The Economic Design of the Double Sampling $\bar{X}$ Chart with Measurement Errors

K. S. Khee Yong Si^{1*}, Ming Ha Lee², XinYing Chew³, Man F. Lau⁴,
Kong Melinda⁵ and H. H. Then Patrick⁶, S. Rashid⁷

^{1, 2, 6}*Faculty of Engineering, Computing and Sciences, Swinburne University of Technology Sarawak Campus, Kuching, Sarawak, Malaysia.*

³*School of Computer Sciences, Universiti Sains Malaysia, Pulau Pinang, Malaysia.*

⁴*School of Software and Electrical Engineering, Swinburne University of Technology, Melbourne, Australia.*

⁵*Faculty of Business, Design and Arts, Swinburne University of Technology Sarawak Campus, Kuching, Sarawak, Malaysia.*

⁷*Department of Mathematics, College of Basic Science, Yadegar-e-Imam Khomeini (RAH) Branch, Islamic Azad University, Tehran, Iran.*

ABSTRACT

Objective: The purpose of this study is to investigate the effect of measurement errors on the economic design of the double sampling (DS) $\bar{X}$ chart. **Methods/Statistical analysis:** The economic design of the DS $\bar{X}$ chart with measurement errors is investigated by using the linear covariate error model. The optimal design parameters of the DS $\bar{X}$ chart are determined through the minimization of the cost function. The effect of the measurement errors is evaluated based on the numerical example over a wide range of the parameters of the measurement errors, where the parameters of the measurement errors are the coefficient B and the measurement error ratio. **Findings:** The numerical results show that an increase in the value of the coefficient B or a decrease in the value of the measurement error ratio in the linear covariate error model leads to the lower false alarm rate and cost with more frequent sampling interval and

*Author for correspondence

smaller number of multiple measurements per item. It can be noticed that the sample sizes at the first and second stages of the DS scheme as well as the out-of-control statistical performance of the DS $\bar{X}$ chart are robust to the measurement errors. In addition, the warning and control limits of the DS $\bar{X}$ chart are also not affected by the measurement errors. **Application/Improvements:** An example is provided to illustrate the implementation of the economic design of the DS $\bar{X}$ chart with measurement errors.

Keywords: cost function, double sampling, linear covariate error model, measurement errors, $\bar{X}$ chart.

1. INTRODUCTION

Shewhart $\bar{X}$ chart proposed by [1] is one of the statistical process control tools used in industries for product quality improvements. However, the Shewhart $\bar{X}$ chart is insensitive to small and moderate shifts. In order to improve the sensitivity of the Shewhart $\bar{X}$ chart, [2] introduced the double sampling (DS) $\bar{X}$ chart by applying two stages of the sampling scheme to monitor the process mean.

Control charts are usually designed by assuming that there is no measurement error in the quality characteristic but measurement errors do exist and this affects the performance of the control charts. A linear covariate error model was proposed by [3] to study the effect of measurement errors on the performance of the $\bar{X}$ and S^2 charts. Their results showed that the presence of measurement errors deteriorates the performance of the control charts. After that, their linear covariate error model has been used in many research works (see, for example [4–7]) to evaluate the performance of control charts with measurement errors.

A unified approach for the cost model of the control charts was proposed by [8], where the cost model is a modification of the earlier work in [9]. The cost model in [8] was used by [10], [11], [12] and [13] for designing the DS $\bar{X}$ chart, the DS s chart, the DS T^2 chart and the synthetic DS $\bar{X}$ chart, respectively, under the assumption of no measurement error. Then, the linear covariate error model in [3] was used by [14] and [15] to investigate the effect of measurement errors on the economic design of the EWMA $\bar{X}$ chart and the upper-sided synthetic S^2 chart, respectively. Their results showed that the cost is affected by the measurement errors.

In this study, the cost model in [8] is adopted for the economic design of the DS $\bar{X}$ chart by applying the linear covariate error model in [3]. The remainder of this paper is organized as follows: Section 2 introduces the DS $\bar{X}$ chart with measurement errors. The cost function for the DS $\bar{X}$ chart with measurement errors as well as the methodology to determine the optimal design parameters for the DS $\bar{X}$ chart are presented in Section 3. An illustrative example is provided in Section 4. The effect of measurement errors on the economic design of the DS $\bar{X}$ chart is investigated in Section 5. Finally, some conclusions are drawn in Section 6.

