New Generalization of Length Biased Exponential Distribution with Applications

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Abstract. In this paper, a compound continuous distribution (i.e. Exponentiated length biased exponential (E-LBE) distribution) is given. Also, the statistical properties of the proposed distribution are examined, and the parameters are obtained by maximum likelihood estimation method. The flexibility, adequacy, and superiority of the proposed model were investigated by means of applications to dataset. The result indicates that the E-LBE distribution outperformed the competing distributions considered.

Keywords: Exponential distribution, length biased, exponential generalized family of distribution, maximum likelihood estimation, hazard functions, survival function, carbon fibre dataset, aircraft windshield dataset.

1 Introduction

Lifetime processes have recently received several attentions through the modelling of their distribution. The development of more composite but flexible distributions therefore depends on how the researchers can compound one or more distributions in order to form a better or comparable distribution [1]. The exponential distribution is used widely statistically to describe the time between events in a Poisson process. This makes the exponential distribution important for a process with continuously memoryless random processes with a constant failure rate; however, in real life it is almost impossible to produce this constant failure rate. Thus, to account for this disadvantage, some exponential distribution generalizations for modeling lifetime data have been recently proposed [2-3]. In recent years many exponential distribution generalizations have been developed, such as the Marshall Olkin length biased exponential distribution [4], exponentiated exponential [5-6], generalized exponentiated moment exponential [7], extended exponentiated exponential [8], Marshall-Olkin exponential Weibull [9], Marshall-Olkin generalized exponential [3], and exponentiated moment exponential [10] distributions.

A random variable $X$ is said to have a length biased exponential distribution with parameter $\beta$ if its probability density function (pdf) and cumulative distribution function (cdf) is given by equation (1) and (2) respectively [11]:

$$g(x; \beta) = \frac{x}{\theta} e^{-\frac{x^\beta}{\theta}}, \quad x > 0, \theta > 0$$

$$G(x) = 1 - \left(1 + \frac{x}{\theta}\right) e^{-x/\theta}, \quad x > 0, \theta > 0$$

where $\theta$ is the scale parameter.

Cordeiro et al. [12] proposed a new way of adding two parameters to a continuous distribution. For a given continuous baseline cumulative distribution function, they defined the cdf and pdf of the exponentiated generalized family of distributions with two extra shape parameters $\alpha > 0$ and $\beta > 0$ given by

$$F(x) = \left(1 - [1 - G(x)]^\alpha\right)^\beta$$

and

$$f(x) = \alpha \beta g(x)[1 - G(x)]^{\alpha-1}[1 - [1 - G(x)]^\alpha]^{\beta-1}$$

respectively, where $\alpha$ and $\beta$ are additional shape parameters.
Thus, we proposed a new generalization of the length biased exponential distribution called the Exponentiated length biased exponential (E-LBE) distribution for modeling lifetime data due to some interesting properties such as “lack of memory”. In the rest of the paper, we define the E-LBE densities, the survival and hazard functions, and plots for different parameter values in Section 2; some of the statistical properties of the proposed E-LBE distribution are discussed in minute details in section 3. Application of the E-LBE distribution to lifetime data in section 4. The concluding remark is presented in section 5.

2 Exponentiated Length Biased Exponential (E-LBE) Distribution

We extend a one parameter length biased exponential distribution to a three parameter E-LBE. The density functions are clearly stated below.

The cumulative distribution function of the E-LBE distribution is given by
\[
F_{E-LBE}(x) = \left\{ 1 - \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha} \right\}^\beta , \quad \alpha > 0, \beta > 0, \theta = 0 \tag{5}
\]

The corresponding probability density function is given by
\[
f_{E-LBE}(x) = \alpha \beta \theta^{-x} \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha-1} \left[ 1 - \left( \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right)^{\alpha} \right]^{\beta-1} , \quad \alpha > 0, \beta > 0, \theta = 0 \tag{6}
\]

The survival function is given by
\[
S_{E-LBE}(x) = 1 - \left\{ 1 - \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha} \right\}^\beta , \quad \alpha > 0, \beta > 0, \theta = 0 \tag{7}
\]

