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Mixed Tukey-Double Moving Average for Monitoring of Process Mean

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Abstract

A double moving average (DMA) control chart is used to detect smaller shifts in the process parameters. The DMA chart depends on the normality assumption for a better detection ability. This article is a similar effort to design an improvement the charting structure in the form of a mixed Tukey-Double moving average control chart (namely Tukey-DMA), specially designed for symmetric and asymmetric processes. The comparative analysis has revealed that the proposed scheme is an effective competitor to the existing counterparts, including Tukey, DMA, and Tukey-MA. The performance of the proposed and the competing charts are measured using Average run length (ARL). Moreover, the proposed design presents some of the aforementioned charts as special cases. For practical considerations, we have implemented the proposed and existing charts to two real-life data sets, one related to Nile river flow and the other one concerning British coal mining disaster.

Keywords: Average run length, double moving average control chart, Tukey's control chart, nonparametric control chart.

1. Introduction

Statistical process control (SPC) is a collection of effective tools for process monitoring, controlling and detecting. These tools consist of control charts, check sheets, Pareto diagrams, histograms, cause, and effect diagram, defect concentration diagrams, and scatter diagrams. Control charts are efficient monitoring tools and they appear as graphical displays with specific lower and upper bounds to monitor the quality of ongoing processes. Control charts have application in different fields like health care (Sitter et al. 1990, Frisén 1992), dairy production (Basseville and Nikiforov 1993), chemical industries (Mason and Antony 2000), and aircraft manufacturing (Ergashev 2003, Golosnoy and Schmid 2006). There are a variety of control charts available for each exclusive type of data. These types of processes require continuous monitoring of their parameters. A popular chart is a Shewhart control chart (Shewhart 1931), which uses only information based on the most recent observation. Therefore, the Shewhart control chart can detect a large shift in the process but become less efficient in detecting process shifts of small magnitude. In the past few decades, there were several control charts that detected small process changes. For example, the cumulative sum control chart (CUSUM) was introduced by Page (1954). It was based on the cumulative sum of differences between sample values and average. Next, an exponentially weighted moving average control chart (EWMA) was proposed by Roberts (1959). It was based on two different weighted average observations. In 2004, Khoo (2004) developed a moving average control chart (MA), which was based on a simple moving average that is easily computed. Khoo et al. (2008) proposed a double moving average control chart (DMA chart) as an alternative to moving average chart for early detection of small to moderate shift in the process mean. It can be used with both continuous and discrete distributions. The CUSUM, EWMA, MA and DMA charts are memory control charts which are superior to the Shewhart control chart when the detection of small and moderate shifts is focused. This is because they use information about a process contained in the entire sequence of points. Then, research on the use of the DMA chart for detecting process shifts in process variability is desirable.

These control chart that hinges on the distributional assumption (such as normality) is known as a parametric chart. However, in many real situations, these assumptions may not always be fulfilled, for example, in measurements of semiconductor and chemical processes, quantification of cutting tool wear processes, lifetimes of accelerated life test samples. These types of characteristics are often of skewed nature (Bai and Choi 1995, Choobineh and Branting 1986, Nelson 1979).

Alemi (2004) proposed a Tukey's control chart (Tukey) as an alternative control chart for distribution free process. Many authors have investigated its performance under different distribution setups. Borckardt et al. (2005, 2006), Torng and Lee (2008), and Sukparungsee (2013) studied its performance for symmetric and skew data. Lee (2011) recommended asymmetrical control limits to deal with skewed data, and Sukparungsee (2012) assessed its robustness. Tercero-Gomez et al. (2012) introduced some modifications of Tukey to increase its performance to get optimum results. Tercero-Gomez et al. (2014) used the modified Tukey design for a robust estimation of variance. Lee and Torng (2015) and Lee (2011) introduced some further adjustments to its design. Khaliq et al. (2015) used different performance strategies to observe the performance of Tukey and X/MR charts. Tukey's chart appears as an efficient choice in case of skewed data. Mekparyup et al. (2014a, 2014b) used some modification to IQR to set the symmetrical and asymmetrical control limits' coefficients of Tukey. The memory structure of Tukey's chart is the main concern of our current study.

