Optimum Production Run Length and Process Mean Setting

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Abstract

In this paper, the author presented a modified Chen and Chung's model considering that the process mean may not be equal to the target value when the process is in the in-control state. Taguchi's asymmetric quadratic quality loss function will be applied in evaluating the product quality. Subsequently, the modified economic manufacturing quantity (EMQ) model based on modified the Chen and Chung's model is formulated for obtaining the expected total cost per year. The numerical result shows that for an in-control process, the modified EMQ model when the process mean is not equal to the target value has smaller expected total cost per year than that of the modified EMQ model when the process mean is equal to the target value.

***Key Words*:** Economic Manufacturing Quantity (EMQ), Production Run Length, Process Mean, Taguchi's Asymmetric Quadratic Quality Loss Function

1. Introduction

The traditional economic manufacturing quantity (EMQ) model assumes that the product for a manufacturing process is perfect. Hence, the occurrence of a defective product for this model has been neglected. Previous researchers, like Porteus [1] and Rosenblatt and Lee [2,3], first proposed the imperfect quality of the EMQ model. Subsequently, some works addressed the integrated model on production, inspection, maintenance, and quality. Lee and Rosenblatt [4,5] and Lee and Park [6] introduced some inspection and maintenance mechanisms to monitor a production process. Rahim [7] and Rahim and Ben-Daya [8] presented an integrated model for jointly determining the production quantity, inspection policy, and parameters of a statistical control chart. Al-Sultan [9] pointed out that optimization methods have been successfully applied to the economic models integrating production, maintenance, and quality. Wright and Mehrez [10] presented a literature review that includes the connection between quality and inventory. Recently, Tahera et al. [11] addressed a review on a joint determination of process level and production run length. In 1997, Sana et al. [12,13] proposed a volume flexible inventory model considering the demand rate of defective items sold at a reduced price as a function of the reduction rate of the selling price. They further addressed the imperfect production system including the unit production cost taken to be a function of the finite production rate. In 2009, Sana [14,15] considered the production-inventory model with imperfect production system for defective items restored to their original quality by rework. His model also discusses and provides an optimal solution for product reliability parameter and dynamic production rate.

Economic selection of process parameters has been an important topic in modern statistical process control. The optimum process mean setting has an effect on the expected total profit/cost, defective fraction, inspection/reprocessing cost. Recently, there is also considerable attention paid to the filling/canning problem for determining the optimum manufacturing target and other important parameters. Jang et al. [16] proposed the optimum process mean and production cycle settings for a linear

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trend process. Young et al. [17] discussed the process mean setting under the variance reduction and a specified process capability. Lee and Elsayed [18] presented a two-stage screening method for determining the process mean and screening limits. Anis [19] considered the cost of non-conformance for obtaining an optimum process mean. Hong and Cho [20] proposed the problem of a joint design of process mean and tolerance limits based on measurement error.

In 1986, Taguchi [21] presented the quadratic quality loss function for redefining the product quality. According to him, product quality is the society's loss when the product is sold to the customer. The total loss of a society includes the producer's loss (the set-up cost, the holding cost, the inspection cost, and the production cost for the producer) and the consumer's loss (including the quality cost). An optimum product quality from Taguchi's [21] point should be defined as a product quality characteristic with minimum bias and variance. Recently, Taguchi's [21] quality loss function was successfully applied in the problem of optimum process mean settings. Kim and Cho [22] adopted a truncated Weibull quality characteristic and quadratic quality loss function for determining an optimum process mean. Rahim and Tuffaha [23] proposed the quadratic and linear quality loss functions applied in the determination of production run length and process mean. Chan and Ibrahim [24] and Chan et al. [25,26] addressed the multivariate quadratic quality loss functions applied in the determination of optimum process mean for the nominal-the-best, smaller-the-better, and larger-the-better quality characteristics, respectively. Teeravaraprug [27] adopted the quadratic quality loss function for evaluating the quality cost of a product for two different markets and obtained the optimum process mean based on maximizing the expected profit per item. Chen [28,29] proposed a modified Pulak and Al-Sultan's [30] model with quality loss for determining the optimum process parameters under the rectifying inspection plan.