The hazard, reverse hazard and cumulative hazard function is given by equation (8), (9), (10) respectively
\[
h_{E-LBE}(x) = \frac{\alpha \beta \theta^{-x} \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha-1} \left[ 1 - \left( \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right)^{\alpha} \right]^{\beta-1}}{1 - \left( 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right)^{\alpha} } , \quad \alpha > 0, \beta > 0, \theta = 0 \tag{8}
\]
\[
r_{E-LBE}(x) = \frac{\alpha \beta \theta^{-x} \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha-1} \left[ 1 - \left( \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right)^{\alpha} \right]^{\beta-1}}{\left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha} } , \quad \alpha > 0, \beta > 0, \theta = 0 \tag{9}
\]
\[
H_{E-LBE}(x) = -\log \left\{ 1 - \left\{ 1 - \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha} \right\}^\beta \right\} , \quad \theta > 0, \gamma > 0, \beta = 0 \tag{10}
\]

The odd of the E-LBE distribution is given by
\[
O_{E-LBE}(x) = \frac{\left\{ 1 - \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha} \right\}^\beta}{1 - \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha} } , \quad \alpha > 0, \beta > 0, \theta = 0 \tag{11}
\]

The plots for different parameter values of the E-LBE distribution are given in figure 1-4 below.

![Figure 1. cdf plot of the E-LBE at different parameter values.](image-url)
Figure 2. pdf plot of the E-LBE at different parameter values.

Figure 3. Survival plot of the E-LBE distribution at different parameter values.

Figure 4. Hazard plot of the E-LBE distribution at different parameter values.
3 Some Statistical Properties of the E-LBE Distribution

In this section, we examine in minute details, some basic properties such as the asymptotic behavior, parameter estimation and order statistics of the E-LBE distribution.

3.1 Asymptotic Behavior

The behavior of the E-LBE model in equation (6) is examined as \( x \to 0 \) and as \( x \to \infty \).

\[
\lim_{x \to 0} f_{E-LBE}(x) = \lim_{x \to 0} \theta^{-2} x^{-\gamma/\theta} \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha-1} \left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\beta-1} = 0
\]

\[
\lim_{x \to \infty} f_{E-LBE}(x) = \lim_{x \to \infty} \theta^{-2} x^{-\gamma/\theta} \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha-1} \left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\beta-1} = 0
\]

This clearly shows that the Exponentiated length biased exponential distribution is unimodal. A clear observation of figure 2 shows the E-LBE model has only one peak. This supports our claim that the E-LBE distribution has only one mode. It can also be shown that for the E-LBE distribution,

\[
\lim_{x \to \infty} F(x) = \lim_{x \to \infty} \left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha-1} \left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\beta} = 1
\]

3.2 Parameter Estimation

Using maximum likelihood estimation techniques, we estimate the unknown parameter of the E-LBE model based on a complete sample. Let \( X_1, \ldots, X_n \) indicate a random sample of the complete E-LBE distribution data, and then the sample's likelihood function is given as

\[
L = \prod_{i=1}^{n} f(x_i; \alpha, \beta, \theta)
\]

where

\[
L = \prod_{i=1}^{n} \theta^{-2} x_i^{-\gamma/\theta} \left[ \left( 1 + \frac{x_i}{\theta} \right) e^{-x_i/\theta} \right]^{\alpha-1} \left[ 1 - \left( 1 + \frac{x_i}{\theta} \right) e^{-x_i/\theta} \right]^{\beta-1}
\]

The log likelihood function may be expressed as

\[
L(x) = n \ln \alpha - n \ln \beta - 2 n \ln \theta - \alpha \sum_{i=1}^{n} \frac{x_i}{\theta} + \sum_{i=1}^{n} \ln x_i + (\alpha - 1) \sum_{i=1}^{n} \left( 1 + \frac{x_i}{\theta} \right) + (\beta - 1) \sum_{i=1}^{n} \ln \left[ 1 - \left( 1 + \frac{x_i}{\theta} \right) e^{-x_i/\theta} \right]^{\alpha-1} \left[ 1 - \left( 1 + \frac{x_i}{\theta} \right) e^{-x_i/\theta} \right]^{\beta} \]

