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Optimal Design of One-sided Exponential EWMA Charts Based on Median Run Length and Expected Median Run Length

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Abstract

Exponential type charts are useful tools to monitor the time between events in high-quality processes with a low defect rate. Most studies on exponential charts are

designed with the average run length (ARL) metric. The only use of ARL in the design of control charts is sometimes criticized because the shape of the run length (RL) distribution of control charts changes with the shift size. In fact, the RL distribution of the exponential exponentially weighted moving average (EWMA) chart is skewed, especially when the process is in-control. Hence, the median run length (MRL) serves as a more meaningful indicator. Moreover, in some situations, the shift size in the process is unknown in advance. Under this case, the expected median run length ($EMRL$) can be used as the metric. In this paper, the RL properties of both the upper- and lower-sided exponential EWMA charts are studied through a Markov chain approach. Two optimal design procedures are developed for one-sided exponential EWMA charts based on the MRL and $EMRL$, respectively. The choices of reflecting boundaries for one-sided exponential EWMA charts are discussed through many numerical studies. The MRL and $EMRL$ performances of the one-sided exponential EWMA charts are investigated.

Keywords: Exponential chart; Median run length; Expected median run length; Exponentially weighted moving average chart.

1 Introduction

Quality of a product is important for manufacturing or service organizations to improve their competitiveness (see Oakland (2007)). Statistical Process Control (SPC) plays an important role in the quality improvement of a product. As a useful tool in SPC, control charts are usually used to monitor the state of processes.

Control charts are usually designed under the assumption that the quality character-

istic follows a normal distribution. This assumption is not appropriate in the monitoring of some particular processes, such as in monitoring the rate of occurrences of congenital malformations (see Lucas (1985)), in monitoring the consecutive radiation pulses (see Luo et al. (2012)), and in monitoring the medical errors (see Doğu (2012)), where the exponential distribution is usually assumed for the time between events (TBE) data. Lucas (1985) first investigated the properties of the exponential chart. Following Lucas (1985), many research works on exponential charts were performed. Gan (1994) developed an optimal design procedure of the exponential Cumulative Sum (CUSUM) control charts. Based on the average time to signal (*ATS*), Liu et al. (2006) compared the properties of several exponential charts. The Phase I implementation of the exponential chart was further considered by Jones and Champ (2002). More related research works on exponential charts can be found in Santiago and Smith (2013), Yang et al. (2015), Zhang et al. (2005, 2006), to name a few. These researches are mainly focused on two-sided exponential charts. In fact, one-sided charts are more appropriate for processes for which the direction of the potential mean shift is anticipated (see Shu et al. (2007)). Some existing researches focused on one-sided exponential charts can be found in Gan (1998), Ozsan et al. (2010), Pehlivan and Testik (2010). Moreover, if a two-sided chart is needed, a combined scheme of both the lower- and upper-sided charts could be designed instead, and there is practically no difference between the combined scheme and the two-sided case (see Reynolds et al. (1990)).

Exponentially Weighted Moving Average (EWMA) type charts gained extensive attention from many researchers for its advantage in detecting small to moderate shift sizes in a process (see Chandrasekaran et al. (1995), Gan (1991), Waldmann (1986)). Much researches on EWMA type charts can be found in Haq (2019), Knoth (2015), Maravelakis et al. (2019)

and so on. These researches are mainly based on the assumption of normally distributed observations. For non-normally distributed observations, researches have also been studied to investigate the performance of EWMA type charts. In high-quality processes, TBE data are sometimes assumed to be exponentially distributed. Based on this fact, Gan (1998), Gan and Chang (2000) developed the exponential EWMA control chart to monitor the rate of occurrences of rare events and presented a program to determine the average run length (ARL) profiles of the exponential EWMA chart. Liu et al. (2007) proposed a new EWMA chart to monitor the exponentially distributed TBE data using the double square root (SQRT) transformation. Pehlivan and Testik (2010) investigated the sensitivity of the exponential EWMA chart in detecting the process shift and they concluded that the exponential EWMA chart could be extremely robust to departures from the assumed exponential distribution. The conditional expected values were employed to monitor small mean shifts in Raza et al. (2016). By transforming the exponential data to approximately normal ones, Khan et al. (2016) proposed an EWMA chart to monitor the exponentially distributed data. The effect of parameter estimation on the performance of the exponential EWMA chart has been analyzed in Ozsan et al. (2010). A survey of the related research works on exponential EWMA charts can be found in Ali et al. (2016).

Generally, the ARL is used as a criterion to evaluate the performance of control charts. Nevertheless, the only use of ARL has been criticized by some researchers (see Khoo (2004), Khoo et al. (2011), Lee and Khoo (2017b), Tang et al. (2019), Waldmann (1986) and so on). The ARL is regarded as the representation of the “central tendency” of the run length (RL) distribution, however, it is clearly not suitable as its shape becomes asymmetric. Furthermore, it has been pointed out that the RL distribution of control charts may be skewed,

especially when the process is in-control. Therefore, the interpretation of the *ARL* is sometimes confusing for practitioners to evaluate a control chart's performance with skewed *RL* distributions. For example (see Section 2, Table 1), a lower-sided exponential EWMA chart with $(\lambda^-, h^-) = (0.4, 0.2045)$ has an in-control *ARL* of 500, while 50% of in-control *RLs* is smaller than 348. When the process is out-of-control ($c = 0.6$), the *ARL* is 57.1, and 50% of the out-of-control *RLs* is smaller than 41. Instead, the median run length (*MRL*), defined as the median number of samples that are plotted on a chart before an out-of-control signal is issued, has no such interpretation problem. In the above example, the in-control and out-of-control *MRL* values are 348 and 41, respectively, which indicate that half of the in-control and out-of-control *RLs* are smaller than 348 and 41, respectively. For practitioners, the interpretation based on the *MRL* is more intuitive than the one based on the *ARL*. Hence, more and more researchers promote using the *MRL* as a better criterion to evaluate the performance of control charts (see Lee and Khoo (2006, 2017a), Nyau et al. (2017), Teoh et al. (2016)). Moreover, practitioners may not have enough historical knowledge of shift sizes in a process. To circumvent this problem, the expected *MRL* (*EMRL*) is recommended as a measure of a chart's performance when practitioners cannot specify the exact value of the shift size (see Tang et al. (2019), Teoh et al. (2016), You et al. (2016)).

In fact, *RL* distributions of one-sided exponential EWMA control charts are also skewed, especially when the process is in-control (see Section 2). The *MRL* and *EMRL* are good alternatives to evaluate the properties of one-sided exponential EWMA control charts. As far as we know, there is no research conducted on the *MRL* or *EMRL* properties of exponential charts yet. The purpose of this paper is to fill this gap and to develop the optimal design procedures for both the upper- and lower-sided exponential EWMA charts based on *MRL*

and *EMRL*. The rest of this paper is organized as follows: Section 2 introduces the one-sided exponential EWMA charts and briefly discusses problems arising from the only use of *ARL*. Then, an optimal design procedure is developed for the upper- and lower-sided exponential EWMA charts based on *MRL* and *EMRL* in Section 3. The performances of these one-sided exponential EWMA charts are investigated in Section 4 and the effect of parameter estimation is briefly discussed in Section 5. Finally, some conclusions and recommendations are given in Section 6. The *RL* properties of the chart are presented using a Markov chain approach in the Appendix.

2 One-Sided Exponential EWMA Charts

As in most reported research works, let us assume that the TBE variable X follows an exponential distribution with a single parameter θ . The probability density function (p.d.f.) $f(x)$ and cumulative distribution function (c.d.f.) $F(x)$ of the exponential distribution are given as follows:

$$f(x) = \frac{1}{\theta} e^{-\frac{x}{\theta}}, \quad x \geq 0 \quad (1)$$

$$F(x) = 1 - e^{-\frac{x}{\theta}}, \quad x \geq 0 \quad (2)$$

The process is said to be in-control when $\theta = \theta_0$, where θ_0 is the known in-control mean of the process. Otherwise, the process is out-of-control when $\theta = c\theta_0$ ($c \neq 1$), where $c = \theta/\theta_0$ is a constant that reflects the shift in θ_0 .

Since this paper focuses on one-sided charts, we introduce the following upper- and lower-

sided exponential EWMA charts:

- If the goal is to detect an increase in the process mean ($c > 1$), the upper-sided exponential EWMA chart is used. The charting statistic for the t th sample is computed as follows:

$$Q_t^+ = \max(B^+, (1 - \lambda^+)Q_{t-1}^+ + \lambda^+ X_t), \quad t = 1, 2, \dots \quad (3)$$

where $0 < \lambda^+ \leq 1$ and B^+ are the smoothing parameter and the reflecting boundary, respectively. The initial value Q_0^+ is generally constrained by $B^+ \leq Q_0^+ < h^+$, where $UCL = h^+$ is the upper control limit of the chart. An out-of-control signal is issued when $Q_t^+ > h^+$.