Recently, there are several authors introduced different designs of design of Tukey's control chart. In 2015, Khaliq and Riaz (2016) proposed a CUSUM-Tukey chart to improved detection of shift for normal and non-normal data based on ARL, EQL PCL, and RARL. Next, Khaliq et al. (2016) introduced the EWMA-Tukey chart to monitoring the parameter change of symmetrical and asymmetrical distribution data process faster and had more efficient than Tukey and EWMA control charts. In 2016, Supchottharee et al. (2016) presented the double exponentially weighted moving average-Tukey's control chart (DEWMA-Tukey) to monitor the mean parameter change and found that its efficiency was better than Tukey, DEWMA, and EWMA-Tukey control charts. Later, Riaz et al. (2017) proposed a mixed Tukey EWMA-CUSUM chart (namely MEC-Tukey) to detect a shift of parameter and had more efficient than Shewhart, EWMA, CUSUM and Tukey chart. Recently, Taboran et al. (2018) presented the moving average-Tukey's control chart (MA-Tukey) to monitoring the change with symmetrical distribution and show that its better performance than Shewhart, Tukey and MA chart.

In this paper, we aim to propose a mixed design of DMA and Tukey chart, namely Tukey- DMA, for efficient and robust monitoring of location parameters. The performance of the proposed Tukey-

DMA is investigated under both states (in-control and out-of-control) for different fundamental probability distributions. The remaining part of the article is organized as: section 2 includes the details regarding different control charts and the design of the Tukey-DMA chart. Section 3 presents the performance evaluation techniques. Section 4 presents real applications. The concluding of this study is given in Section 5.

2. Control Charts and Design of New Control Chart

2.1. Tukey's control chart (Tukey chart)

The Tukey chart is one of the popularly nonparametric control charts was introduced by Alemi (2004) which is an observed valued control chart and applied the principle of Box plot to set up its control limit. Let X_i is an observation based on the distribution of interest. The control limits of Tukey's chart are defined as

$$UCL = Q_3 + k_1(IQR) \text{ and } LCL = Q_1 - k_1(IQR), \tag{1}$$

where UCL and LCL from (1) were upper and lower control limits, respectively. The value of Q_1 and Q_3 refer to the first and third quartile, $IQR = Q_3 - Q_1$ refers to the inter-quartile range and k_1 is a coefficient of control limit of Tukey chart.

2.2. Double moving average control chart (DMA chart)

A double moving average control chart (DMA chart) was proposed by Khoo et al. (2008). The observations of DMA statistics are the collected double moving average of the MA statistic. The DMA of span w at the time t is defined as

$$DMA_i = \begin{cases} \dfrac{MA_i + MA_{i-1} + MA_{i-2} + \dots}{i} & ; i \le w \\ \dfrac{MA_i + MA_{i-1} + \dots + MA_{i-w+1}}{w} & ; w < i < 2w-1 \\ \dfrac{MA_i + MA_{i-1} + \dots + MA_{i-w+1}}{w} & ; i \ge 2w-1, \end{cases} \tag{2}$$

where MA_i on (2) refers to a statistic of MA chart. It is a time-weighted moving control chart based on a simple unweighted moving average. Assume $X_1, X_2, \dots$ where $X_i \sim N(\mu, \sigma^2)$ for $1, 2, \dots$ is obtained from a process. The MA statistic of span w at a time i defined as (see Montgomery (2005))

$$MA_i = \frac{X_i + X_{i-1} + \dots + X_{i-w+1}}{w}; i \ge w \tag{3}$$

For the period $i < w$, the average of all measurements up to periods i defines the MA. The mean and variance based on an in-control process of the DMA chart are

$$E(DMA_i) = \mu_0 \tag{4}$$

and

$$Var(DMA_i) = \begin{cases} \dfrac{\sigma^2}{i} & ; i \le w \\ \dfrac{\sigma^2}{w} & ; w < i < 2w-1 \\ \dfrac{\sigma^2}{w} & ; i \ge 2w-1. \end{cases} \tag{5}$$