By taking the derivative with respect to \( \alpha, \beta \), and \( \theta \) and fixing the outcome to zero, we have

\[
\frac{\partial L(x)}{\partial \theta} = -2 n + \alpha \sum_{i=1}^{n} \frac{x_i}{\theta^2} - (\alpha - 1) \sum_{i=1}^{n} \frac{x_i}{\theta^2} + \frac{a(\beta-1) \sum_{i=1}^{n} \left( 1 + \frac{x_i}{\theta} \right) e^{-x_i/\theta}}{1 - \frac{\left( 1 + \frac{x_i}{\theta} \right) e^{-x_i/\theta}}{\left( \frac{x_i}{\theta} \right) e^{-x_i/\theta}}} = 0
\]

\[
\frac{\partial L(x)}{\partial \alpha} = \frac{n}{\alpha} - \frac{\sum_{i=1}^{n} \frac{x_i}{\theta} + \sum_{i=1}^{n} \left( 1 + \frac{x_i}{\theta} \right) - \frac{\beta-1 \sum_{i=1}^{n} \left( 1 + \frac{x_i}{\theta} \right) e^{-x_i/\theta}}{\left( \frac{x_i}{\theta} \right) e^{-x_i/\theta}}}{1 - \frac{\left( 1 + \frac{x_i}{\theta} \right) e^{-x_i/\theta}}{\left( \frac{x_i}{\theta} \right) e^{-x_i/\theta}}} = 0
\]

\[
\frac{\partial L(x)}{\partial \beta} = \frac{n}{\beta} + \sum_{i=1}^{n} \ln \left[ 1 - \left( 1 + \frac{x_i}{\theta} \right) e^{-x_i/\theta} \right]^{\alpha-1} \left[ 1 - \left( 1 + \frac{x_i}{\theta} \right) e^{-x_i/\theta} \right]^{\beta} = 0
\]

Solving equation (18)-(20) iteratively, will give the estimate of the parameters of the E-LBE model.

3.3 Order Statistics

We considered a random sample denoted by \( X_1, \ldots, X_n \) from the densities of the E-LBE distribution. Then,

\[
f_{X_{(i)}}(x) = \frac{n!}{(i-1)!(n-i)!} f_{E-LBE}(x) F_{E-LBE}(x)^{i-1} \left[ 1 - F_{E-LBE}(x) \right]^{n-i}
\]

The probability density function of the \( i \)th order statistics for the E-LBE distribution is given as

\[
f_{X_{(i)}}(x) = \frac{n!}{(i-1)!(n-i)!} \alpha \beta \gamma/\theta \left[ \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha-1} \left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\beta-1} \left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\alpha-1} \left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\beta} = 1
\]

The E-LBE distribution has minimum order statistics given as
\[ f_{1,n}(x) = a \beta (1 + \frac{x}{\theta})^{-1} \left( \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right)^{a-1} \left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\beta-1} \]  

And maximum order statistics given as

\[ f_{n,n}(x) = n a \beta (1 + \frac{x}{\theta})^{-1} \left( \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right)^{a-1} \left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\beta-1} \left[ 1 - \left( 1 + \frac{x}{\theta} \right) e^{-x/\theta} \right]^{\beta n-1} \]  

(17)  

(18)

### 4 Data Analysis

Here, the importance and flexibility of the Exponentiated length biased exponential distribution by comparing the results of the model fit with that of other Exponentiated- G family of distributions. Two dataset were used in this study to compare between fits of the Exponentiated length biased exponential distribution (E-LBE) with that of Exponentiated Generalized Extended Exponential (E-E) [13], Exponentiated-Lomax (E-L) [14], and, Exponentiated-Weibull (E-W) [15]. The first data set being The tensile strength of 100 carbon fibers reported by [16, 17, 18, 19], and the second being the Aircraft Windshield dataset reported by [20]. Several criterions were used to determine the distribution for the best fit: Akaike Information Criteria (AIC), Consistent Akaike Information Criteria (CAIC), Bayesian Information Criteria (BIC), and Hannan and Quinn Information Criteria (HQIC). The Shapiro Wilk (S-W), Anderson Darling (A) statistic and Kolmogorov Smirnov (KS) statistic were also provided.

#### Data I. Tensile strength of carbon fibre

| 3.7, 3.11, 4.42, 3.28, 3.75, 2.96, 3.39, 3.31, 3.15, 2.81, 1.41, 2.76, 3.19, 1.59, 2.17, 3.51, 0.84, 1.61, 1.57, 1.89, 2.74, 3.27, 2.41, 3.09, 2.43, 2.53, 2.81, 3.31, 2.35, 2.77, 2.68, 4.91, 1.57, 2.00, 1.17, 2.17, 0.39, 2.79, 1.08, 2.88, 2.73, 2.87, 3.19, 1.87, 2.95, 2.67, 4.20, 2.85, 2.55, 2.17, 2.97, 3.68, 0.81, 1.22, 5.08, 1.69, 3.68, 4.70, 2.03, 2.82, 2.50, 1.47, 3.22, 3.15, 2.97, 2.93, 3.33, 2.56, 2.59, 2.83, 1.36, 1.84, 5.56, 1.12, 2.48, 1.25, 2.48, 2.03, 1.61, 2.05, 3.60, 3.11, 1.69, 4.90, 3.39, 3.22, 2.25, 3.56, 2.38, 1.92, 0.98, 1.59, 1.73, 1.71, 1.18, 4.38, 0.85, 1.80, 2.12, 3.65.