In 1996, Chen and Chung [31] presented the quality selection problem in imperfect production systems for obtaining the optimum production run length and target level. Rahim and Tuffaha [23] further proposed the modified Chen and Chung's [31] model with quality loss and sampling inspection. However, the in-control process mean is assumed to be equal to the target value and no defective item exists when the production process is in statistical control for the Chen and Chung's [31] and Rahim and Tuffaha's [23] models. In fact, the process mean may not be equal to the target value and a defective item may exists when the production process is in the in-control state. In this paper, the author further proposes a modified EMQ model based on the modified Chen and Chung's [31] model considering that the process mean may not be equal to the target value when the process is in the in-control state. Taguchi's [21] asymmetric quadratic quality loss function will be applied in evaluating a product's quality. By solving the modified EMQ model, one can obtain the optimum production run length and process mean with the minimum expected total cost per year. Finally, the sensitivity analyses of cost parameters will be provided for illustration.

2. Taguchi's Asymmetric Quadratic Quality Loss Function

Assume that y is the nominal-is-best quality characteristic. Then the asymmetric quality loss function is defined as

$$L(y) = \begin{cases} k_2(y-m)^2, & y \le m \\ k_1(y-m)^2, & y > m \end{cases} \quad (1)$$

When the loss function is $k_2\,(\mathrm{y}-\mathrm{m})^2$, the constant k_2 can be obtained as follows: Find the limit value Δ_2, above which an item performs unsatisfactorily – for example, in more than 50% of cases – and assess the corresponding consumer's penalty A_2. Substituting A_2 and Δ_2 in the loss function for an individual item, i.e., $L(y) = k_2\,(y - m)^2$, and solving for k_2, we obtain $k_2 = \dfrac{A_2}{\Delta_2^2}$. Similarly, we can obtain the constant k_1 as follows: Find the limit value Δ_1, above which an item performs unsatisfactorily – for example, in more than 50% of cases – and assess the corresponding consumer's penalty A_1. Substituting A_1 and Δ_1 in the loss function for an individual item, i.e., $L(y) = k_1\,(y - m)^2$, and solving for k_1, we obtain $k_1 = \dfrac{A_1}{\Delta_1^2}$.

3. Chen and Chung's Model

There are some assumptions made in Chen and

Chung [31], such as

(1) When the production cycle starts, the process is in the in-control state. Once a shift has occurred, the process will remain in an out-of-control state until it is discovered by inspection and followed by some restoration work. Otherwise, the out-of-control state will remain until the end of the production run.
(2) τ denotes the elapse time until the occurrence of an assignable cause assumed to be exponentially distributed with a mean of $1/\lambda$ (λ is the time parameter and is distributed as exponential when the production process is in the in-control state).
(3) The process mean can be adjusted and controlled and the shape of the quality characteristic does not change when the process mean is adjusted or changed.
(4) If the value of the quality characteristic is equal to or greater than the lower specification limit, the item is sold at a regular price. On the other hand, the item is sold as a scrap at a reduced price.

From Chen and Chung [31, p. 2054], the expected gross profit per item at time t is

$$\begin{aligned} E(\pi) &= g_0 P(\tau > t) + g_1 P(\tau < t) \\ &= g_1 + (g_0 - g_1)\exp(-\lambda t) \end{aligned} \tag{2}$$

where g_0 is the expected revenue per item for an in-control process and g_1 is the expected revenue per item for an out-of-control process.

Then the expected total revenue in the production run T is

$$\begin{aligned} p\int_0^T E(\pi)dt &= p\int_0^T [g_1 + (g_0 - g_1)\exp(-\lambda t)]dt \\ &= p\{Tg_1 + (g_0 - g_1)[1 - \exp(-\lambda t)]/\lambda\} \end{aligned} \tag{3}$$

where p is the production rate in pieces per hour.

Hence, the expected total profit per item for each production cycle T is

$$Z = \frac{p\int_0^T E(\pi)dt}{pT} = g_1 + \frac{(g_0 - g_1)(1 - e^{-\lambda T})}{\lambda T} \tag{4}$$

4. Modified Chen and Chung's Model

There are some assumptions made in the modified Chen and Chung's [31] model, such as

(1) The quality characteristic X is normally distributed with an unknown process mean μ which can be easily adjusted, but the process variance σ^2 is known.
(2) When the production cycle starts, the process is in the in-control state. Once a shift has occurred, the process will remain in an out-of-control state until it is discovered by inspection and followed by some restoration work. Otherwise, the out-of-control state will remain until the end of the production run.
(3) The asymmetric quadratic quality loss function is used in measuring a product's quality.
(4) The elapse time until the occurrence of an assignable cause is assumed to be exponentially distributed with a mean of $1/\lambda$.
(5) The process mean of the in-control process is not equal to the target value.