Therefore, the control limit of DMA chart can compute from (4) and (5) as following

$$LCL/UCL = \begin{cases} \mu_0 \pm H\dfrac{\sigma}{\sqrt{i}} & ; i \le w \\ \mu_0 \pm H\dfrac{\sigma}{\sqrt{w}} & ; w < i < 2w-1 \\ \mu_0 \pm H\dfrac{\sigma}{\sqrt{w}} & ; i \ge 2w-1 \end{cases} \tag{6}$$

when μ_0 refers to the target value for the mean, σ refers to a standard deviation and H is a coefficient of control limit of the DMA chart.

2.3. The design of the proposed mixed Tukey-DMA control chart

In this section, Tukey's control chart-double moving average (Tukey-DMA chart) was proposed. We extend the idea of Tukey by combining its features with the DMA chart to closing the gap of parametric control chart. In order to design of the Tukey using the DMA setup, the design structure of the proposed Tukey-DMA chart is as follows:

$$Tukey-DMA_i = \begin{cases} \dfrac{MA_i + MA_{i-1} + MA_{i-2} + \ldots}{i} & ; i \le w \\ \dfrac{MA_i + MA_{i-1} + \ldots + MA_{i-w+1}}{w} & ; w < i < 2w-1 \\ \dfrac{MA_i + MA_{i-1} + \ldots + MA_{i-w+1}}{w} & ; i \ge 2w-1. \end{cases} \tag{7}$$

Note that the moving average of the sample, $Tukey-MA_i$ of span w at the time i is computed by Taboran (2018). That is

$$Tukey-MA_i = \frac{X_i + X_{i-1} + \ldots + X_{i-w+1}}{w}; i \ge w. \tag{8}$$

For period $i < w,$ the average of all sample up to period i defines the moving average at the time $i,$ is

$$Tukey-MA_i = \frac{X_i + X_{i-1} + \ldots + X_{i-w+1}}{i}. \tag{9}$$

The control limit of Tukey-DMA chart consists of three cases, which can be defined in the form of three quantities as follows:

For periods, $i \le w,$

$$\begin{aligned} LCL &= Q_1 - K\frac{IQR}{\sqrt{ni^2}}\sqrt{\sum_{j=1}^{i}\frac{1}{j}} \\ CL &= Q_2 \\ UCL &= Q_3 + K\frac{IQR}{\sqrt{ni^2}}\sqrt{\sum_{j=1}^{i}\frac{1}{j}}. \end{aligned} \tag{10}$$

For periods, $w < i < 2w-1,$

$$LCL = Q_1 - K\frac{IQR}{\sqrt{nw^2}}\sqrt{\sum_{j=i-w+1}^{w-1}\frac{1}{j}+(j-w+1)\left(\frac{1}{w}\right)}$$
$$CL = Q_2 \tag{11}$$
$$UCL = Q_3 + K\frac{IQR}{\sqrt{nw^2}}\sqrt{\sum_{j=i-w+1}^{w-1}\frac{1}{j}+(j-w+1)\left(\frac{1}{w}\right)}.$$

For periods, $i \geq 2w-1$,

$$LCL = Q_1 - K\frac{IQR}{\sqrt{nw^2}}$$
$$CL = Q_2 \tag{12}$$
$$UCL = Q_3 + K\frac{IQR}{\sqrt{nw^2}},$$

where K refers to a coefficient of control limit of the Tukey-DMA chart. The Tukey-DMA chart is constructed by plotting the Tukey-DMA statistics computed from (7) on the chart against the sample number i with control limits given in (10)-(12). The process is declared as in-control whenever $LCL \leq Tukey - DMA_i \leq UCL.$ Otherwise, the process is declared as out of control.

