi.org/10.1080/00224065.1986.11978984

Kotz, S & Lovelace, C.R. (1998). *Introduction to Process Capability Indices: Theory and Practice*, Arnold, London.

Montgomery, D. C. (2009). *Introduction to statistical quality control*. 6th ed. New York: John Wiley and Sons.

Page, E.S. (1954). Continuous inspection schemes. Biometrika, 41, 100-115. https://doi.org/10.2307/2333009

Pearn,W.L, Kotz,S. & Johnson, N.L (1992). Distributional and inferential properties of process capability indices. Journal of Quality Technology, 24(4), 216–231. https://doi.org/10.1080/00224065.1992.11979403

Roberts, S.W. (1959). Control chart tests based on geometric moving averages, Technometrics. 1(3), 239-250. https://doi.org/10.1080/00401706.1959.10489860

Spiring, F.A. (1997), 'A unifying approach to process capability indices' Journal of Quality Technology 29, 49–58. https://doi.org/10.1080/00224065.1997.119797724

Subramani J and Balamurali S (2012) Control charts for variables with specified process capabilities indices. International Journal of Probability and Statistics, 1(4), 101–110. https://doi.org/10.5923/j.ijps.20120104.03

Sukparungsee, S. (2018). Robustness of Generally Weıghted Movıng Average Sıgned – Rank Control Chart for Monıtorıng a Shıft of Skew Processes. MATTER: International Journal of Science and Technology, 4(3), 125-137. https://dx.doi.org/10.20319/mijst.2018.43.125137

Vannman, K (1995). A unified approach to capability indices. Statistical Sinica, 5, 805–820.

Vannman, K & Kotz, S (1995). A superstructure of capability indices—asymptotics and its implications. International Journal of Reliability, Quality and Safety Engineering**,** 2, 343–360. https://doi.org/10.1142/s0218539395000253