- If the goal is to detect a decrease in the process mean ($c < 1$), the lower-sided exponential EWMA chart is used. The charting statistic for the t th sample is computed as follows:

$$Q_t^- = \min(B^-, (1 - \lambda^-)Q_{t-1}^- + \lambda^- X_t), \quad t = 1, 2, \dots \quad (4)$$

where $0 < \lambda^- \leq 1$ and B^- are the smoothing constant and the reflecting boundary, respectively. The initial value Q_0^- is generally constrained by $h^- < Q_0^- \leq B^-$, where $LCL = h^-$ is the lower control limit of the chart. An out-of-control signal is issued when $Q_t^- < h^-$.

As in Gan (1998) and Pehlivan and Testik (2010), without loss of generality, we assume that the in-control mean $\theta_0 = 1$ and the initial values $Q_0^- = Q_0^+ = \theta_0 = 1$ (other situations with specific initial values can be analyzed similarly). Furthermore, the reflecting boundary $B^+(B^-)$ is used to ensure that the charting statistic is at most a certain distance away from

the control limit $h^+(h^-)$, which can improve the sensitivity of the chart (see Pehlivan and Testik (2010)).

In order to draw attention to the use of the MRL metric, some ARL and percentile values of the RL distribution are presented in Table 1 when $\lambda^- \in \{0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1\}$ and the in-control ARL (denoted as ARL_0) roughly equals to 500 for the lower sided exponential EWMA chart. In this article, the RL properties of one-sided exponential EWMA charts can be obtained using the Markov chain approach given in the Appendix. Moreover, the values of the reflecting boundaries are set to be $B^+ = 0.5$ and $B^- = 2.0$ (discussed in Section 3.1). It is obvious that there is a large difference between ARL_0 and in-control MRL (denoted as MRL_0) when the process is in-control. However, the difference between ARL and MRL values decreases with the shift size increasing. For example, if $(\lambda^-, h^-) = (0.05, 0.6861)$, when the process is in-control ($c = 1$), the ARL_0 and MRL_0 are 500.1 and 351, respectively. When the process is out-of-control ($c = 0.2$), the ARL and the MRL values decrease down to 10.2 and 10, respectively. Similar results can also be drawn from other values of (λ^-, h^-) shown in Table 1. It is noted that the shape of the RL distribution of the lower-sided exponential EWMA chart changes with the shift size, i.e., from highly right skewed when the process is in-control to nearly symmetric when the process is out-of-control.

On the other hand, for the upper-sided exponential EWMA chart, Table 2 also shows the ARL and some percentiles of the RL distribution with $\lambda^+ \in \{0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1\}$ and the ARL_0 roughly equals to 500. It can be seen that the difference between ARL and MRL also changes with the shift size. For example, if $(\lambda^+, h^+) = (0.2, 2.2378)$, ARL_0 and MRL_0 are 500 and 347, respectively, when the process is in-control ($c = 1$). When the mean shift c changes to $c = 5$, ARL and MRL values are 3.1 and 3, respectively.

(Please Insert Tables 1-2 to Here)

For a skewed RL distribution, the interpretation solely based on the ARL is different from the one with respect to a nearly symmetric distribution. A practitioner should be advised against viewing ARL as a symbol of “half of the time” because ARL only provided information about the expected RL (see Khoo et al. (2011), Nyau et al. (2017)). It is not intuitive enough and can sometimes result in misunderstandings when the RL distribution changes with the shift size. Fortunately, the percentiles of the RL distribution provide more information on the performance of a control chart, no matter the RL distribution is skewed or symmetric. As a good alternative, the MRL has been suggested by some researchers to evaluate the properties of control charts (see Khoo et al. (2011), Lee and Khoo (2017a), Nyau et al. (2017), Tang et al. (2019), Teoh et al. (2017), to name a few). In this article, for one-sided exponential EWMA charts, the MRL is also suggested as the criterion to be investigated.

3 Optimal Design of One-sided Exponential EWMA Control Charts

In this section, we mainly focus on the optimal design of one-sided (upper- and lower-sided) exponential EWMA charts based on the MRL and $EMRL$, respectively. The setting of the reflecting boundaries B^+ and B^- are discussed first, and the procedure for the design of the smoothing parameter and control limits of the chart are developed lately.

3.1 Choices of the reflecting boundaries B^+ and B^- for the *MRL*-based one-sided exponential EWMA charts

In order to design the *MRL*-based one-sided exponential EWMA control charts, the reflecting boundary B^+ (B^-) of the upper-sided (lower-sided) EWMA control chart should be selected first. For the *ARL*-based exponential EWMA charts, by doing many numerical analyses, values of the reflecting boundaries have been suggested to be $B^+ = 0.5$ and $B^- = 2.0$ by Gan (1998). These values are also used in other researches conducted on the *ARL*-based exponential EWMA chart (see Ozsan et al. (2010)). Now, we are wondering if these suggested values can also be used for the *MRL*-based one-sided exponential EWMA charts? Considering this issue, many numerical simulations have been performed for different values of $\lambda^- \in \{0.1, 0.3, 0.5, 0.7\}$ and mean shifts $c \in \{0.1, 0.2, \dots, 1.0\}$ when $MRL_0 \in \{100, 500, 1000\}$, for the lower-sided exponential EWMA chart. The control chart limit h^- is selected to produce the desired MRL_0 for different combinations of λ^- and B^- . Owing to the space limitation, only the numerical simulation with $MRL_0 = 100$ is presented in Table 3. It can be noted that the control chart limit h^- generally increases as the reflecting boundary B^- increases. When B^- is larger than 2.0, the value of h^- converges to a constant. For example, when $\lambda^- = 0.3$, the value of h^- converges to 0.348 with the increase in B^- . Moreover, it can also be seen that, for fixed values of c , the out-of-control *MRL* value (denoted as MRL_1) decreases as the reflecting boundary B^- increases, which implies that the sensitivity of the control chart increases. For values of B^- larger than 2.0, it can be noted that the detection ability of the lower-sided exponential EWMA chart generally remains the same. For example, when $\lambda^- = 0.3$ and $c = 0.8$, if the value of B^- increases

from 1.0 up to 1.5, the MRL_1 values decrease from 44 down to 40. While if the value of B^- increases up to 2.3 or 2.5, the MRL_1 values are both equal to 39. For other values of the desired MRL_0 , similar results can also be drawn. Consequently, as in Gan (1998), a reasonable value of the reflecting boundary B^- for the MRL -based lower-sided exponential EWMA chart is 2.0. In the rest of this article, the reflecting boundary B^- is set to be 2.0.

For the upper-sided exponential EWMA chart, similar numerical simulations are also performed to investigate the choice of the reflecting boundary B^+ for different values of $MRL_0 \in \{100, 500, 1000\}$. Owing to the space limitation, these results are not presented here. It can be concluded from the results that a reasonable value of the reflecting boundary B^+ is 0.5, which leads to a good detection ability of the upper-sided exponential EWMA chart for different values of λ^+ and MRL_0 . In this article, the value of the reflecting boundary B^+ is set to be 0.5.

(Please Insert Table 3 to Here)

3.2 Design procedure of one-sided exponential EWMA charts based on the MRL

When the process is in-control ($c = 1$), it is expected that the control chart runs with a small false alarm rate, i.e., a large MRL_0 . While at the same time, the chart is also expected to detect a mean shift quickly, i.e., a small MRL_1 , when the process is out-of-control ($c \neq 1$). The optimal design of the one-sided exponential EWMA charts based on the MRL consists in finding the smallest MRL_1 value for a specified mean shift c (denoted as c_{opt}) with the

constraint on the desired MRL_0 , i.e.,

$$(\lambda^*, h^*) = \underset{(\lambda, h)}{\operatorname{argmin}} MRL_1(\lambda, h, c_{\text{opt}}), \quad (5)$$

subject to

$$MRL(\lambda^*, h^*, c = 1) = MRL_0, \quad (6)$$

where λ and h are the smoothing parameter and the control chart limit, respectively. It is noted that λ stands for λ^+ or λ^- for the upper- or the lower-sided exponential EWMA charts, respectively. Similarly, h stands for h^+ or h^- for the upper- or lower-sided exponential EWMA charts, respectively. The upper-sided exponential EWMA chart is used to detect an increase in the mean shift ($c_{\text{opt}} > 1$). On the contrary, the lower-sided exponential EWMA chart is employed if the specified mean shift decreases ($c_{\text{opt}} < 1$).

For a specified value of MRL_0 and the interested mean shift c_{opt} , one can obtain the optimal parameter combinations of the one-sided exponential EWMA chart using Eqs. (5) and (6). The procedure is summarized as follows:

- (1) Specify the desired MRL_0 and the interested mean shift c_{opt} .
- (2) Initialize the smoothing constant $\lambda = 0.05$.
- (3) Determine the control limit h for the corresponding λ , based on the desired MRL_0 specified in Step (1).
- (4) Compute the MRL_1 for the corresponding combinations (λ, h) specified in Step (3) and

c_{opt} .

- (5) Repeat Steps (3) to (4) for all values of λ varying from 0.05 to 1 with a step size 0.001.
- (6) Record the combinations (λ, h) that produce the minimum MRL_1 for the specified c_{opt} as the optimal parameter combinations.

Since the MRL is a discrete quantity, there may exist several values of control limit h for each smoothing constant λ , based on the constraint on the specified MRL_0 . Without loss of generality, the median of all the h values is selected for the corresponding λ . It is noted that there may exist several optimal parameter combinations (λ, h) that produce the same minimum value of MRL_1 for a specified mean shift c_{opt} . In this situation, the median of all the optimal λ values and the corresponding h are selected in this article.