2. DOUBLE SAMPLING $\bar{X}$ CHART WITH MEASUREMENT ERRORS

Assume that Y_{ij} is the true value of the quality characteristic to be monitored during the process, in which sample $i = 1, 2, 3, \dots$ are taken from the process with the sample of size n_S , where n_1 ($S = 1$) is the small sample size and n_2 ($S = 2$) is the large sample size. It is also assumed that Y_{ij} follows a normal distribution with the mean of $\mu_0 + \delta\sigma_0$ and the standard deviation of σ_0 , where μ_0 , σ_0 and δ are the known in-control process mean, the known in-control process standard deviation and the standardized mean shift, respectively. Note that $\delta = 0$ when the process is in-control, while $\delta \neq 0$ when the process is out-of-control, where the process mean is shifted from $\mu = \mu_0$ to $\mu = \mu_0 + \delta\sigma_0$. As suggested by [3], the true value of the quality characteristic Y_{ij} cannot be observed directly but it can be estimated from X_{ijk} , for $k = 1, 2, 3, \dots, m$, where m is the number of multiple measurements per item in a sample. The relationship between X_{ijk} and Y_{ij} can be described by using the linear covariate error model as follows:

$$X_{ijk} = A + BY_{ij} + \varepsilon_{ijk}, \quad (1)$$

where A and B are the known constants. Here, ε_{ijk} is the normal random error term with the mean of 0 and the standard deviation of σ_ε . The sample mean for each sample is given as

$$\bar{X}_{is} = \frac{1}{mn_S} \sum_{j=1}^{n_S} \sum_{k=1}^m X_{ijk}. \quad (2)$$

Based on the DS scheme in [2], $n_S = n_1$ is the sample size taken at the first stage of the DS scheme, whereas $n_S = n_2$ is the additional sample size taken at the second stage of the DS scheme. Substituting (1) into (2) gives

$$\bar{X}_{is} = A + \frac{1}{n_S} \left(B \sum_{j=1}^{n_S} Y_{ij} + \frac{1}{m} \sum_{j=1}^{n_S} \sum_{k=1}^m \varepsilon_{ijk} \right). \quad (3)$$

The sample mean for the DS scheme is obtained as

$$\bar{X}_i = \begin{cases} \bar{X}_{i1} & \text{at the first stage of the DS scheme} \\ \frac{n_1 \bar{X}_{i1} + n_2 \bar{X}_{i2}}{n_1 + n_2} & \text{at the second stage of the DS scheme} \end{cases}. \quad (4)$$

The mean and variance of the sample mean are computed as

$$E(\bar{X}_i) = A + B\mu \quad (5)$$

and

$$V(\bar{X}_i) = \frac{1}{n} \left(B^2 \sigma_0^2 + \frac{\sigma_\varepsilon^2}{m} \right), \quad (6)$$

respectively, where $n = n_1$ is the sample size for the first stage of the DS scheme, while

$n = (n_1 + n_2)$ is the sample size for the second stage of the DS scheme. Consequently, the warning and control limits of the DS $\bar{X}$ chart with measurement errors are given as

$$LCL_1 = A + B\mu_0 - k_1 \sqrt{\frac{1}{n_1} \left(B^2 \sigma_0^2 + \frac{\sigma_\varepsilon^2}{m} \right)}, \quad (7)$$

$$LWL = A + B\mu_0 - w \sqrt{\frac{1}{n_1} \left(B^2 \sigma_0^2 + \frac{\sigma_\varepsilon^2}{m} \right)}, \quad (8)$$

$$UWL = A + B\mu_0 + w \sqrt{\frac{1}{n_1} \left(B^2 \sigma_0^2 + \frac{\sigma_\varepsilon^2}{m} \right)}, \quad (9)$$

$$UCL_1 = A + B\mu_0 + k_1 \sqrt{\frac{1}{n_1} \left(B^2 \sigma_0^2 + \frac{\sigma_\varepsilon^2}{m} \right)}, \quad (10)$$