3. Performance of Control Chart

Control chart performance is traditionally quantified in terms of the average run length (ARL). Run length is defined as the number of observations in process from the start of the control to the first out-of-control signal. After this observation, the process of counting is stopped, and the calculation of the run length is recommenced for the next in-control observation. Accordingly, ARL is the mean of the run length of the realized control chart. There were divided into two types, in-control processor (ARL_0) and out-of-control processor (ARL_1). The minimum ARL_1 indicated the most efficient control chart. This research consists of two methods for estimating ARL. First, Tukey and DMA charts were estimated using explicit formula and second, Tukey-MA and Tukey-DMA charts were estimated by Monte Carlo simulation (MC). The measure was mathematically defined as

$$ARL = \frac{\sum_{i=1}^{N} RL_i}{N};\ i = 1,2,...,N, \tag{13}$$

where RL_i refers to the observed value before outside the control limit of the i realization and N refers to the number of realizations, where $N = 200{,}000$ realizations.

4. Numerical Results

4.1. ARL of the control chart

In this section, estimating the numerical result of ARL_0 and ARL_1 of Tukey, DMA, Tukey-MA and Tukey-DMA chart was proposed by comparing it with explicit formula and MC. The numerical result for ARL_0 and ARL_1 of Tukey, Tukey-MA, and Tukey-DMA chart were calculated from (13). The numerical result for ARL_0 and ARL_1 of the DMA chart was calculated by an explicit formula. This research was study underlying Normal and Exponential distribution. In the case of an in-control, the probability distribution includes Normal(0,1) and Exponential(1). The parameter of DMA, Tukey-MA, and Tukey-DMA chart, the moving average of width (w) was 2, 5, 10 and 15. If an in-control average run length value (ARL_0) was 370, the coefficient control limit (H) will equal to 3. In the case of an out-of-control parameter of Normal and Exponential processes, $\mu_1 = \mu_0(1+\delta)$ and $\beta_1 = \beta_0(1+\delta)$, respectively. The parameter magnitude values of δ were 0.05, 0.10, 0.25, 0.50, 0.75, 1, 1.5, 2, 3, and 4. The ARL of the proposed chart with Tukey, DMA and Tukey-MA chart as shown in Tables 1 and 2.

Table 1 ARL for normal distribution by varying w

δ	Tukey	DMA				TUKEY-MA				TUKEY-DMA			
		$w=2$	$w=5$	$w=10$	$w=15$	$w=2$	$w=5$	$w=10$	$w=15$	$w=2$	$w=5$	$w=10$	$w=15$
0.0	370.9	370.4	370.4	370.4	370.4	370.4	370.8	370.4	370.0	370.2	370.7	370.0	370.1
0.0	402.7	352.9	282.3	162.9	**98.92**	330.2	293.3	311.2	328.0	253.3	428.6	204.2	191.6
0.1	390.6	308.6	158.1	56.22	**37.86**	308.1	256.4	252.5	253.9	235.6	361.8	159.7	137.6
0.2	314.5	155.8	30.12	17.97	**24.75**	209.0	135.2	105.4	93.47	152.8	155.6	57.14	40.80
0.5	173.8	44.97	**8.98**	12.90	13.25	89.50	44.03	29.71	25.06	59.96	39.06	14.30	10.05
0.7	90.29	16.22	6.59	7.51	6.96	39.61	17.81	12.15	10.38	24.99	13.44	5.80	**4.22**
1.0	48.37	7.62	5.22	5.01	4.98	19.32	8.74	6.25	5.41	11.70	6.02	2.95	**1.95**
1.5	16.21	3.28	3.19	3.17	3.17	5.99	3.06	2.35	2.07	3.38	1.86	0.72	**0.41**
2.0	6.71	2.28	2.32	2.32	2.32	2.37	1.38	1.10	0.96	1.22	0.59	0.17	**0.11**
3.0	2.07	1.53	1.53	1.53	1.53	0.53	0.34	0.26	0.22	0.17	0.04	0.01	0.01
4.0	1.20	1.16	1.16	1.16	1.16	0.11	0.06	0.04	0.03	0.02	0.00	0.00	0.00

Bold number gives minimum ARL_1.