3.3 Design procedure of one-sided exponential EWMA charts based on the $EMRL$

The optimal MRL -based chart proposed in this paper is effective in detecting a shift of particular size and the computation of the MRL requires the exact value of the mean shift c . However, the practitioners are not always able to specify the exact shift size in advance, but the range of shift is roughly known in practice (see Celano et al. (2013)). In this case, the shift size c should be considered as a random quantity that may vary according to a certain distribution and the $EMRL$ can be used instead of the MRL , i.e.,

$$EMRL = \int_{\Omega} MRL(\lambda, h, c) \times f_c(c) dc, \quad (7)$$

where $f_c(c)$ is the p.d.f. of the mean shift c over the range Ω . It is generally assumed explicitly (see Domangue and Patch (1991), Sparks (2000)) or implicitly (see Reynolds and Stoumbos (2004)) that all process shifts occur with an equal probability, for example, the shift in the mechanical parts produced by multi-purpose Computer Numerical Control (CNC) machines (see Celano et al. (2013)), thus a uniform distribution for c is recommended. Whereas, other p.d.f. of the mean shift c , like for instance, truncated normal distribution (see Ryu et al. (2010)), Rayleigh distribution (see Wu et al. (2004)), to name a few, can be considered according to the historic data of the out-of-control cases or the practitioner's knowledge about the process. Following Castagliola et al. (2011), Tang et al. (2019), Teoh et al. (2017), a uniform distribution is assumed in this article.

The optimal parameter combinations (λ^*, h^*) of the one-sided exponential EWMA chart based on the *EMRL* can be obtained as follows:

$$(\lambda^*, h^*) = \underset{(\lambda, h)}{\operatorname{argmin}} \quad EMRL_1(\lambda, h, \Omega), \quad (8)$$

subject to

$$MRL(\lambda^*, h^*, c = 1) = MRL_0, \quad (9)$$

where $EMRL_1$ is the out-of-control *EMRL* value computed using Eq. (7). The optimal design procedure of the *EMRL*-based one-sided exponential EWMA charts is similar to the steps in Section 3.2 except that the interested mean shift c_{opt} and the MRL_1 are replaced by the interested mean shift range Ω and the $EMRL_1$, respectively.

4 Performance Evaluation Based on MRL

In this section, the performances of both the upper- and lower-sided exponential EWMA charts are studied. The optimal charting parameter combinations used here are obtained following the procedures described in Sections 3.2 and 3.3.

4.1 Performance evaluation for the mean shift of known size

The MRL profiles for the lower-sided exponential EWMA chart and the lower-sided exponential Shewhart chart are displayed in Table 4, for different values of the specified mean shifts $c_{\text{opt}} \in \{0.2, 0.4, 0.6, 0.8\}$ and the desired $MRL_0 \in \{100, 200, 300, 500\}$. The optimal parameter combinations (λ^-, h^-) of the lower-sided exponential EWMA chart and the lower control limit (LCL) of the corresponding lower-sided exponential Shewhart chart are given in rows 4 and 5.

It is shown that the lower-sided exponential EWMA chart with a small optimal λ^- value has better performance for small shift sizes. At the same time, the chart with a large optimal λ^- value performs better in the cases of large shift sizes. For example, considering the case of $MRL_0 = 300$, the MRL_1 values increases from 54 up to 77 when λ^- increases from 0.052 up to 0.196 when the mean shift $c = 0.8$, which implies that the control chart with $\lambda^- = 0.052$ detects the mean shift ($c = 0.8$) more quickly than the chart with $\lambda^- = 0.196$. While, if the mean shift c decreases down to 0.2, the MRL_1 values are 10 and 7 for $\lambda^- = 0.052$ and $\lambda^- = 0.196$, respectively, which implies that the control chart with $\lambda^- = 0.196$ detects the mean shift ($c = 0.2$) more quickly than the chart with $\lambda^- = 0.052$.

By comparing the performances of the lower-sided exponential EWMA chart with the

lower-sided exponential Shewhart chart, it is also noted that the EWMA-type chart is superior to the Shewhart-type chart in most cases. The lower-sided exponential Shewhart chart only performs slightly better than the lower-sided exponential EWMA chart when the mean shift is large ($c < 0.05$). For instance, when $MRL_0 = 200$, the MRL_1 values of the lower-sided exponential EWMA chart with optimal parameter combinations designed for $c_{\text{opt}} = 0.4$ are all smaller than the ones of the lower-sided exponential Shewhart chart when $c \geq 0.03$. When $c = 0.01$, the $MRL_1 = 2$ for the lower-sided exponential Shewhart chart is a little smaller than the $MRL_1 = 4$ for the lower-sided exponential EWMA chart.

Moreover, the MRL profiles of the upper-sided exponential EWMA and Shewhart charts are also displayed in Table 5 for $MRL_0 \in \{100, 200, 300, 500\}$. In order to observe the effect of the shift size comprehensively, we chose several representative values from Gan (1998), i.e., $c_{\text{opt}} \in \{1.04, 1.4, 2, 5\}$. The optimal parameter combinations (λ^+, h^+) of the upper-sided exponential EWMA chart and the upper control limit (UCL) of the upper-sided exponential Shewhart chart are displayed in rows 4 and 5. Similar to the lower-sided exponential EWMA chart, the upper-sided exponential EWMA chart with a small value of λ^+ gives better performance for smaller shift sizes compared with the upper-sided exponential Shewhart chart. From Table 5, it is also clear that the upper-sided exponential EWMA chart consistently performs better than the upper-sided exponential Shewhart chart, for small to moderate shift sizes ($1 < c < 3$). The upper-sided exponential Shewhart chart only outperforms the upper-sided exponential EWMA chart when the mean shift is large ($c > 3$). Furthermore, as in Kumar and Baranwal (2019), a comparative study is carried out to compare the charts designed for a fixed nominal ARL_0 and the corresponding MRL_0 . Table 6 presents the MRL and ARL values of the chart for different parameter combinations

of (λ^-, h^-) and c when $MRL_0 = 350$ and $ARL_0 = 500$. It is noted that the parameter combinations (λ^-, h^-) are obtained by optimizing the MRL -based chart (the upper part in Table 6) and the ARL -based chart (the lower part in Table 6) for different values of c_{opt} . The MRL and ARL values corresponding to $c = c_{\text{opt}}$ are also bolded in the table. It can be concluded from the table that for the specific $c = c_{\text{opt}}$ in column 1, the MRL of the MRL -based chart performs a little better than the ARL -based chart and the ARL of the ARL -based chart performs a little better than the MRL -based chart. For example, when $c_{\text{opt}} = 0.6$, the $MRL = 23$ for the MRL -based chart performs a little better than the $MRL = 24$ for the ARL -based chart when $c = 0.6$. At the same time, the $ARL = 26.6$ for the ARL -based chart performs a little better than the $ARL = 27.1$ for the MRL -based chart when $c = 0.6$ (see the bolded values in columns 4 and 5).

(Please Insert Tables 4–6 to Here)

4.2 Performance evaluation for the mean shift of unknown size

When the mean shift is unknown, but the range of the shift size can be roughly specified, the optimal parameter combinations and properties of the lower-sided exponential EWMA chart and the lower-sided exponential Shewhart chart are provided in Table 7 for several uniform distributions of shift size $\Omega \in \{[0.1, 0.3], [0.3, 0.5], [0.5, 0.7], [0.7, 0.9]\}$ when $MRL_0 \in \{100, 200, 300, 500\}$. For example, if $MRL_0 = 200$, the optimal parameter combinations (λ^-, h^-) and the corresponding $EMRL_1$ value of the lower-sided exponential EWMA chart over the shift size range $\Omega = [0.3, 0.5]$ are $(0.204, 0.406)$ and 10.3, respectively. Using the optimal parameter combinations (λ^-, h^-) , the out-of-control MRL value of the exponential

EWMA chart is 10 when $c = 0.4$.

From Tables 4 and 7, it is noticed that the performance of the lower-sided exponential EWMA chart designed based on $EMRL$ is close to the one designed based on MRL , if the specified mean shift c is in the mean shift range Ω . For example, when $MRL_0 = 200$ and $c_{opt} = 0.6$ in Table 4, the MRL_1 values of the lower-sided exponential EWMA chart are 28, 19, 14 for shift sizes of 0.7, 0.6, 0.5, respectively. While in Table 7, the MRL_1 values are 28, 19, 14, respectively, when using the parameter combinations ($\lambda^- = 0.087, h^- = 0.610$) designed based on $\Omega = [0.5, 0.7]$. This implies that the optimal parameter combinations obtained based on $EMRL$ can be considered as a robust alternative to the parameter combinations obtained based on MRL if the specified mean shift c of the optimal MRL -based chart is in the range Ω of the optimal $EMRL$ -based chart. Furthermore, Table 7 also shows the superiority of the lower-sided exponential EWMA chart over the lower-sided exponential Shewhart chart. For example, when $MRL_0 = 200$, the MRL_1 values of the lower-sided exponential EWMA chart are smaller than the ones of the lower-sided exponential Shewhart chart when $c \in [0.05, 0.9]$. The lower-sided exponential Shewhart chart is more sensitive than the EWMA type chart only when $c < 0.05$. Similar findings are also obtained for the upper-sided exponential EWMA chart. Due to the space limitation, these results are not presented here.