$$LCL_2 = A + B\mu_0 - k_2 \sqrt{\frac{1}{n_1 + n_2} \left(B^2 \sigma_0^2 + \frac{\sigma_\varepsilon^2}{m} \right)} \quad (11)$$

and

$$UCL_2 = A + B\mu_0 + k_2 \sqrt{\frac{1}{n_1 + n_2} \left(B^2 \sigma_0^2 + \frac{\sigma_\varepsilon^2}{m} \right)}, \quad (12)$$

where LCL_1 , LWL , UWL , UCL_1 are the lower control limit, the lower warning limit, the upper warning limit and the upper control limit at the first stage of the DS scheme, respectively; while LCL_2 and UCL_2 are the lower control limit and the upper control limit at the second stage of the DS scheme, respectively.

The sample statistic plotted on the DS $\bar{X}$ chart is the standardized value of $\bar{X}_i$ that can be calculated as

$$Z_i = \frac{\bar{X}_i - (A + B\mu_0)}{\sqrt{\frac{1}{n} \left(B^2 \sigma_0^2 + \frac{\sigma_\varepsilon^2}{m} \right)}}. \quad (13)$$

Then, the warning and control limits of the DS $\bar{X}$ chart can be simplified to $LCL_1 = -k_1$, $LWL = -w$, $UWL = w$, $UCL_1 = k_1$, $LCL_2 = -k_2$ and $UCL_2 = k_2$, with the regions of the DS $\bar{X}$ chart are: $I_1 = [-w, w]$, $I_2 = [-k_1, -w] \cup [w, k_1]$, $I_3 = [-k_2, k_2]$, $I_4 = (-\infty, -k_1) \cup (k_1, \infty)$ and $I_5 = (-\infty, -k_2) \cup (k_2, \infty)$. Here I_1 , I_2 and I_3 are the in-control regions, while I_4 and I_5 are the out-of-control regions. These regions are constructed in a single control chart with two scales as shown in Figure 1, where the left scale represents the first stage of the DS scheme, whereas the right scale represents the second stage of the DS scheme.

Figure 1. Graphical view of the DS $\bar{X}$ chart.

For each sample, the sample of size n_1 is taken at the first stage of the DS scheme. Note that when the sample statistic (i.e. standardized value of the sample mean) in (13) is plotted within region I_2 , the process goes to the second stage of the DS scheme, where the additional sample of size n_2 is taken and the sample size is $(n_1 + n_2)$ at the second stage of the DS scheme. The probability of taking the additional sample is defined as

$$\begin{aligned} \Pr(Z_i \in I_2) = & \Phi\left(k_1 + \frac{B\delta\sqrt{n_1}}{\sqrt{B^2 + \gamma^2/m}}\right) - \Phi\left(w + \frac{B\delta\sqrt{n_1}}{\sqrt{B^2 + \gamma^2/m}}\right) \\ & + \Phi\left(-w + \frac{B\delta\sqrt{n_1}}{\sqrt{B^2 + \gamma^2/m}}\right) \\ & - \Phi\left(-k_1 + \frac{B\delta\sqrt{n_1}}{\sqrt{B^2 + \gamma^2/m}}\right), \end{aligned} \quad (14)$$

where $\gamma^2 = \sigma_\varepsilon^2/\sigma_0^2$ is the measurement error ratio. Hence, the average sample size of the DS $\bar{X}$ chart is computed as

$$\bar{n} = n_1 + n_2 \Pr(Z_i \in I_2). \quad (15)$$

Note that $\bar{n} = \bar{n}_0$ is the in-control average sample size when $\delta = 0$, while $\bar{n} = \bar{n}_\delta$ is the out-of-control average sample size when $\delta \neq 0$. The average run length of the DS $\bar{X}$ chart is calculated as

$$\text{ARL} = \frac{1}{1 - p_a}, \quad (16)$$

where p_a is the probability of a sample statistic plotted within the in-control regions,

which can be computed as follows:

$$\begin{aligned}
 p_a = & \Phi\left(w + \frac{B\delta\sqrt{n_1}}{\sqrt{B^2 + \gamma^2/m}}\right) - \Phi\left(-w + \frac{B\delta\sqrt{n_1}}{\sqrt{B^2 + \gamma^2/m}}\right) \\
 & + \int_{z \in I_2} \left(\Phi\left(k_2\sqrt{\frac{n_1+n_2}{n_2}} + \frac{B\delta(n_1+n_2)}{\sqrt{n_2(B^2 + \gamma^2/m)}} - z\sqrt{\frac{n_1}{n_2}}\right) \right. \\
 & \left. - \Phi\left(-k_2\sqrt{\frac{n_1+n_2}{n_2}} + \frac{B\delta(n_1+n_2)}{\sqrt{n_2(B^2 + \gamma^2/m)}} - z\sqrt{\frac{n_1}{n_2}}\right) \right) \phi(z) dz,
 \end{aligned} \tag{17}$$

where $\Phi(\cdot)$ and $\phi(z)$ are the cumulative distribution function and the probability density function of the standardized normal random variable, respectively.

3. COST MODEL

The general cost model in [8] is adopted in this study to determine the optimal design parameters of the DS $\bar{X}$ chart by allowing multiple measurements on each item in a sample. The assumptions for the cost model are: (1) the process begins in an in-control state; (2) the quality characteristic of the process is normally distributed with the in-control mean of μ_0 and the standard deviation of σ_0 ; (3) the occurrence of the assignable cause results in a process mean shift; (4) the occurrence of the assignable cause is modeled by a Poisson process with the mean of $1/\lambda$; (5) the quality cycle follows a renewal process introduced by [16]. Let $E(C)$ and $E(T)$ be the expected cost in a cycle and the expected cycle time, respectively, then the expected cost per hour is obtained as

$$E(A) = \frac{E(C)}{E(T)}, \tag{18}$$

where

$$\begin{aligned}
 E(C) = & \frac{C_0}{\lambda} + C_1(ARL_1 h - \tau + \bar{n}_\delta E + r_1 T_1 + r_2 T_2) \\
 & + (a + b_1 \bar{n}_0 + b_2 \bar{n}_0(m-1))s \\
 & + (a + b_1 \bar{n}_\delta + b_2 \bar{n}_\delta(m-1)) \\
 & \times \left(ARL_1 + \frac{(\bar{n}_\delta E + r_1 T_1 + r_2 T_2)}{h} \right) + \frac{sY}{ARL_0} + W
 \end{aligned} \tag{19}$$

and

$$E(T) = \frac{1}{\lambda} + \frac{(1-r_1)sT_0}{ARL_0} + ARL_1 h - \tau + \bar{n}_\delta E + T_1 + T_2. \tag{20}$$

The parameters of the cost model are:

- λ failure rate
- C_0 cost per hour due to non-conformities during the in-control period
- C_1 cost per hour due to non-conformities during the out-of-control period

τ	expected time of occurrence of the assignable cause, given that it occurs between two consecutive samples = $\frac{1 - (1 + \lambda h)e^{-\lambda h}}{\lambda(1 - e^{-\lambda h})}$
E	expected time to sample and chart one item
T_1	expected time to detect the assignable cause
T_2	expected time to repair the process
T_0	expected time spent searching for a false alarm
r_1	1 if the production continues during the search; 0 if the production ceases during the search
r_2	1 if the production continues during the repair; 0 if the production ceases during the repair
s	average number of samples during the in-control period = $\frac{e^{-\lambda h}}{1 - e^{-\lambda h}}$
Y	cost of the false alarm
W	cost of searching and repairing the assignable cause
a	fixed cost per sample
b_1	variable cost per unit for the initial measurement of a sample
b_2	variable cost per unit for the subsequent measurement of a sample
m	number of multiple measurements per item in a sample
$\bar{n}_0$	in-control average sample size
$\bar{n}_\delta$	out-of-control average sample size
h	sampling interval
δ	process mean shift
ARL_0	in-control average run length
ARL_1	out-of-control average run length

The design parameters of the DS $\bar{X}$ chart are n_1 , n_2 , w , k_1 , k_2 and h . The solution procedure for the economic design of the DS $\bar{X}$ chart with measurement errors is to determine the optimal design parameters by minimizing the $E(A)$ value with the following constraints: $n_1 < n_2$, $n_1 + n_2 \leq 20$, $w < k_1$, $k_2 > 0$, $0.01 \leq h \leq 3$ and $m \leq 20$, where n_1 , n_2 and m are positive integers. This non-linear constrained optimization problem is solved by using Evolver, where Evolver is an add-in tool for Microsoft Excel.