#### Table 1. Descriptive statistics

<table>
<thead>
<tr>
<th>Min.</th>
<th>1st Qu.</th>
<th>Median</th>
<th>Mean</th>
<th>3rd Qu.</th>
<th>Max.</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.39</td>
<td>1.830</td>
<td>2.675</td>
<td>2.601</td>
<td>3.197</td>
<td>5.560</td>
<td>0.3590264</td>
<td>3.126169</td>
<td>1.042162</td>
</tr>
</tbody>
</table>

From Table 1, we noticed that the data set is slightly positively skewed with the coefficient of Skewness being 0.3590264 and a variance of 1.042162.

#### Table 2. MLEs, SW, AD and K-S of parameters for carbon fibre data

<table>
<thead>
<tr>
<th>Model</th>
<th>Estimates</th>
<th>SW</th>
<th>K-S</th>
<th>AD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \hat{\alpha} )</td>
<td>( \hat{\beta} )</td>
<td>( \hat{\theta} )</td>
<td>( \hat{\gamma} )</td>
</tr>
<tr>
<td>E-LBE (Proposed Model)</td>
<td>0.1258965</td>
<td>2.352451</td>
<td>0.802146</td>
<td>-</td>
</tr>
<tr>
<td>E-E</td>
<td>1.000577</td>
<td>7.369123</td>
<td>1.000591</td>
<td>-</td>
</tr>
<tr>
<td>E-L</td>
<td>7.2779943</td>
<td>7.7351071</td>
<td>0.01976084</td>
<td>7.27799442</td>
</tr>
<tr>
<td>E-W</td>
<td>0.4738824</td>
<td>1.2467461</td>
<td>0.5004734</td>
<td>2.4426383</td>
</tr>
</tbody>
</table>

For all competing distributions using the strength of carbon fibre data set, Table 2 shows parameter estimate and the value for the Shapiro Wilk (S-W), Anderson Darling (AD), Kolmogorov Smirnov (K-S) statistic.
Table 3. Log-likelihood, AIC, AICC, BIC and HQIC values of models fitted for carbon fibre data

<table>
<thead>
<tr>
<th>Model</th>
<th>Negative LL</th>
<th>AIC</th>
<th>CAIC</th>
<th>BIC</th>
<th>HQIC</th>
<th>P-VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-LBE (Proposed Model)</td>
<td>141.102</td>
<td>287.0541</td>
<td>287.0711</td>
<td>297.4529</td>
<td>293.0452</td>
<td>0.9245884</td>
</tr>
<tr>
<td>E-E</td>
<td>147.627</td>
<td>300.0541</td>
<td>300.3041</td>
<td>307.8696</td>
<td>303.2172</td>
<td>0.1358611</td>
</tr>
<tr>
<td>E-L</td>
<td>147.5959</td>
<td>303.1957</td>
<td>303.6168</td>
<td>313.6164</td>
<td>307.4312</td>
<td>0.1253873</td>
</tr>
<tr>
<td>E-W</td>
<td>142.0108</td>
<td>292.0215</td>
<td>292.4426</td>
<td>302.4422</td>
<td>296.239</td>
<td>0.7624059</td>
</tr>
</tbody>
</table>

From Table 3, the E-LBE has the highest log-likelihood values of -141.102 and the lowest AIC, CAIC, BIC and HQIC values of 287.0541, 287.0711, 297.4529, and 293.0452 respectively. For this reason, it is chosen as the most appropriate model amongst the considered models.

Data II. Aircraft windshield data set

0.040, 1.866, 2.385, 3.443, 0.301, 1.876, 2.481, 3.467, 0.309, 1.899, 2.610, 3.478, 0.557, 1.911, 2.625, 3.578, 0.943, 1.912, 2.632, 3.595, 1.070, 1.914, 2.646, 3.699, 1.124, 1.981, 2.661, 3.779, 1.248, 2.010, 2.688, 3.924, 1.281, 2.038, 2.823, 4.035, 1.281, 2.085, 2.890, 4.121, 1.303, 2.089, 2.902, 4.167, 1.432, 2.097, 2.962, 4.240, 1.480, 2.135, 2.964, 4.255, 1.505, 2.154, 2.964, 4.278, 1.506, 2.194, 3.000, 4.305, 1.568, 2.194, 3.103, 4.376, 1.615, 2.223, 3.114, 4.449, 1.619, 2.224, 3.117, 4.485, 1.652, 2.229, 3.166, 4.570, 1.652, 2.300, 3.344, 4.602, 1.757, 2.324, 3.376, 4.663.