From the above assumption, the expected total cost for a production cycle T should include the set-up cost, the holding cost, and the quality loss per item. The modified model with the quality cost per item for each production cycle T is

$$Z = g_1 + \frac{(g_0 - g_1)(1 - e^{-\lambda T})}{\lambda T} \tag{5}$$

where g_0 is the expected quality cost of an in-control process,

$$g_0 = \sigma^2\{\frac{m-\mu}{\sigma}\phi(\frac{m-\mu}{\sigma})(k_1 - k_2) + k_1 + \Phi(\frac{m-\mu}{\sigma})(k_2 - k_1)\}$$

g_1 is the expected quality cost of an out-of-control process,

$$\begin{aligned} g_1 = \sigma^2\{&\delta^2[k_1 + (k_2 - k_1)\Phi(\frac{m-\mu-\delta\sigma}{\sigma})] \\ &+ 2\delta(k_1 - k_2)\phi(\frac{m-\mu-\delta\sigma}{\sigma}) \\ &+ (k_1 - k_2)\frac{m-\mu-\delta\sigma}{\sigma}\phi(\frac{m-\mu-\delta\sigma}{\sigma}) \\ &+ k_1 + (k_2 - k_1)\Phi(\frac{m-\mu-\delta\sigma}{\sigma})\} \end{aligned}$$

If the process mean of the in-control process is equal to the target value, then one has $g_0 = \frac{1}{2}\sigma^2(k_1 + k_2)$ and $g_1 = \sigma^2\{(1 + \delta^2)[k_1 + (k_2 - k_1)\Phi(-\delta)] + \delta(k_1 - k_2)\phi(-\delta)\}$.

5. Modified Economic Manufacturing Quantity Model

There are three main assumptions for the traditional EMQ model: (1) A perfect quality occurs in the production process; (2) There is no shortage of cost; (3) The demand for the produced item is continuous and constant and all demands must be met (production rate > demand rate).

Based on the above assumptions, the expected total cost of the traditional EMQ model which includes the set-up cost and the holding cost is as follows:

$$ETC(T) = \frac{SW}{pT} + \frac{B(p-d)T}{2} \tag{6}$$

where ETC is the expected total cost per year; W is the demand quantity in units per year; d is the demand quantity in units per day; S is the set-up cost for each production run; p is the production rate in units per day; B is the holding cost per unit item per year; T is the production run length.

One sets the first derivative of ETC equal to zero, and solves for the economic manufacturing quantity, Q (= pT). We have the optimum economic manufacturing quantity and production run length as $Q_E^* = \sqrt{\frac{2WSp}{B(p-d)}}$ and $T_E^* = \sqrt{\frac{2WS}{p(p-d)B}}$, respectively.

Hence, the expected total cost per year for the modified EMQ model based on the modified Chen and Chung's [31] model with expected quality loss is as follows:

$$\begin{aligned} ETC_1(T,\mu) &= \frac{SW}{pT} + \frac{B(p-d)T}{2} + WZ \\ &= \frac{SW}{pT} + \frac{B(p-d)T}{2} + W[g_1 + \frac{(g_0 - g_1)(1-e^{-\lambda T})}{\lambda T}] \end{aligned} \tag{7}$$

Assume that λT is sufficiently small, then $e^{-\lambda T} = 1 - \lambda T + \frac{(\lambda T)^2}{2}$. By applying this approximation, Eq. (7) can be rewritten as

$$ETC_1(T,\mu) \approx \frac{SW}{pT} + \frac{B(p-d)T}{2} + W[g_1 + (g_0 - g_1)(1 - \frac{\lambda T}{2})] \tag{8}$$