(Please Insert Table 7 to Here)

5 The Effect of Parameter Estimation on the One-Sided Exponential EWMA Charts

Parameter estimation is an important research issue in control charts because the selection of Phase I samples influences the performance of control charts via the degree of accuracy in the estimator. Suppose that $\{Z_1, Z_2, \dots, Z_m\}$ is a sample from an in-control Phase I sample, then a common estimator for θ_0 is the maximum likelihood estimator $\hat{\theta}_0 = \frac{1}{m} \sum_{i=1}^m Z_i$. In order to investigate the effect of parameter estimation on the RL distribution of the chart, Tables 8 and 9 show the effect of the amount of Phase I data (i.e., m) on the Phase II performance of the optimal lower-sided charts. Table 8 presents the in-control MRL values for the lower-sided exponential EWMA chart when $m \in \{5, 10, 20, 30, 50, 100, +\infty\}$. Note that the parameter combinations of (λ^-, h^-) are the optimal settings for the specific $MRL_0 \in \{100, 300\}$ and $c_{\text{opt}} \in \{0.2, 0.4, 0.6, 0.8\}$ when the process parameter is known ($m = +\infty$). It is found that there is a difference between the in-control MRL values corresponding to the known parameter cases and the ones corresponding to the estimated parameter cases, especially for small values of λ^- and m . For example, when $MRL_0 = 100$ and $\lambda^- = 0.487$, the in-control MRL of the chart are 122 and 100 corresponding to $m = 5$ and $m = +\infty$, respectively. If $\lambda^- = 0.06$, the in-control MRL value of the chart are 174 and 100 corresponding to $m = 5$ and $m = +\infty$, respectively.

Moreover, when $MRL_0 = 300$, for the same parameter combinations (λ^-, h^-) presented in Table 8, the out-of-control 5th percentile of RL distribution, MRL and 95th percentile of RL distribution calculated using Eqs. (A.11) and (A.12) in the Appendix are also presented in Table 9. It is shown that the difference of MRL_1 between the known and estimated

parameters cases becomes large when m decreases. For example, when $c_{\text{opt}} = 0.8$, the MRL_1 value equals to 78 when $m = 5$. If m increases from 5 up to 100, the MRL_1 value decreases from 78 down to 55, which is more close to the $MRL_1 = 54$ corresponding to the known parameter case. It is obvious that the MRL_1 value of the chart with estimated parameter tends to be close to their known parameter counterpart, as m increases. Furthermore, it can also be noted that as the c_{opt} decreases, the difference of MRL_1 between the known and estimated parameters cases decreases. This fact implies that the effect of the parameter estimation becomes small when a large shift happens in the process. In addition, the 5th percentile of the RL distribution increases and the 95th percentile of the RL distribution decreases when m increases.

Due to the space limitation, the results for the upper-sided exponential EWMA chart are not presented here. Based on the results presented above, the RL distribution of the chart is obviously affected by the estimated parameter. To obtain a close performance to the chart with known parameter, the number m of Phase I samples should be large enough to minimize the effect of parameter estimation.

(Please Insert Tables 8–9 to Here)

6 Conclusions and Recommendations

Since the shape of the RL distributions of control charts changes with shift size, this paper studied the properties of the exponential EWMA chart based on MRL and $EMRL$ when the process shift sizes are either known or unknown, respectively. For an increase or a decrease in the process mean, the optimal design procedures of the upper- and lower-sided

exponential EWMA charts based on MRL have been presented. In practice, when the shift size is unknown in advance, based on $EMRL$, the optimal design procedures for both the upper- and lower-sided charts are also presented. Moreover, through the comparisons of the MRL -based one-sided exponential EWMA chart and the Shewhart chart, it is noted that the EWMA type chart generally performs better than the Shewhart type chart, except for large shift sizes in the process. As this work is based on the univariate variable, future research works may be extended to the chart for monitoring the multivariate exponential distributed processes.

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Appendix

The RL properties of one-sided exponential EWMA charts can be obtained using the Markov chain approach. The states of the Markov chain are defined by partitioning the control

interval into a finite set of sub-intervals and by considering the midpoint value within each sub-interval to approximate the value of the corresponding statistic. Assuming a discrete-time Markov chain with N transient states, the transition probability matrix \mathbf{Q} is given as follows:

$$\mathbf{Q} = \begin{pmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,N} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,N} \\ \vdots & \vdots & \vdots & \vdots \\ p_{N,1} & p_{N,2} & \cdots & p_{N,N} \end{pmatrix}, \quad (\text{A.1})$$

where $p_{i,j}$ is the probability of a transition from state i to state j in one step. Let \mathbf{q} be the initial probabilities associated with the N transient states, i.e., $\mathbf{q} = (q_1, q_2, \dots, q_N)^\top$. As stated in Latouche and Ramaswami (1999) or Neuts (1981), the RL of the one-sided exponential EWMA chart is a Discrete Phase-type (DPH) random variable of parameters (\mathbf{Q}, \mathbf{q}) , the probability mass function (p.m.f.) $f_{RL}(\ell|\mathbf{Q}, \mathbf{q})$ and the c.d.f. $F_{RL}(\ell|\mathbf{Q}, \mathbf{q})$ of the RL distributions are given as follows:

$$f_{RL}(\ell|\mathbf{Q}, \mathbf{q}) = \mathbf{q}^\top \mathbf{Q}^{\ell-1} \mathbf{r}, \quad (\text{A.2})$$

$$F_{RL}(\ell|\mathbf{Q}, \mathbf{q}) = 1 - \mathbf{q}^\top \mathbf{Q}^\ell \mathbf{1}. \quad (\text{A.3})$$

where $\mathbf{r} = (\mathbf{1} - \mathbf{Q}\mathbf{1})$ with $\mathbf{1} = (1, 1, \dots, 1)^\top$. The ARL of the one-sided exponential EWMA chart is

$$ARL = \mathbf{q}^\top (\mathbf{I} - \mathbf{Q})^{-1} \mathbf{1}. \quad (\text{A.4})$$

Following Gan (1993), the 100γ th ($0 < \gamma < 1$) percentile of the RL distribution, denoted by ℓ_γ is defined as

$$F_{RL}(\ell_\gamma - 1 | \mathbf{Q}, \mathbf{q}) \leq \gamma \quad \text{and} \quad F_{RL}(\ell_\gamma | \mathbf{Q}, \mathbf{q}) > \gamma, \quad (\text{A.5})$$

Moreover, the MRL of the one-sided exponential EWMA chart can be computed by setting $\gamma = 0.5$,

$$F_{RL}(MRL - 1 | \mathbf{Q}, \mathbf{q}) \leq 0.5 \quad \text{and} \quad F_{RL}(MRL | \mathbf{Q}, \mathbf{q}) > 0.5. \quad (\text{A.6})$$

For the upper-sided exponential EWMA chart, the interval between the reflecting boundary B^+ and the control limit h^+ is divided into N subintervals, each with width $\Delta^+ = \frac{h^+ - B^+}{N}$. When the number N of subintervals is sufficiently large ($N = 500$ in this paper), this finite approach provides an effective method that allows the RL properties to be accurately evaluated. The statistic Q_t^+ is said to be in transient state j at time t if $H_j^+ - \frac{\Delta^+}{2} \leq Q_t^+ < H_j^+ + \frac{\Delta^+}{2}$, where $H_j^+ = B^+ + (j - \frac{1}{2})\Delta^+$ ($j = 1, 2, \dots, N$) represents the midpoint of the j th sub-interval. The statistic Q_t^+ is in the absorbing state if Q_t^+ falls outside the control limits. Then, the transition probability $p_{i,j}$ is given as:

$$p_{i,j} = \begin{cases} \Pr(Q_t^+ < H_1^+ + \frac{\Delta^+}{2} | Q_{t-1}^+ = H_i^+) & \text{for } j = 1 \\ \Pr(H_j^+ - \frac{\Delta^+}{2} \leq Q_t^+ < H_j^+ + \frac{\Delta^+}{2} | Q_{t-1}^+ = H_i^+) & \text{for } j = 2, \dots, N \end{cases} \quad (\text{A.7})$$

After some algebraic calculations, we can obtain

$$p_{i,j} = \begin{cases} F\left(\frac{B^+ + \Delta^+ - (1-\lambda^+)H_i^+}{c\lambda^+}\right) & \text{for } j = 1 \\ F\left(\frac{H_j^+ + \frac{\Delta^+}{2} - (1-\lambda^+)H_i^+}{c\lambda^+}\right) - F\left(\frac{H_j^+ - \frac{\Delta^+}{2} - (1-\lambda^+)H_i^+}{c\lambda^+}\right) & \text{for } j = 2, \dots, N \end{cases} \quad (\text{A.8})$$

where $F(\cdot)$ is c.d.f. of the exponential distribution (see Eq. (2)).