4. AN ILLUSTRATIVE EXAMPLE

An example is provided in this section to illustrate the implementation of the economic design of the DS $\bar{X}$ chart with measurement errors. The pre-determined parameters are $\lambda = 0.02$, $C_0 = 114.24$, $C_1 = 949.2$, $E = T_0 = T_1 = 0.083$, $r_1 = 1$, $r_2 = 0$, $Y = W = 977.4$, $a = 0$, $b_1 = 4.22$, $b_2 = 0.5$ and $\delta = 0.86$. It is assumed that $\gamma^2 = \sigma_\varepsilon^2/\sigma_0^2 = 2$, $A = 0$ and $B = 1$ for the linear covariate error model. Using the solution procedure described in Section 3, the optimal design parameters of the DS $\bar{X}$ chart are obtained as $n_1 = 3$, $n_2 = 11$, $w = 1.352$, $k_1 = 3.717$, $k_2 = 2.322$ and $h = 1.125$ with $E(A) = 215.86$, $ARL_0 = 108.45$, $ARL_1 = 2.68$ and $m = 5$. For the economic design of the DS $\bar{X}$ chart without measurement errors, the optimal design parameters of the DS $\bar{X}$ chart are $n_1 = 2$, $n_2 = 10$, $w = 1.475$, $k_1 = 4.478$, $k_2 = 2.599$ and $h = 0.673$ corresponding to $E(A) = 194.96$, $ARL_0 = 280.91$, $ARL_1 = 3.15$ and $m = 1$. This result implies that under the assumption of no measurement errors, the percentage of error in the minimum expected cost per hour is $(215.86 - 194.96)/215.86 \times 100 = 9.68\%$.

5. THE EFFECT OF MEASUREMENT ERRORS ON THE ECONOMIC DESIGN

The same numerical example as in the previous section is used to investigate the effect of γ^2 and B on the economic design of the DS $\bar{X}$ chart by covering a wide range of γ^2 and B values.

Figures 2(a)–(g) show the graphs of the n_1 , n_2 , w , k_1 , k_2 , m , h , ARL_0 , ARL_1 and $E(A)$ values against the measurement error ratio γ^2 , where $A = 0$ and $B = 1$. Figure 2(a) shows that the sample size (i.e. n_1 or n_2) is generally robust to the measurement error ratio γ^2 . The warning and control limits (i.e. w , k_1 and k_2) of the DS $\bar{X}$ chart are not significantly affected by the changes in the γ^2 value as shown in Figure 2(b). From Figures 2(c) and 2(d), increasing in the value of γ^2 gives the larger values in the sampling interval h and the number of multiple measurements per item m , respectively. A larger γ^2 value results in a smaller ARL_0 value (see Figure 2(e)) and a higher $E(A)$ value (see Figure 2(g)). An “up-down” trend of ARL_1 is observed in Figure 2(f) with the changes in the value of measurement error ratio γ^2 .

Figure 2(a). Effect of γ^2 on the sample sizes.

Figure 2(b). Effect of γ^2 on the warning and control limits.

Figure 2(c). Effect of γ^2 on the sampling interval.

Figure 2(d). Effect of γ^2 on the number of multiple measurements per item.

Figure 2(e). Effect of γ^2 on the in-control average run length.

Figure 2(f). Effect of γ^2 on the out-of-control average run length.

Figure 2(g). Effect of γ^2 on the expected cost per hour.

Figure 3(a). Effect of B on the sample sizes.

Figure 3(b). Effect of B on the warning and control limits.

Figure 3(c). Effect of B on the sampling interval.

Figure 3(d). Effect of B on the number of multiple measurements per item.

Figure 3(e). Effect of B on the in-control average run length.

Figure 3(f). Effect of B on the out-of-control average run length.

Figure 3(g). Effect of B on the expected cost per hour.