To minimize the expected total cost per year, partially differentiate Eq. (8) with respect to T and μ, and letting the partial derivatives equal to zero, i.e.,

$$\frac{\partial ETC_1(T,\mu)}{\partial T} = -\frac{SW}{pT^2} + \frac{B(p-d)}{2} - W(g_0 - g_1)\frac{\lambda}{2} = 0 \tag{9}$$

$$\frac{\partial ETC_1(T,\mu)}{\partial \mu} = W[\frac{\partial g_1}{\partial \mu} + (\frac{\partial g_0}{\partial \mu} - \frac{\partial g_1}{\partial \mu})(1 - \frac{\lambda T}{2})] = 0 \tag{10}$$

where

$$\begin{aligned} \frac{\partial g_0}{\partial \mu} = \sigma^2\{&\frac{-1}{\sigma}\phi(\frac{m-\mu}{\sigma})(k_1 - k_2) + \frac{m-\mu}{\sigma}(k_1 - k_2)\phi(\frac{m-\mu}{\sigma})\frac{m-\mu}{\sigma^2} \\ &- \frac{1}{\sigma}\phi(\frac{m-\mu}{\sigma})(k_2 - k_1)\} \end{aligned} \tag{11}$$

$$\begin{aligned} \frac{\partial g_1}{\partial \mu} = \sigma^2\{&\frac{-1}{\sigma}\phi(\frac{m-\mu-\delta\sigma}{\sigma})(k_2 - k_1)\delta^2 \\ &+2\delta(k_1 - k_2)\phi(\frac{m-\mu-\delta\sigma}{\sigma})\frac{m-\mu-\delta\sigma}{\sigma^2} - \frac{1}{\sigma}\phi(\frac{m-\mu-\delta\sigma}{\sigma})(k_1 - k_2) \\ &+(k_1 - k_2)\frac{m-\mu-\delta\sigma}{\sigma}\phi(\frac{m-\mu-\delta\sigma}{\sigma})\frac{m-\mu-\delta\sigma}{\sigma^2} \\ &-\frac{1}{\sigma}\phi(\frac{m-\mu-\delta\sigma}{\sigma})(k_2 - k_1)\} \end{aligned} \tag{12}$$

It is difficult to show that the Hessian matrix of Eq. (8) is positive definite because the expected total cost per year includes the standard normal probability density function $\phi(\cdot)$ and the cumulative standard normal distribution function $\Phi(\cdot)$. It is very complex in obtaining the second differentiation in g_0 and g_1, with respect to μ of Eqs. (11) and (12). One cannot prove that Eq. (8) has a closed-form solution. From Eq. (9), one has an explicit expression of T in terms of other variables:

$$T_1^* = \sqrt{\frac{2SW}{p[(p-d)B - W\lambda(g_0 - g_1)]}} \tag{13}$$

where

$$\begin{aligned} g_0 &= \sigma^2\{\frac{m-\mu}{\sigma}\phi(\frac{m-\mu}{\sigma})(k_1 - k_2) + k_1 + \Phi(\frac{m-\mu}{\sigma})(k_2 - k_1)\}; \\ g_1 &= \sigma^2\{\delta^2[k_1 + (k_2 - k_1)\Phi(\frac{m-\mu-\delta\sigma}{\sigma})] \\ &+2\delta(k_1 - k_2)\phi(\frac{m-\mu-\delta\sigma}{\sigma}) + (k_1 - k_2)\frac{m-\mu-\delta\sigma}{\sigma}\phi(\frac{m-\mu-\delta\sigma}{\sigma}) \\ &+k_1 + (k_2 - k_1)\Phi(\frac{m-\mu-\delta\sigma}{\sigma})\}. \end{aligned}$$

The expected quality cost of the in-control process is less than that of the out-of-control process because the latter has more defective items than the former. From $g_0 < g_1$, we have $T_1^* \le T_E^*$.

The optimal solution in Eq. (8) is valid only if the expected total cost is convex. The second derivative of Eq. (8) with respect to T is $\frac{\partial^2 ETP}{\partial T^2} = \frac{2WS}{pT^3} > 0$. Hence, the optimal solution exists for the given parameters. For the given parameters, one can adopt the direct search method for obtaining the economic production run length T^* and the optimum process mean μ^*. The solution procedure for the above Eq. (8) is as follows:

Step 1. Compute $T_E^* = \sqrt{\frac{2WS}{p(p-d)B}}$.

Step 2. Set the minimum searched value T, $T_{\min} = 0.01$, and let the maximum searched value T, $T_{\max} = T_E^*$.