Similarly, the transition probability $p_{i,j}$ of the lower-sided exponential EWMA chart can be obtained:

$$p_{i,j} = \begin{cases} 1 - F\left(\frac{B^- - \Delta^- - (1-\lambda^-)H_i^-}{c\lambda^-}\right) & \text{for } j = 1 \\ F\left(\frac{H_j^- + \frac{\Delta^-}{2} - (1-\lambda^-)H_i^-}{c\lambda^-}\right) - F\left(\frac{H_j^- - \frac{\Delta^-}{2} - (1-\lambda^-)H_i^-}{c\lambda^-}\right) & \text{for } j = 2, \dots, N \end{cases} \quad (\text{A.9})$$

where $H_j^- = B^- - (j - \frac{1}{2})\Delta^-$ ($j = 1, 2, \dots, N$) represents the midpoint of the j th sub-interval and $\Delta^- = \frac{B^- - h^-}{N}$. By using Eq. (A.6), one can easily compute the *MRL* of the upper- and lower-sided exponential EWMA charts.

If the process parameter is estimated, let $w = \theta_0/\hat{\theta}_0$ represents the ratio of the actual in-control mean to its estimator. It is known that w is distributed according to an inverse gamma distribution, denoted as $\text{IG}(m, m)$, and the p.d.f. of w is,

$$f_W(w) = \frac{m^m}{(m-1)!} w^{-m-1} e^{-\frac{m}{w}}. \quad (\text{A.10})$$

Since w is an independent random variable, the unconditional c.d.f. $F_{RL}(\ell|\hat{\mathbf{Q}}, \mathbf{q})$ and the *MRL* of the *RL* distribution can be obtained as follows:

$$F_{RL}(\ell|\hat{\mathbf{Q}}, \mathbf{q}) = \int_0^{+\infty} (1 - \mathbf{q}^\top \hat{\mathbf{Q}}^\ell \mathbf{1}) f_W(w) dw. \quad (\text{A.11})$$

$$F_{RL}(MRL - 1|\hat{\mathbf{Q}}, \mathbf{q}) \leq 0.5 \quad \text{and} \quad F_{RL}(MRL|\hat{\mathbf{Q}}, \mathbf{q}) > 0.5. \quad (\text{A.12})$$

where the *conditional* transition probability matrix $\hat{\mathbf{Q}} = [\hat{p}_{i,j}]_{N \times N}$ is computed as follows:

- For the upper-sided exponential EWMA chart with estimated parameters

$$\hat{p}_{i,j} = \begin{cases} F\left(\frac{B^+ + \Delta^+ - (1-\lambda^+)H_i^+}{wc\lambda^+}\right) & \text{for } j = 1 \\ F\left(\frac{H_j^+ + \frac{\Delta^+}{2} - (1-\lambda^+)H_i^+}{wc\lambda^+}\right) - F\left(\frac{H_j^+ - \frac{\Delta^+}{2} - (1-\lambda^+)H_i^+}{wc\lambda^+}\right) & \text{for } j = 2, \dots, N \end{cases} \quad (\text{A.13})$$

- For the lower-sided exponential EWMA chart with estimated parameters

$$\hat{p}_{i,j} = \begin{cases} 1 - F\left(\frac{B^- - \Delta^- - (1-\lambda^-)H_i^-}{wc\lambda^-}\right) & \text{for } j = 1 \\ F\left(\frac{H_j^- + \frac{\Delta^-}{2} - (1-\lambda^-)H_i^-}{wc\lambda^-}\right) - F\left(\frac{H_j^- - \frac{\Delta^-}{2} - (1-\lambda^-)H_i^-}{wc\lambda^-}\right) & \text{for } j = 2, \dots, N \end{cases} \quad (\text{A.14})$$

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Table 1: The percentiles of the RL distribution and ARL for the lower-sided exponential EWMA chart when $ARL_0 = 500$

| (λ^-, h^-) | c | ARL | 5th | 10th | 20th | 30th | 40th | 50th | 60th | 70th | 80th | 90th |
|--------------------|-----|-------|-----|------|------|------|------|------|------|------|------|------|
| (0.05,0.6861) | 1.0 | 500.1 | 39 | 65 | 122 | 187 | 262 | 351 | 459 | 599 | 797 | 1134 |
| | 0.8 | 74.8 | 19 | 23 | 31 | 39 | 48 | 58 | 71 | 87 | 110 | 149 |
| | 0.6 | 26.6 | 13 | 15 | 17 | 19 | 21 | 24 | 26 | 30 | 35 | 43 |
| | 0.4 | 14.9 | 10 | 11 | 12 | 13 | 13 | 14 | 15 | 16 | 17 | 20 |
| | 0.2 | 10.2 | 9 | 9 | 9 | 10 | 10 | 10 | 10 | 10 | 11 | 11 |
| (0.10,0.5450) | 1.0 | 500.2 | 35 | 62 | 119 | 185 | 260 | 350 | 459 | 600 | 799 | 1139 |
| | 0.8 | 91.0 | 16 | 21 | 30 | 41 | 53 | 67 | 85 | 107 | 139 | 193 |
| | 0.6 | 27.8 | 11 | 12 | 15 | 17 | 20 | 23 | 27 | 32 | 38 | 49 |
| | 0.4 | 13.5 | 8 | 9 | 10 | 11 | 12 | 12 | 13 | 15 | 16 | 19 |
| | 0.2 | 8.5 | 7 | 7 | 8 | 8 | 8 | 8 | 8 | 9 | 9 | 9 |
| (0.20,0.3793) | 1.0 | 500.2 | 32 | 59 | 117 | 183 | 259 | 349 | 459 | 601 | 801 | 1143 |
| | 0.8 | 122.1 | 14 | 20 | 34 | 49 | 66 | 87 | 113 | 145 | 192 | 271 |
| | 0.6 | 35.0 | 9 | 11 | 14 | 18 | 22 | 27 | 33 | 41 | 52 | 70 |
| | 0.4 | 13.6 | 7 | 7 | 8 | 9 | 11 | 12 | 13 | 15 | 18 | 22 |
| | 0.2 | 7.2 | 5 | 6 | 6 | 6 | 7 | 7 | 7 | 8 | 8 | 9 |
| (0.40,0.2045) | 1.0 | 500.0 | 30 | 57 | 115 | 181 | 258 | 348 | 459 | 601 | 802 | 1146 |
| | 0.8 | 175.4 | 14 | 23 | 43 | 66 | 92 | 123 | 161 | 210 | 279 | 398 |
| | 0.6 | 57.1 | 8 | 10 | 17 | 24 | 32 | 41 | 53 | 68 | 89 | 125 |
| | 0.4 | 18.5 | 5 | 6 | 8 | 10 | 12 | 14 | 17 | 21 | 27 | 36 |
| | 0.2 | 6.9 | 4 | 4 | 5 | 5 | 6 | 6 | 7 | 8 | 9 | 10 |
| (0.60,0.1091) | 1.0 | 499.6 | 29 | 55 | 114 | 180 | 257 | 347 | 458 | 601 | 802 | 1146 |
| | 0.8 | 221.2 | 15 | 26 | 52 | 81 | 115 | 154 | 203 | 266 | 354 | 505 |
| | 0.6 | 86.0 | 8 | 12 | 22 | 33 | 46 | 61 | 79 | 103 | 136 | 194 |
| | 0.4 | 28.8 | 5 | 6 | 9 | 13 | 16 | 21 | 27 | 34 | 44 | 62 |
| | 0.2 | 8.5 | 3 | 4 | 4 | 5 | 6 | 7 | 8 | 10 | 12 | 15 |
| (0.80,0.0492) | 1.0 | 500.6 | 28 | 55 | 114 | 180 | 257 | 348 | 459 | 602 | 804 | 1150 |
| | 0.8 | 267.5 | 16 | 30 | 62 | 97 | 138 | 186 | 245 | 322 | 429 | 613 |
| | 0.6 | 125.3 | 9 | 15 | 30 | 46 | 65 | 88 | 115 | 150 | 200 | 285 |
| | 0.4 | 48.2 | 5 | 7 | 13 | 19 | 26 | 34 | 44 | 57 | 76 | 108 |
| | 0.2 | 13.4 | 3 | 4 | 5 | 6 | 8 | 10 | 13 | 16 | 20 | 28 |
| (1.00,0.0020) | 1.0 | 500.5 | 26 | 53 | 112 | 179 | 256 | 347 | 459 | 602 | 805 | 1152 |
| | 0.8 | 400.5 | 21 | 43 | 90 | 143 | 205 | 278 | 367 | 482 | 644 | 922 |
| | 0.6 | 300.5 | 16 | 32 | 67 | 108 | 154 | 208 | 275 | 362 | 483 | 691 |
| | 0.4 | 200.5 | 11 | 22 | 45 | 72 | 103 | 139 | 184 | 241 | 322 | 461 |
| | 0.2 | 100.5 | 6 | 11 | 23 | 36 | 52 | 70 | 92 | 121 | 161 | 231 |