Figures 3(a)–(g) show the graphs of the n_1 , n_2 , w , k_1 , k_2 , m , h , ARL_0 , ARL_1 and $E(A)$ values against the B value, where $A = 0$ and $\gamma^2 = 2$. Figure 3(a) shows that the sample size (i.e. n_1 or n_2) is generally robust to the B value. The warning and control limits are also robust to the B value as shown in Figure 3(b). From Figures 3(c) and 3(d), it can be observed that an increase in the B value results in a shorter sampling interval h and a smaller number of multiple measurements per item m . An increase in the value of B leads to a larger ARL_0 value and a smaller $E(A)$ value as shown in Figures 3(e) and 3(g), respectively. From Figure 3(f), an “up-down” trend is observed for the ARL_1 value with the changes in the B value.

6. CONCLUSIONS

In this study, the economic design for the DS $\bar{X}$ chart considering the presence of measurement errors is investigated. The methodology for determining the optimal design parameters of the DS $\bar{X}$ chart with measurement errors is presented. The effect of measurement errors on the economic design of the DS $\bar{X}$ chart is investigated through numerical examples.

Several conclusions can be drawn from the numerical analysis. The sampling interval, the number of multiple measurements per item, the in-control average run length and the expected cost per hour are affected by the measurement error ratio γ^2 and the coefficient B in the linear covariate error model. In order to achieve the minimum expected cost per hour, a smaller γ^2 value or a larger B value leads to a shorter sampling interval and a smaller number of multiple measurements per item. The larger ARL_0 value (i.e. the lower false alarm rate) is observed with the decreasing value in γ^2 or the increasing value in B . This implies that the in-control statistical performance of the DS $\bar{X}$ chart is improved with a smaller γ^2 value or a larger B value. The negative effect of measurement errors can be economically reduced (i.e. the lower expected cost per hour) by a smaller γ^2 value or a larger B value.

ACKNOWLEDGEMENT

The authors would like to acknowledge the Sarawak Multimedia Authority (SMA) in financing this research through Sarawak Digital Economy Research Grant.

REFERENCES

- [1] Shewhart, W. A., 1924, "Some applications of statistical methods to the analysis of physical and engineering data," *Bell System Technical Journal*, 3(1), pp. 43–87.
- [2] Daudin, J. J., 1992, "Double sampling $\bar{X}$ charts," *J. Qual. Technol.*, 24(2), pp. 78–87.
- [3] Linna, K. W., and Woodall, W. H., 2001, "Effect of measurement error on Shewhart control charts," *J. Qual. Technol.*, 33(2), pp. 213–222.
- [4] Hu, X. L., Castagliola, P., Sun J. S., and Khoo, M. B. C., 2015, "The effect of measurement errors on the synthetic $\bar{X}$ chart," *Qual. Reliab. Eng. Int.*, 31(8), pp. 1769–1778.
- [5] Hu, X. L., Castagliola, P., Sun J. S., and Khoo, M. B. C., 2016, "The performance of variable sample size $\bar{X}$ chart with measurement errors," *Qual. Reliab. Eng. Int.*, 32(3), pp. 969–983.
- [6] Sabahno, H., Amiri, A., and Castagliola, P., 2018, "Performance of the variable parameters $\bar{X}$ control chart in presence of measurement errors," *J. Test. Eval.*, 47(1), pp. 480–497.
- [7] Tang, A., Castagliola, P., Sun, J. S., and Hu, X. L., 2018, "The effect of measurement errors on the adaptive EWMA $\bar{X}$ chart," *Qual. Reliab. Eng. Int.*, 34(4), pp. 609–630.
- [8] Lorenzen, T. J., and Vance, L. C., 1986, "The economic design of control charts: A unified approach," *Technometrics*, 28(1), pp. 3–10.
- [9] Duncan, A. J., 1956, "The economic design of $\bar{X}$ charts used to maintain current control of a process," *J. Am. Stat. Assoc.*, 51(274), pp. 228–242.
- [10] Torng, C. C., Lee, P. H., Liao, H. S., and Liao, N. Y., 2009, "An economic design of double sampling $\bar{X}$ charts for correlated data using genetic algorithms," *Expert Syst. Appl.*, 36(10), pp. 12621–12626.
- [11] Lee, M. H., and Khoo, M. B. C., 2018, "Economic-statistical design of double sampling s control chart," *Int. J. Qual. Res.*, pp. 337–362.
- [12] Lee, M. H., and Khoo, M. B. C., 2019, "Economic-statistical design of synthetic double sampling T^2 chart," *Commun. Stat. – Theory Methods*, 48(23), pp. 5862–5876.
- [13] Lee, M. H., and Khoo, M. B. C., 2019, "The economic and economic statistical designs of synthetic double sampling $\bar{X}$ chart," *Commun. Stat. – Simul. Comput.*,