Step 3. Set the minimum searched value μ, $\mu_{\min} = m - 4\sigma$, and let the maximum searched value μ, $\mu_{\max} = m + 4\sigma$.

Step 4. Let $T = T_{\min}$ and $\mu = \mu_{\min}$. Compute $ETC_1(T, \mu)$ by Eq. (8). Let $T = T_{\min} + 0.01$. Repeat this step until $T = T_{\max}$.

Step 5. Let $\mu = \mu_{\min} + 0.01$. Repeat Step 4 until $\mu = \mu_{\max}$.

Step 6. Select the maximum expected total cost from the above Steps 1–5 as the best policy. The corresponding parameters of T^* and μ^* values having the minimum $ETC_1(T, \mu)$ is the optimal solution.

The optimal solution of the modified EMQ model depends on the parameters of cost. The influences of them need to be illustrated using a sensitivity analysis.

5. Numerical Example and Sensitivity Analysis

5.1 Numerical Example

Suppose that the demand for an item is $W = 20{,}000$ items per year and there are 250 working days per year. The production rate is $p = 100$ items per day. The holding cost is $B = 10$ per item per year, and the set-up cost is $S = 20$ per run. The quality characteristic is normally distributed with a known standard deviation $\sigma = 0.05$. Let the magnitude of a mean shift $\delta = 1$, the quality loss coefficients $k_1 = 1$ and $k_2 = 2$, the target value $m = 10$, and the parameter of the exponential distribution, $\lambda = 0.05$.

Assume that the process mean of the in-control process is not equal to the target value. By solving Eq. (8), we obtain the optimum solution with $T^* = 6.29$, $\mu^* = 10.27$, and $ETC_1(T^*, \mu^*) = 1322.029$. Next, assume that the process mean of the in-control process is equal to the target value. Then by solving Eq. (8), we obtain the optimum solution with $T^* = 6.31$ and $ETC_1(T^*, \mu^*) = 1344.011$.

5.2 Sensitivity Analysis

Tables 1–2 list the sensitivity analyses of some parameters by considering the process mean that is either equal to or not equal to the target value for an in-control process. From Tables 1–2, one has the follow consequences:

1. The demand quantity in units per year (W), the production rate in units per day (p), the demand quantity in units per day (d), the holding cost per unit item per year (B), and the set-up cost for each production run (S) have a major effect on the production run length and expected total cost per year for both the modified EMQ models.
2. The process standard deviation (σ) and the target value (m) have a major effect on the process mean for the modified EMQ model if the process mean is not equal to the target value for an in-control process.
3. For an in-control process, the optimum production run length and the expected total cost per year of the modified EMQ model if the process mean is not equal to the target value are less than those of the modified model if the process mean is equal to the target value. Hence, adopting the modified model of the latter will overestimate the expected total cost per year.

6. Discussion and Conclusion

In this paper, the author presents a modified EMQ model based on the modified Chen and Chung's [31] model by considering that the process mean is not equal to the target value for an in-control process. Taguchi's [21] asymmetric quadratic quality loss function is applied in evaluating a product's quality. The numerical result shows that for an in-control process, the modified EMQ model when the process mean is not equal to the target value has smaller expected total cost per year than

Table 1. Sensitivity analyses of parameters for the modified EMQ model considering that the process mean is not equal to the target value for an in-control process