Table 2: The percentiles of the RL distribution and ARL for the upper-sided exponential EWMA chart when $ARL_0 = 500$

| (λ^+, h^+) | c | ARL | 5th | 10th | 20th | 30th | 40th | 50th | 60th | 70th | 80th | 90th |
|--------------------|-------|-------|-----|------|------|------|------|------|------|------|------|------|
| (0.05,1.4167) | 1.00 | 500.0 | 31 | 58 | 116 | 182 | 258 | 348 | 459 | 601 | 801 | 1144 |
| | 1.04 | 306.7 | 23 | 39 | 74 | 114 | 160 | 215 | 282 | 368 | 489 | 696 |
| | 1.40 | 35.5 | 7 | 9 | 14 | 18 | 23 | 28 | 34 | 42 | 53 | 72 |
| | 5.00 | 3.4 | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 5 | 6 |
| | 10.00 | 2.1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 4 |
| (0.10,1.7141) | 1.00 | 500.0 | 29 | 56 | 114 | 181 | 257 | 348 | 458 | 601 | 803 | 1147 |
| | 1.04 | 329.5 | 21 | 39 | 77 | 120 | 170 | 230 | 302 | 396 | 528 | 753 |
| | 1.40 | 39.6 | 5 | 8 | 13 | 18 | 23 | 30 | 37 | 47 | 61 | 84 |
| | 5.00 | 3.2 | 1 | 1 | 2 | 2 | 2 | 3 | 3 | 4 | 5 | 6 |
| | 10.00 | 1.9 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 |
| (0.20,2.2378) | 1.00 | 500.0 | 27 | 54 | 113 | 180 | 256 | 347 | 458 | 602 | 804 | 1149 |
| | 1.04 | 353.1 | 20 | 39 | 81 | 127 | 181 | 245 | 324 | 425 | 567 | 810 |
| | 1.40 | 48.4 | 5 | 8 | 13 | 19 | 26 | 35 | 45 | 58 | 76 | 108 |
| | 5.00 | 3.1 | 1 | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 6 |
| | 10.00 | 1.8 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 3 |
| (0.40,3.2213) | 1.00 | 500.0 | 27 | 54 | 112 | 179 | 256 | 347 | 458 | 602 | 804 | 1150 |
| | 1.04 | 374.7 | 20 | 40 | 84 | 134 | 192 | 260 | 343 | 451 | 602 | 861 |
| | 1.40 | 63.0 | 4 | 8 | 15 | 23 | 33 | 44 | 58 | 76 | 101 | 143 |
| | 5.00 | 3.1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 4 | 4 | 6 |
| | 10.00 | 1.8 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 |
| (0.60,4.2015) | 1.00 | 500.0 | 26 | 53 | 112 | 179 | 256 | 347 | 458 | 602 | 804 | 1150 |
| | 1.04 | 384.8 | 20 | 41 | 86 | 138 | 197 | 267 | 353 | 463 | 619 | 885 |
| | 1.40 | 73.2 | 5 | 8 | 17 | 27 | 38 | 51 | 67 | 88 | 117 | 167 |
| | 5.00 | 3.2 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 4 | 5 | 6 |
| | 10.00 | 1.8 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 3 |
| (0.80,5.1986) | 1.00 | 500.0 | 26 | 53 | 112 | 179 | 256 | 347 | 458 | 602 | 804 | 1151 |
| | 1.04 | 390.5 | 21 | 42 | 88 | 140 | 200 | 271 | 358 | 470 | 628 | 898 |
| | 1.40 | 80.1 | 5 | 9 | 18 | 29 | 41 | 56 | 73 | 96 | 129 | 184 |
| | 5.00 | 3.3 | 1 | 1 | 1 | 2 | 2 | 2 | 3 | 4 | 5 | 7 |
| | 10.00 | 1.8 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 3 |
| (1.00,6.2147) | 1.00 | 500.0 | 26 | 53 | 112 | 179 | 256 | 347 | 458 | 602 | 804 | 1151 |
| | 1.04 | 393.7 | 21 | 42 | 88 | 141 | 201 | 273 | 361 | 474 | 633 | 906 |
| | 1.40 | 84.7 | 5 | 9 | 19 | 31 | 44 | 59 | 78 | 102 | 136 | 194 |
| | 5.00 | 3.5 | 1 | 1 | 1 | 2 | 2 | 3 | 3 | 4 | 5 | 7 |
| | 10.00 | 1.9 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 3 |

Table 3: The MRL of the lower-sided exponential EWMA chart when $MRL_0 = 100$

| | | $\lambda^- = 0.1$ | | | | | | $\lambda^- = 0.3$ | | | | | |
|-----|----------------|-------------------|-------|-------|-------|-------|-------|-------------------|-------|-------|-------|-------|-------|
| c | B^- h^- | 1.0 | 1.5 | 2.0 | 2.3 | 2.5 | 5.0 | 1.0 | 1.5 | 2.0 | 2.3 | 2.5 | 5.0 |
| | | 0.591 | 0.629 | 0.631 | 0.631 | 0.631 | 0.630 | 0.323 | 0.344 | 0.348 | 0.348 | 0.348 | 0.348 |
| 1.0 | | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 0.9 | | 59 | 53 | 52 | 52 | 52 | 52 | 67 | 63 | 62 | 62 | 62 | 62 |
| 0.8 | | 37 | 31 | 31 | 31 | 31 | 30 | 44 | 40 | 39 | 39 | 39 | 39 |
| 0.7 | | 24 | 20 | 20 | 20 | 20 | 20 | 29 | 26 | 25 | 25 | 25 | 25 |
| 0.6 | | 17 | 15 | 14 | 14 | 14 | 14 | 19 | 17 | 16 | 16 | 16 | 16 |
| 0.5 | | 13 | 11 | 11 | 11 | 11 | 11 | 13 | 12 | 11 | 11 | 11 | 11 |
| 0.4 | | 10 | 9 | 9 | 9 | 9 | 9 | 9 | 8 | 8 | 8 | 8 | 8 |
| 0.3 | | 8 | 7 | 7 | 7 | 7 | 7 | 7 | 6 | 6 | 6 | 6 | 6 |
| 0.2 | | 7 | 6 | 6 | 6 | 6 | 6 | 5 | 5 | 5 | 5 | 5 | 5 |
| 0.1 | | 6 | 6 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 |
| | | $\lambda^- = 0.5$ | | | | | | $\lambda^- = 0.7$ | | | | | |
| c | B^- h^- | 1.0 | 1.5 | 2.0 | 2.3 | 2.5 | 5.0 | 1.0 | 1.5 | 2.0 | 2.3 | 2.5 | 5.0 |
| | | 0.190 | 0.201 | 0.204 | 0.205 | 0.205 | 0.205 | 0.106 | 0.110 | 0.112 | 0.113 | 0.113 | 0.113 |
| 1.0 | | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 0.9 | | 72 | 70 | 69 | 69 | 69 | 68 | 77 | 75 | 75 | 74 | 74 | 74 |
| 0.8 | | 51 | 48 | 47 | 47 | 46 | 46 | 57 | 55 | 54 | 54 | 54 | 54 |
| 0.7 | | 35 | 32 | 31 | 31 | 31 | 31 | 42 | 40 | 39 | 38 | 38 | 38 |
| 0.6 | | 24 | 22 | 21 | 21 | 21 | 21 | 29 | 28 | 27 | 27 | 27 | 26 |
| 0.5 | | 16 | 14 | 14 | 14 | 14 | 14 | 20 | 19 | 18 | 18 | 18 | 18 |
| 0.4 | | 11 | 10 | 9 | 9 | 9 | 9 | 13 | 12 | 12 | 12 | 12 | 12 |
| 0.3 | | 7 | 7 | 6 | 6 | 6 | 6 | 9 | 8 | 8 | 8 | 8 | 8 |
| 0.2 | | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 0.1 | | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |

Table 4: The MRL of the lower-sided exponential EWMA chart and the lower-sided exponential Shewhart chart when $MRL_0 \in \{100, 200, 300, 500\}$