Table 2 ARL for exponential distribution varying w

δ	Tukey	DMA				TUKEY-MA				TUKEY-DMA			
		$w=2$	$w=5$	$w=10$	$w=15$	$w=2$	$w=5$	$w=10$	$w=15$	$w=2$	$w=5$	$w=10$	$w=15$
0.0	370.1	370.4	370.4	370.4	370.4	370.6	370.1	370.4	370.7	370.4	370.3	370.8	370.5
0.0	396.0	272.4	198.3	100.4	**61.74**	289.4	301.5	288.8	260.3	229.5	197.3	145.4	120.7
0.1	358.9	184.8	82.52	32.32	**29.70**	216.6	211.7	191.5	168.7	172.0	139.7	96.85	76.66
0.2	251.2	55.73	**14.37**	15.60	21.58	104.0	89.61	73.74	62.15	83.97	61.12	38.37	28.04
0.5	129.0	13.20	**6.79**	9.58	8.98	43.37	33.84	26.46	22.19	35.56	24.06	14.86	10.79
0.7	67.34	5.77	**5.19**	5.42	5.24	23.44	17.64	13.81	11.64	19.47	13.13	8.47	6.23
1.0	36.86	**3.62**	3.95	3.83	3.82	14.79	11.08	8.71	7.38	12.40	8.61	5.77	4.18
1.5	12.97	2.29	2.52	2.50	2.50	7.73	5.86	4.65	3.94	6.53	4.88	3.30	**2.20**
2.0	5.63	1.82	1.90	1.90	1.90	4.97	3.79	3.03	2.59	4.22	3.31	2.12	**1.32**
3.0	1.89	1.37	1.38	1.38	1.38	2.74	2.13	1.72	1.49	2.36	1.92	1.05	**0.63**
4.0	1.16	1.17	1.17	1.17	1.17	1.85	1.45	1.18	1.04	1.59	1.27	0.64	**0.41**

Bold number gives minimum ARL_1.

4.2. Comparison of the performance of the control chart

A comparison of ARL of the proposed control with Tukey, DMA and Tukey-MA chart for normal and exponential distribution in Tables 3 and 4, respectively. In the case of Normal(0,1) distribution, the DMA chart has a smaller ARL_1 than Tukey, Tukey-MA and Tukey-DMA chart for $0.05 \le \delta \le 0.25$. For moderate and larger shifts, Tukey-DMA chart has better performance than Tukey, DMA and Tukey-MA chart. In the case of Exponential (1) distribution, DMA chart has smaller ARL_1 than Tukey, Tukey-MA and Tukey-DMA chart for $0.05 \le \delta \le 1.00$. In the case of large shifts, Tukey-DMA has better performance than Tukey, DMA, and Tukey-MA chart.

Table 3 Comparison of ARL for normal distributions

δ	Tukey	DMA(w)	Tukey-MA(w)	Tukey-DMA(w)
0.00	370.91	370.40	370.44	370.12 (15)
0.05	402.74	**98.92** (15)	311.27 (10)	191.65 (15)
0.10	390.68	**37.86** (15)	252.54 (10)	137.62 (15)
0.25	314.58	**17.97** (10)	105.46 (15)	40.80 (15)
0.50	173.83	12.89 (10)	29.71 (15)	**10.05** (15)
0.75	90.29	6.59 (5)	12.15 (15)	**4.22** (15)
1.00	48.37	5.22 (5)	6.25 (15)	**1.95** (15)
1.50	16.21	3.19 (5)	2.35 (15)	**0.41** (15)
2.00	6.71	2.28 (2)	1.10 (15)	**0.11** (15)
3.00	2.07	1.53 (2)	0.26 (15)	**0.01** (15)
4.00	1.20	1.16 (2)	0.04 (15)	**0.00** (15)

Bold number gives minimum ARL_1.