W	T^*	μ^*	$ETC_1(T^*, \mu^*)$
16000	5.63	10.26	1176.521
18000	5.97	10.26	1251.110
20000	6.29	10.27	1322.029
22000	6.60	10.27	1389.821
24000	6.89	10.28	1454.906
d	T^*	μ^*	$ETC_1(T^*, \mu^*)$
60	4.46	10.27	1844.044
70	5.15	10.27	1605.118
80	6.29	10.27	1322.029
90	7.25	10.28	1153.534
100	12.44	10.28	695.314
σ	T^*	μ^*	$ETC_1(T^*, \mu^*)$
0.03	6.31	10.17	1285.477
0.04	6.30	10.21	1301.471
0.05	6.29	10.27	1322.029
0.06	6.28	10.33	1347.151
0.07	6.26	10.38	1376.832
p	T^*	μ^*	$ETC_1(T^*, \mu^*)$
85	13.50	10.27	749.725
95	7.44	10.27	1182.178
100	6.29	10.28	1322.029
110	4.91	10.27	1532.768
120	4.07	10.27	1687.760
B	T^*	μ^*	$ETC_1(T^*, \mu^*)$
6	8.10	10.27	1038.713
8	7.03	10.27	1189.232
10	6.29	10.27	1322.029
12	5.75	10.27	1442.198
14	5.33	10.28	1552.777
δ	T^*	μ^*	$ETC_1(T^*, \mu^*)$
0.3	6.32	10.27	1315.553
0.5	6.32	10.27	1316.694
1.0	6.29	10.27	1322.029
1.5	6.25	10.27	1330.882
2.0	6.20	10.27	1343.192
S	T^*	μ^*	$ETC_1(T^*, \mu^*)$
16	5.63	10.27	1187.805
18	5.97	10.29	1256.787
20	6.29	10.27	1322.029
22	6.60	10.27	1384.079
24	6.89	10.28	1443.365
λ	T^*	μ^*	$ETC_1(T^*, \mu^*)$
0.03	6.30	10.27	1319.362
0.04	6.30	10.27	1320.723
0.05	6.29	10.27	1322.029
0.06	6.29	10.27	1323.282
0.07	6.28	10.27	1324.485
m	T^*	μ^*	$ETC_1(T^*, \mu^*)$
6	6.29	6.27	1322.029
8	6.29	8.27	1322.029
10	6.29	10.27	1322.029
12	6.29	12.27	1322.029
14	6.29	14.27	1322.029
k_1	T^*	μ^*	$ETC_1(T^*, \mu^*)$
1	6.29	10.27	1322.029
1.5	6.28	10.27	1350.576
k_2	T^*	μ^*	$ETC_1(T^*, \mu^*)$
1.5	6.29	10.26	1322.029
2.0	6.29	10.27	1322.029
2.5	6.29	10.27	1322.029
3.0	6.29	10.27	1322.029

Table 2. Sensitivity analyses of parameters for the modified model considering that the process mean is equal to the target value for an in-control process

W	T^*	$ETC_1(T^*, \mu^*)$
16000	5.64	1194.336
18000	5.98	1271.019
20000	6.31	1344.011
22000	6.61	1413.856
24000	6.90	1480.977
d	T^*	$ETC_1(T^*, \mu^*)$
60	4.47	1866.843
70	5.15	1627.604
80	6.31	1344.011
85	7.28	1175.105
95	12.53	714.875
σ	T^*	$ETC_1(T^*, \mu^*)$
0.03	6.32	1293.388
0.04	6.31	1315.536
0.05	6.31	1344.011
0.06	6.30	1378.811
0.07	6.29	1419.935
k_1	T^*	$ETC_1(T^*, \mu^*)$
1	6.31	1344.011
1.5	6.28	1361.571
k_2	T^*	$ETC_1(T^*, \mu^*)$
1.5	6.30	1333.021
2.0	6.31	1344.011
2.5	6.31	1354.999
3.0	6.32	1365.986
S	T^*	$ETC_1(T^*, \mu^*)$
16	5.63	1187.805
18	5.97	1256.787
20	6.29	1322.029
22	6.60	1384.079
24	6.89	1443.365
p	T^*	$ETC_1(T^*, \mu^*)$
85	13.59	768.915
95	7.46	1203.669
100	6.31	1344.011
110	4.91	1555.363
120	4.08	1710.738
B	T^*	$ETC_1(T^*, \mu^*)$
6	8.13	1059.934
8	7.05	1210.899
10	6.31	1344.011
12	5.76	1464.416
14	5.33	1575.183
δ	T^*	$ETC_1(T^*, \mu^*)$
0.3	6.33	1339.141
0.5	6.33	1339.624
1.0	6.31	1344.011
1.5	6.27	1352.508
2.0	6.21	1364.725
λ	T^*	$ETC_1(T^*, \mu^*)$
0.03	6.31	1342.473
0.04	6.31	1343.258
0.05	6.31	1344.011
0.06	6.30	1344.733
0.07	6.30	1345.426

that of the modified EMQ model when the process mean is equal to the target value. One should consider using this modified EMQ model in order to reduce overestimation of the expected total cost per year. Further study should address the problem of the larger-is-better, smaller-is-better, or multivariable quality loss function applied in formulating the modified EMQ model.

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