- 48(8), pp. 2313–2332.
- [14] Saghaei, A., Fatemi Ghomi, S. M. T., and Jaberi, S., 2014, “Economic design of exponentially weighted moving average control chart based on measurement error using genetic algorithm,” *Qual. Reliab. Eng. Int.*, 30(8), pp. 1153–1163.
- [15] Hu, X. L., Castagliola, P., Sun, J. S., and Khoo, M. B. C., 2016, “Economic design of the upper-sided synthetic S^2 chart with measurement errors,” *Int. J. Prod. Res.*, 54(19), pp. 5651–5670.
- [16] Ross, S. M., 1970, *Applied Probability Models with Optimization Applications*, San Francisco: Holden–Day.

AUTHORS’ BIOGRAPHIES

K. S. Khee Yong Si is a full time master student by research mode. He currently studies in the Faculty of Engineering, Computing and Science, Swinburne University of Technology Sarawak Campus. He obtained his Bachelor of Engineering in Electrical and Electronic from Swinburne University of Technology Sarawak Campus.

Ming Ha Lee is a senior lecturer in the Faculty of Engineering, Computing and Science at Swinburne University of Technology Sarawak Campus, Malaysia. She received her BTech from Universiti Sains Malaysia, her MSc from Universiti Putra Malaysia and her PhD from Universiti Sains Malaysia.

XinYing Chew is a senior lecturer in the School of Computer Sciences, Universiti Sains Malaysia. She holds a PhD in statistical quality control from University Sains Malaysia. She is a certified trainer with Human Resources Development Fund, Malaysia. Her research papers are published in several renowned international peer-reviewed journals, such as *Computers & Industrial Engineering*, *Quality and Reliability Engineering International* and etc. She is also an adjunct research fellow of Swinburne University of Technology Sarawak Campus. Prior to her academic career, she worked in the Advanced Analytics research team of a renown U.S. multinational company. Her areas of research are in advanced analytics and statistical quality / process control.

Man F. Lau received his BSc (Hons) from The University of Hong Kong and PhD from The University of Melbourne. He joined Swinburne University of Technology in 2000. He received 2 ARC DP research grants in 2005 (a 3-year ARC DP project) and 2007 (a 5-year ARC DP project). His currently research interests are on Data Mining and Testing Prediction Models. Currently, he is working on a Big Data project on testing Optimal Oil Drilling Prediction Models based on past 15+ years of oil drilling data.

Kong Melinda is a senior lecturer in the Faculty of Business, Design and Arts at Swinburne University of Technology Sarawak Campus, Malaysia. She obtained her Bachelor of Education in Teaching English to Speakers of Other Languages/TESOL from the University of Southampton (United Kingdom/UK) before getting a Master of Arts in TESOL from the Institute of Education, University College London (UK). She also pursued a PhD in Education at the University of Melbourne (Australia) under full scholarships from the university.

H. H. Then Patrick is the director for the Centre for Digital Futures Swinburne Sarawak. He is a strong advocate of R&D and commercialization of innovations in Big Data, Data Mining and Internet of Things. He has established industry collaboration at national and international levels. He has been leading multiple industry-funded projects in research and development in collaboration with prominent ICT partners such as Sarawak Information Systems Sdn Bhd (SAINS), IDS (Malaysia) Sdn Bhd in Sarawak, and organizations around the world. He has established partnership between Swinburne and international commercial partners such as Fusionex International Ltd, UK, D&J Human Care, South Korea, and Easy Global Market, France. He is a member of the Institute of Electrical and Electronics Engineers USA and the Australian Computer Society.