| | | $MRL_0 = 100$ | | | | $MRL_0 = 200$ | | | | | |
|-------------|-------|---------------|-------|-------|-------|---------------|-------|-------|-------|-------|----------|
| | | EWMA | | | | Shewhart | EWMA | | | | Shewhart |
| c_{opt} | | 0.8 | 0.6 | 0.4 | 0.2 | | 0.8 | 0.6 | 0.4 | 0.2 | |
| λ^- | | 0.060 | 0.101 | 0.258 | 0.487 | $LCL =$ | 0.051 | 0.100 | 0.220 | 0.435 | $LCL =$ |
| c | h^- | 0.736 | 0.629 | 0.390 | 0.211 | 0.0069 | 0.716 | 0.579 | 0.386 | 0.207 | 0.0035 |
| 1.00 | | 100 | 100 | 100 | 100 | 100 | 200 | 200 | 200 | 200 | 200 |
| 0.90 | | 49 | 52 | 60 | 69 | 90 | 82 | 91 | 108 | 127 | 180 |
| 0.80 | | 29 | 31 | 37 | 46 | 80 | 43 | 48 | 60 | 80 | 160 |
| 0.70 | | 20 | 20 | 24 | 31 | 70 | 28 | 28 | 35 | 49 | 140 |
| 0.60 | | 14 | 14 | 16 | 21 | 60 | 20 | 19 | 21 | 30 | 120 |
| 0.50 | | 11 | 11 | 11 | 14 | 50 | 15 | 14 | 14 | 19 | 100 |
| 0.40 | | 9 | 9 | 8 | 9 | 40 | 12 | 11 | 10 | 12 | 80 |
| 0.30 | | 8 | 7 | 6 | 6 | 30 | 10 | 9 | 8 | 8 | 60 |
| 0.20 | | 7 | 6 | 5 | 5 | 20 | 9 | 7 | 6 | 5 | 40 |
| 0.10 | | 6 | 5 | 4 | 3 | 10 | 8 | 6 | 5 | 4 | 20 |
| 0.05 | | 6 | 5 | 4 | 3 | 5 | 7 | 6 | 5 | 4 | 10 |
| 0.03 | | 6 | 5 | 4 | 3 | 3 | 7 | 6 | 5 | 3 | 6 |
| 0.01 | | 5 | 5 | 4 | 3 | 1 | 7 | 6 | 4 | 3 | 2 |
| | | $MRL_0 = 300$ | | | | $MRL_0 = 500$ | | | | | |
| | | EWMA | | | | Shewhart | EWMA | | | | Shewhart |
| c_{opt} | | 0.8 | 0.6 | 0.4 | 0.2 | | 0.8 | 0.6 | 0.4 | 0.2 | |
| λ^- | | 0.052 | 0.089 | 0.196 | 0.407 | $LCL =$ | 0.051 | 0.079 | 0.180 | 0.375 | $LCL =$ |
| c | h^- | 0.688 | 0.580 | 0.392 | 0.206 | 0.0023 | 0.664 | 0.577 | 0.387 | 0.206 | 0.0014 |
| 1.00 | | 300 | 300 | 300 | 300 | 300 | 500 | 500 | 500 | 500 | 500 |
| 0.90 | | 111 | 124 | 150 | 183 | 270 | 161 | 179 | 229 | 288 | 450 |
| 0.80 | | 54 | 59 | 77 | 109 | 240 | 70 | 78 | 108 | 162 | 400 |
| 0.70 | | 33 | 34 | 42 | 64 | 210 | 40 | 41 | 55 | 90 | 350 |
| 0.60 | | 23 | 22 | 25 | 38 | 180 | 27 | 26 | 30 | 49 | 300 |
| 0.50 | | 17 | 16 | 16 | 22 | 150 | 20 | 18 | 19 | 28 | 250 |
| 0.40 | | 14 | 12 | 11 | 14 | 120 | 16 | 14 | 13 | 16 | 200 |
| 0.30 | | 11 | 10 | 9 | 9 | 90 | 13 | 11 | 10 | 10 | 150 |
| 0.20 | | 10 | 8 | 7 | 6 | 60 | 11 | 10 | 8 | 7 | 100 |
| 0.10 | | 8 | 7 | 6 | 4 | 30 | 9 | 8 | 6 | 5 | 50 |
| 0.05 | | 8 | 7 | 5 | 4 | 15 | 9 | 8 | 6 | 4 | 25 |
| 0.03 | | 8 | 7 | 5 | 4 | 9 | 9 | 7 | 6 | 4 | 15 |
| 0.01 | | 8 | 6 | 5 | 4 | 3 | 8 | 7 | 5 | 4 | 5 |

Table 5: The MRL of the upper-sided exponential EWMA chart and the upper-sided exponential Shewhart chart when $MRL_0 \in \{100, 200, 300, 500\}$

| | | $MRL_0 = 100$ | | | | | $MRL_0 = 200$ | | | | |
|-------|-------------|---------------|-------|-------|-------|----------|---------------|-------|-------|-------|----------|
| | | EWMA | | | | Shewhart | EWMA | | | | Shewhart |
| c | c_{opt} | 1.04 | 1.40 | 2.00 | 5.00 | $UCL =$ | 1.04 | 1.40 | 2.00 | 5.00 | $UCL =$ |
| | λ^+ | 0.054 | 0.086 | 0.318 | 0.525 | 4.9651 | 0.051 | 0.064 | 0.160 | 0.552 | 5.6616 |
| | h^+ | 1.297 | 1.448 | 2.376 | 3.154 | | 1.363 | 1.437 | 1.917 | 3.653 | |
| 1.00 | | 100 | 100 | 100 | 100 | 100 | 200 | 200 | 200 | 200 | 200 |
| 1.02 | | 84 | 85 | 88 | 90 | 90 | 161 | 163 | 169 | 177 | 179 |
| 1.04 | | 71 | 73 | 79 | 81 | 82 | 132 | 134 | 144 | 157 | 160 |
| 1.10 | | 47 | 49 | 57 | 60 | 63 | 80 | 82 | 94 | 113 | 119 |
| 1.20 | | 29 | 30 | 37 | 40 | 44 | 45 | 46 | 53 | 70 | 78 |
| 1.40 | | 16 | 16 | 19 | 21 | 24 | 22 | 22 | 24 | 34 | 40 |
| 2.00 | | 7 | 7 | 7 | 7 | 8 | 9 | 9 | 8 | 10 | 12 |
| 3.00 | | 4 | 4 | 3 | 3 | 4 | 5 | 5 | 4 | 4 | 5 |
| 5.00 | | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 2 |
| 10.00 | | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 1 |
| | | $MRL_0 = 300$ | | | | | $MRL_0 = 500$ | | | | |
| | | EWMA | | | | Shewhart | EWMA | | | | Shewhart |
| c | c_{opt} | 1.0 | 1.4 | 2.0 | 5.0 | $UCL =$ | 1.0 | 1.4 | 2.0 | 5.0 | $UCL =$ |
| | λ^+ | 0.051 | 0.055 | 0.141 | 0.596 | 6.0681 | 0.050 | 0.054 | 0.146 | 0.525 | 6.5798 |
| | h^+ | 1.407 | 1.432 | 1.907 | 4.094 | | 1.454 | 1.481 | 2.031 | 4.029 | |
| 1.00 | | 300 | 300 | 300 | 300 | 300 | 500 | 500 | 500 | 500 | 500 |
| 1.02 | | 235 | 237 | 248 | 263 | 266 | 380 | 382 | 407 | 432 | 439 |
| 1.04 | | 189 | 190 | 207 | 232 | 237 | 296 | 298 | 334 | 376 | 388 |
| 1.10 | | 108 | 110 | 129 | 164 | 173 | 157 | 160 | 198 | 255 | 275 |
| 1.20 | | 56 | 57 | 68 | 100 | 109 | 75 | 76 | 98 | 147 | 167 |
| 1.40 | | 26 | 26 | 29 | 46 | 53 | 32 | 32 | 38 | 62 | 76 |
| 2.00 | | 10 | 10 | 9 | 12 | 15 | 11 | 11 | 11 | 15 | 19 |
| 3.00 | | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 5 | 5 | 6 |
| 5.00 | | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 3 |
| 10.00 | | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 1 | 1 |

Table 6: The *MRL* and *ARL* of the lower-sided exponential EWMA chart when $MRL_0 = 350$ and $ARL_0 = 500$

| <i>MRL</i> -based with $MRL_0 = 350$ | | | | | | | | | |
|--|-------------|------------|-------------|------------|-------------|------------|-------------|------------|------------|
| | c_{opt} | 0.8 | | 0.6 | | 0.4 | | 0.2 | |
| | λ^- | 0.0510 | | 0.0830 | | 0.1480 | | 0.3950 | |
| | h^- | 0.6826 | | 0.5857 | | 0.4535 | | 0.2074 | |
| c | | <i>MRL</i> | <i>ARL</i> | <i>MRL</i> | <i>ARL</i> | <i>MRL</i> | <i>ARL</i> | <i>MRL</i> | <i>ARL</i> |
| 1.0 | | 350 | 499.2 | 350 | 500.4 | 350 | 501.6 | 350 | 502.6 |
| 0.9 | | 124 | 170.5 | 137 | 191.9 | 159 | 225.0 | 209 | 299.8 |
| 0.8 | | 58 | 75.0 | 64 | 85.4 | 77 | 106.6 | 123 | 175.0 |
| 0.7 | | 34 | 41.2 | 36 | 44.7 | 41 | 54.7 | 71 | 100.2 |
| 0.6 | | 24 | 26.6 | 23 | 27.1 | 25 | 30.9 | 41 | 56.6 |
| 0.5 | | 18 | 19.2 | 17 | 18.5 | 16 | 19.3 | 24 | 32.0 |
| 0.4 | | 14 | 14.8 | 13 | 13.7 | 12 | 13.3 | 14 | 18.3 |
| 0.3 | | 12 | 12.0 | 10 | 10.8 | 9 | 9.8 | 9 | 10.9 |
| 0.2 | | 10 | 10.1 | 9 | 8.9 | 7 | 7.7 | 6 | 6.9 |
| 0.1 | | 9 | 8.8 | 8 | 7.6 | 6 | 6.4 | 5 | 4.8 |
| <i>ARL</i> -based with $ARL_0 = 500.0$ | | | | | | | | | |
| | c_{opt} | 0.8 | | 0.6 | | 0.4 | | 0.2 | |
| | λ^- | 0.0501 | | 0.0530 | | 0.1446 | | 0.3519 | |
| | h^- | 0.6859 | | 0.6755 | | 0.4592 | | 0.2363 | |
| c | | <i>MRL</i> | <i>ARL</i> | <i>MRL</i> | <i>ARL</i> | <i>MRL</i> | <i>ARL</i> | <i>MRL</i> | <i>ARL</i> |
| 1.0 | | 350 | 499.6 | 350 | 499.5 | 349 | 499.9 | 348 | 500.0 |
| 0.9 | | 123 | 169.9 | 125 | 172.0 | 157 | 222.8 | 202 | 288.6 |
| 0.8 | | 58 | 74.8 | 59 | 75.7 | 76 | 105.2 | 115 | 163.5 |
| 0.7 | | 34 | 41.1 | 34 | 41.4 | 41 | 53.9 | 65 | 91.6 |
| 0.6 | | 24 | 26.6 | 24 | 26.6 | 24 | 30.5 | 37 | 51.1 |
| 0.5 | | 18 | 19.2 | 18 | 19.1 | 16 | 19.2 | 22 | 28.9 |
| 0.4 | | 14 | 14.9 | 14 | 14.7 | 12 | 13.2 | 13 | 16.9 |
| 0.3 | | 12 | 12.1 | 12 | 11.9 | 9 | 9.8 | 9 | 10.4 |
| 0.2 | | 10 | 10.2 | 10 | 10.0 | 7 | 7.7 | 6 | 6.9 |
| 0.1 | | 9 | 8.8 | 9 | 8.7 | 6 | 6.4 | 5 | 4.9 |