Table 4 Comparison of ARL for exponential distributions

δ	Tukey	DMA(w)	Tukey-MA(w)	Tukey-DMA(w)
0.00	370.10	370.40	370.75	370.54
0.05	396.09	**61.74** (15)	260.36 (15)	120.77 (15)
0.10	358.92	**29.70** (15)	168.76 (15)	76.66 (15)
0.25	251.23	**15.60** (10)	62.15 (15)	28.04 (15)
0.50	129.06	**9.58** (10)	22.19 (15)	10.79 (15)
0.75	67.34	**5.42** (10)	11.64 (15)	6.23 (15)
1.00	36.86	**3.83** (10)	7.38 (15)	4.18 (15)
1.50	12.97	2.50 (10)	3.94 (15)	**2.20** (15)
2.00	5.63	1.90 (10)	2.59 (15)	**1.32** (15)
3.00	1.89	1.38 (10)	1.49 (15)	**0.63** (15)
4.00	1.16	1.17 (10)	1.04 (15)	0.41 **(15)**

Bold number gives minimum ARL_1.

5. Real Data Application

This section highlights the significance of the Tukey-DMA design using two real-life data. We have considered two applications: the first one is about Nile river flow data and the second one is the British coal mining disaster.

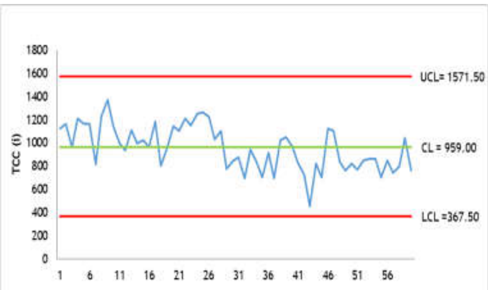
5.1. Application I

For this application, we have selected Nile river flow data. The following Nile river flow is reproduced from Cobb (1978). Based on the data, we have observed Nile river flow to follow a Normal (1100, 125) distribution. Based on the said information, we have the following statistics:

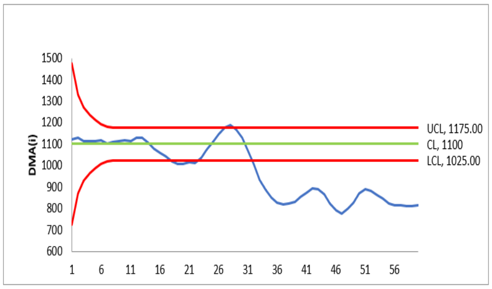
$$Q_1 = 842.71,\ Q_3 = 1{,}113.59,\ IQR = 270.88.$$

For this data, we have made fourth control charts including Tukey, DMA, Tukey-MA and Tukey-DMA chart. The graphical displays of these control charts, along with data display, are provided in Figure 1. The Tukey control chart is represented in Figure 1(a), DMA chart in Figure 1 (b), Tukey-MA chart in Figure 1(c) and Tukey-DMA chart in Figure 1(d). It is observed that the quickest detection of a change on rate of Nile river flow is DMA chart which first signals to out of control limit at 18th

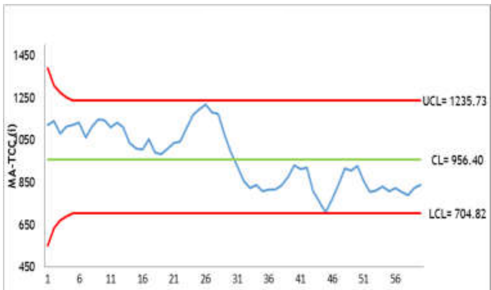
observation while Tukey-DMA chart can first detect at 18th observation. Otherwise, Tukey and Tukey-MA could not detect any change. It concluded that the DMA chart can perform better Tukey-DMA chart. Unfortunately, the DMA chart need to know the parameter or population distribution while the Tukey-DMA chart is overcome this limitation in order to use control chart to detect a change in process.