Table 4. Descriptive statistics for the aircraft windshield dataset

<table>
<thead>
<tr>
<th>Min.</th>
<th>1st Qu.</th>
<th>Median</th>
<th>Mean</th>
<th>3rd Qu.</th>
<th>Max.</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.040</td>
<td>1.839</td>
<td>2.354</td>
<td>2.557</td>
<td>3.393</td>
<td>4.663</td>
<td>0.09949403</td>
<td>2.347684</td>
<td>1.251768</td>
</tr>
</tbody>
</table>

From Table 4, we noticed that the data set is slightly positively skewed with the coefficient of Skewness being 0.09949403 and a variance of 1.251768.

Table 5. MLEs, SW, AD and K-S of parameters for aircraft windshield dataset

<table>
<thead>
<tr>
<th>Model</th>
<th>Estimates</th>
<th>SW</th>
<th>K-S</th>
<th>AD</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-LBE (Proposed Model)</td>
<td>0.1257653</td>
<td>4.1026541</td>
<td>1.4523654</td>
<td>-</td>
</tr>
<tr>
<td>E-E</td>
<td>0.8705868</td>
<td>3.5604763</td>
<td>0.8705865</td>
<td>-</td>
</tr>
<tr>
<td>E-L</td>
<td>7.6953774</td>
<td>3.6256491</td>
<td>0.01311515</td>
<td>7.6953724</td>
</tr>
<tr>
<td>E-W</td>
<td>0.08926839</td>
<td>0.46205683</td>
<td>0.51865065</td>
<td>3.90195906</td>
</tr>
</tbody>
</table>

For all competing distributions using the strength of Aircraft Windshield Dataset, Table 5 shows parameter estimate and the value for the Shapiro Wilk (S-W), Anderson Darling (AD), Kolmogorov Smirnov (K-S) statistic.

Table 6. Log-likelihood, AIC, AICC, BIC and HQIC values of models fitted for aircraft windshield dataset

<table>
<thead>
<tr>
<th>Model</th>
<th>Negative LL</th>
<th>AIC</th>
<th>CAIC</th>
<th>BIC</th>
<th>HQIC</th>
<th>P-VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-LBE (Proposed Model)</td>
<td>126.9004</td>
<td>260.1845</td>
<td>261.0147</td>
<td>270.9546</td>
<td>264.7480</td>
<td>0.9251659</td>
</tr>
<tr>
<td>E-E</td>
<td>139.8405</td>
<td>285.681</td>
<td>285.981</td>
<td>292.9735</td>
<td>288.6125</td>
<td>0.1711434</td>
</tr>
<tr>
<td>E-L</td>
<td>140.4336</td>
<td>288.8672</td>
<td>289.3736</td>
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<td>292.7759</td>
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<tr>
<td>E-W</td>
<td>127.9121</td>
<td>263.8243</td>
<td>264.3396</td>
<td>273.5476</td>
<td>267.7330</td>
<td>0.8596897</td>
</tr>
</tbody>
</table>

From Table 6, the E-LBE has the highest log-likelihood values of -126.9004 and the lowest AIC, CAIC, BIC and HQIC values of 260.1845, 261.0147, 270.9546, and 264.7480 respectively. Hence, it is chosen as the best model amongst the considered models.
5 Conclusion

The E-LBE distribution has been successfully introduced in this paper and some of its basic statistical properties have been obtained. The pdf of the model and its failure rate have unimodal shapes; this means that the model would be useful to fit real-life events with unimodal failure rates. The model is tractable and flexible and shows high modeling capability as it performs better than the Exponentiated exponential, Exponentiated Lomax, and Exponentiated Weibull distributions; this was judged based on the AIC, CAIC, BIC, NLL and HQIC values of these distributions. The E-LBE distribution is of no doubt a competitive model, and it is hoped that it would be of use in fields like engineering, biology and medicine. Some other statistical properties of the distribution (which were not considered in this paper) can be explored and simulation study can also be conducted.

References