Table 7: The MRL and $EMRL$ of the lower-sided exponential EWMA chart and the lower-sided exponential Shewhart chart when $MRL_0 \in \{100, 200, 300, 500\}$

| | | $MRL_0 = 100$ | | | | $MRL_0 = 200$ | | | | | |
|------|----------------------------------|---------------|-----------|-----------|-----------|---------------|-----------|-----------|-----------|-----------|----------|
| | | EWMA | | | | Shewhart | EWMA | | | | Shewhart |
| | | [0.7,0.9] | [0.5,0.7] | [0.3,0.5] | [0.1,0.3] | $LCL =$ | [0.7,0.9] | [0.5,0.7] | [0.3,0.5] | [0.1,0.3] | $LCL =$ |
| c | Ω λ^- h^- | 0.050 | 0.093 | 0.244 | 0.510 | 0.0069 | 0.050 | 0.087 | 0.204 | 0.414 | 0.0035 |
| | $EMRL_1$ | 30.3 | 14.7 | 8.3 | 4.7 | - | 46.7 | 19.6 | 10.3 | 5.6 | - |
| 0.90 | | 48 | 52 | 60 | 69 | 90 | 82 | 89 | 106 | 126 | 180 |
| 0.80 | | 29 | 30 | 37 | 47 | 80 | 43 | 46 | 58 | 78 | 160 |
| 0.70 | | 19 | 20 | 23 | 32 | 70 | 27 | 28 | 34 | 48 | 140 |
| 0.60 | | 15 | 14 | 16 | 21 | 60 | 19 | 19 | 21 | 29 | 120 |
| 0.50 | | 12 | 11 | 11 | 14 | 50 | 15 | 14 | 14 | 18 | 100 |
| 0.40 | | 10 | 9 | 8 | 9 | 40 | 12 | 11 | 10 | 12 | 80 |
| 0.30 | | 8 | 7 | 6 | 6 | 30 | 10 | 9 | 8 | 8 | 60 |
| 0.20 | | 7 | 6 | 5 | 5 | 20 | 9 | 8 | 6 | 5 | 40 |
| 0.10 | | 6 | 6 | 4 | 3 | 10 | 8 | 7 | 5 | 4 | 20 |
| 0.05 | | 6 | 5 | 4 | 3 | 5 | 7 | 6 | 5 | 4 | 10 |
| 0.03 | | 6 | 5 | 4 | 3 | 3 | 7 | 6 | 5 | 4 | 6 |
| 0.01 | | 6 | 5 | 4 | 3 | 1 | 7 | 6 | 5 | 3 | 2 |
| | | $MRL_0 = 300$ | | | | $MRL_0 = 500$ | | | | | |
| | | EWMA | | | | Shewhart | EWMA | | | | Shewhart |
| | | [0.7,0.9] | [0.5,0.7] | [0.3,0.5] | [0.1,0.3] | $LCL =$ | [0.7,0.9] | [0.5,0.7] | [0.3,0.5] | [0.1,0.3] | $LCL =$ |
| c | Ω λ^- h^- | 0.050 | 0.085 | 0.179 | 0.370 | 0.0023 | 0.050 | 0.070 | 0.157 | 0.330 | 0.0014 |
| | $EMRL_1$ | 59.5 | 22.8 | 11.6 | 6.2 | - | 79.5 | 27.1 | 13.3 | 6.9 | - |
| 0.90 | | 111 | 122 | 146 | 178 | 270 | 160 | 173 | 219 | 276 | 450 |
| 0.80 | | 54 | 59 | 74 | 104 | 240 | 70 | 75 | 101 | 150 | 400 |
| 0.70 | | 33 | 33 | 41 | 60 | 210 | 40 | 40 | 51 | 81 | 350 |
| 0.60 | | 23 | 22 | 24 | 35 | 180 | 27 | 26 | 29 | 44 | 300 |
| 0.50 | | 17 | 16 | 16 | 21 | 150 | 20 | 19 | 18 | 25 | 250 |
| 0.40 | | 14 | 12 | 11 | 13 | 120 | 16 | 14 | 13 | 15 | 200 |
| 0.30 | | 11 | 10 | 9 | 9 | 90 | 13 | 12 | 10 | 10 | 150 |
| 0.20 | | 10 | 8 | 7 | 6 | 60 | 11 | 10 | 8 | 7 | 100 |
| 0.10 | | 9 | 7 | 6 | 5 | 30 | 9 | 8 | 6 | 5 | 50 |
| 0.05 | | 8 | 7 | 5 | 4 | 15 | 9 | 8 | 6 | 4 | 25 |
| 0.03 | | 8 | 7 | 5 | 4 | 9 | 9 | 8 | 6 | 4 | 15 |
| 0.01 | | 8 | 6 | 5 | 4 | 3 | 8 | 8 | 6 | 4 | 5 |

Table 8: The in-control MRL values for the lower-sided exponential EWMA chart with estimated parameters when $m \in \{5, 10, 20, 30, 50, 100, +\infty\}$ and $MRL_0 \in \{100, 300\}$

| | | $MRL_0 = 100$ | | | | $MRL_0 = 300$ | | | |
|-------------|-------|---------------|-------|-------|-------|---------------|-------|-------|-------|
| c_{opt} | | 0.8 | 0.6 | 0.4 | 0.2 | 0.8 | 0.6 | 0.4 | 0.2 |
| λ^- | | 0.060 | 0.101 | 0.258 | 0.487 | 0.052 | 0.089 | 0.196 | 0.407 |
| m | h^- | 0.736 | 0.629 | 0.390 | 0.211 | 0.688 | 0.580 | 0.392 | 0.206 |
| 5 | | 174 | 159 | 135 | 122 | 650 | 554 | 453 | 387 |
| 10 | | 127 | 123 | 114 | 109 | 421 | 392 | 356 | 332 |
| 20 | | 111 | 109 | 105 | 104 | 346 | 334 | 319 | 311 |
| 30 | | 106 | 105 | 103 | 102 | 326 | 318 | 310 | 305 |
| 50 | | 103 | 103 | 101 | 101 | 312 | 307 | 303 | 302 |
| 100 | | 101 | 101 | 101 | 100 | 303 | 301 | 300 | 300 |
| $+\infty$ | | 100 | 100 | 100 | 100 | 300 | 300 | 300 | 300 |

Table 9: The out-of-control 5th, 50th and 95th percentiles of RL distribution for the lower-sided exponential EWMA chart with estimated parameters when $m \in \{5, 10, 20, 30, 50, 100, +\infty\}$ and $MRL_0 = 300$

| c_{opt} | | 0.8 | | | 0.6 | | | 0.4 | | | 0.2 | | |
|-------------|-----|-------|----------|-----|-------|-------|-----|-------|------|-----|-------|------|--|
| λ^- | | 0.052 | | | 0.089 | | | 0.196 | | | 0.407 | | |
| h^- | | 0.688 | | | 0.580 | | | 0.392 | | | 0.206 | | |
| m | 5th | MRL | 95th | 5th | MRL | 95th | 5th | MRL | 95th | 5th | MRL | 95th | |
| 5 | 13 | 78 | $> 10^4$ | 9 | 26 | 87787 | 6 | 12 | 392 | 4 | 6 | 32 | |
| 10 | 14 | 64 | $> 10^4$ | 10 | 24 | 994 | 6 | 12 | 74 | 4 | 6 | 18 | |
| 20 | 15 | 58 | 5566 | 10 | 23 | 181 | 6 | 12 | 40 | 4 | 6 | 14 | |
| 30 | 16 | 57 | 1524 | 10 | 23 | 115 | 6 | 11 | 34 | 4 | 6 | 13 | |
| 50 | 16 | 56 | 595 | 10 | 22 | 83 | 6 | 11 | 30 | 4 | 6 | 13 | |
| 100 | 17 | 55 | 312 | 10 | 22 | 67 | 6 | 11 | 27 | 4 | 6 | 12 | |
| $+\infty$ | 17 | 54 | 174 | 11 | 22 | 55 | 6 | 11 | 25 | 4 | 6 | 12 | |