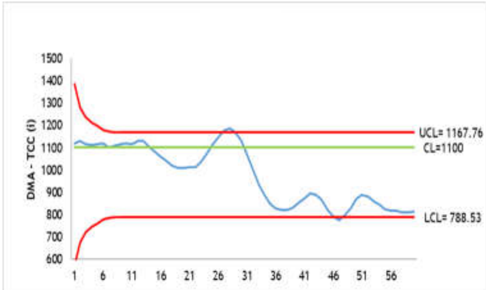
(a) Tukey chart



(b) DMA chart



(c) Tukey-MA chart



(d) Tukey-DMA chart

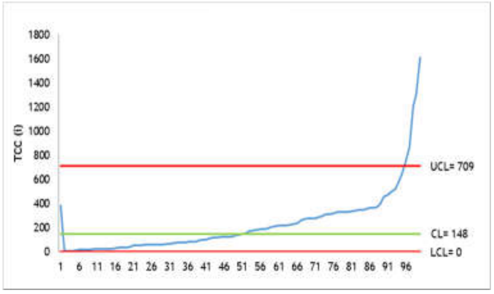
Figure 1 Performance comparison of detection for Nile river flow data

5.2. Application II

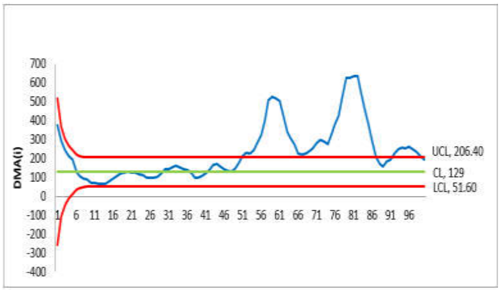
For this application, we have selected the British coal mining disaster. A disaster is defined as involving the death of 10 or more men. The data are taken from Maguire, Pearson, and Wynn (1952). Based on the data, we have observed the British coal mining disaster to follow an exponential (1/129) distribution. Based on the said information, we have the following statistics:

$$Q_1 = 124.51,\ Q_3 = 284.66,\ IQR = 160.15.$$

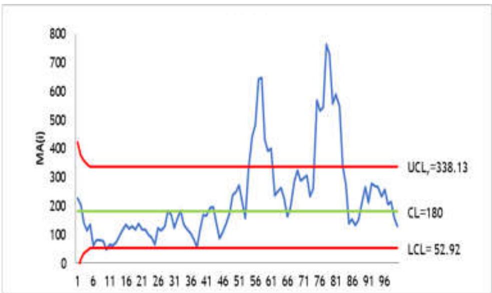
For this data, we have made fourth control charts including Tukey, DMA, Tukey-MA and Tukey-DMA chart. The graphical displays of these control charts, along with data display, are provided in Figure 1. The Tukey control chart is represented in Figure 2(a), DMA chart in Figure 2(b), Tukey-MA chart in Figure 2(c) and Tukey-DMA chart in Figure 2(d). It is observed that the total number of out of control signals are reported as below. Tukey: 96; DMA: 51; Tukey-MA: 10 and Tukey-DMA: 9.



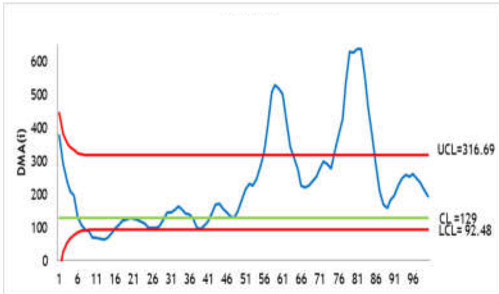
(a) Tukey chart



(b) DMA chart



(c) Tukey-MA chart



(d) Tukey-DMA chart

Figure 2 Performance comparison of detection for British coal mining disaster data

6. Conclusions

This research proposes a Tukey-DMA chart with asymmetrical and symmetrical control limits to monitoring skew population. A comparison study of statistical measurement and real case are given respectively to show the performance of Tukey-DMA chart in the monitoring of the skew population from the theoretical and practical viewpoint. This design is more suitable when data follow the skewed distribution and is also appropriate when the data is from asymmetric distribution. Tukey-DMA chart appeared as an attractive choice in many cases. It is recommended to use the proposed design when the data is highly skewed. This design is more sensitive to a small and sustained shift in the process mean. Real data sets have also supported the proposed design structure of the Tukey-DMA chart for better detection of changes in process parameters.

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