

ISSN Online: 2456-1452
NAAS Rating (2026): 4.49
IJSAM 2026; 11(10): 44-48
www.mathsjournal.com
Received: 26-08-2026
Accepted: 27-09-2026
Published: 09-10-2026

Dr. V Kaviyarasu
Associate Professor,
Bharathiar University,
Coimbatore Tamil Nadu, India

Inbarasi M
Research Scholar, Bharathiar
University, Coimbatore Tamil
Nadu, India

Enhancing EWMA chart using CRSS for cost models: application to implantable cardioverter-defibrillator monitor

Dr. V Kaviyarasu¹, Inbarasi M²

DOI: <https://www.doi.org/10.22271/math.2026.v11.i10a.2716>

ABSTRACT

In monitoring Automatic Implantable Cardioverter-Defibrillators (AICDs), control charts play an important role as lifetime measures such as time-to-failure and overall device longevity often exhibit a skewed distribution rather than a symmetric. When a careful and efficient process monitoring method becomes crucial to maintain reliability and keep costs under control. In this study, an Exponentially Weighted Moving Average (EWMA) control chart is developed using Circular Ranked Set Sampling (CRSS), assuming that the data follow an exponential distribution. The performance of the proposed chart is evaluated through a cost function within the Lorenzen-Vance economic model. The sampling interval and smoothing constant are optimally selected to reduce the expected cost per unit time, without compromising the ability to detect failure rate. Furthermore, Percent Relative Efficiency (PRE) is calculated to compare the efficiency of the CRSS-based estimator with that of the conventional EWMA chart. A numerical example is included to illustrate the economic benefits and improved efficiency achieved by the proposed CRSS-EWMA approach.

Keywords: Average Run Length, EWMA Control Chart, Circular Ranked Set Sampling, Cost function, Ranked Set Sampling

Introduction

Statistical Process Control (SPC) is an important methodology used in manufacturing and industrial processes to monitor process stability and improve product quality. Control charts are one of the most widely used SPC tools for identifying variations in process parameters and detecting the presence of assignable causes. Among the different types of control charts, the Exponentially Weighted Moving Average (EWMA) control chart is particularly effective in detecting small and moderate shifts in the process mean, since it assigns exponentially decreasing weights to past observations and gives more importance to recent data (Lucas *et al.*, 1990) [1].

The statistical performance of control charts is commonly evaluated using measures such as the Average Run Length (ARL). The in-control average run length (ARL_0) represents the expected number of samples taken before a false alarm occurs when the process is operating under control, while the out-of-control average run length (ARL_1) represents the expected number of samples required to detect a shift in the process mean. Although ARL-based design focuses on the statistical efficiency of control charts, it does not consider the economic consequences associated with process monitoring and quality control (Montgomery, 2009) [2].

In real-time industrial applications, implementing a control chart involves several cost components such as sampling and inspection costs. These costs are associated with investigating false alarms, costs of locating and repairing assignable causes, and the loss incurred due to the production of non-conforming items when the process operates in an out-of-control state. Therefore, considering economic aspects in control chart design is essential for achieving efficient process monitoring and minimizing operational costs. The economic design of control charts aims to determine optimal design parameters such as sample size, sampling interval, and control limits by minimizing the expected cost associated with the monitoring system.

To incorporate economic considerations into control chart design, a cost function is introduced to evaluate the expected cost of operating the monitoring system. The unified economic model proposed by Lorenzen *et al.* (1986) [3] evaluates the expected cost per unit time as the ratio of the expected cycle cost to the expected cycle time, allowing optimal chart parameters to be determined while maintaining acceptable statistical performance. In recent years, many researchers have focused on the economic and statistical design of control charts to improve both statistical detection capability and operational efficiency. For example, Linderman *et al.* (2000) [4] developed an economic and economic-statistical design framework for the Multivariate

Corresponding Author:
Inbarasi M
Research Scholar,
Bharathiar University,
Coimbatore Tamil Nadu,
India

Exponentially Weighted Moving Average (MEWMA) control chart, while other studies have applied economic models to optimize sampling intervals and monitoring strategies in SPC systems. Therefore, incorporating economic considerations through a cost function plays a vital role in the design of EWMA control charts. By minimizing the expected cost per unit time while maintaining desirable statistical properties such as ARL performance, economically designed EWMA control charts provide an effective and practical approach for monitoring industrial processes and improving overall production quality.

$$C = \{E[\text{Production Cost}] + E[\text{Alarm and Repair cost}] + E[\text{Sampling cost}]\} / E[\text{Cycle Time}]$$

$$= \{C_0/\lambda + C_1[-r + nE + h(ARL_1) + \gamma_1 T_1 + \gamma_2 T_2] + (sY/ARL_0) + W + (a + bn)/h[(1/\lambda) - r + nE + h(ARL_1) + \gamma_1 T_1 + \gamma_2 T_2]\} \div \{(1/\lambda) + [(1 - \gamma_1)sT_0/ARL_0] - r + nE + h(ARL_1) + T_1 + T_2\} \quad (1)$$

where the design parameters are:

- n = Sample size
- h = interval between samples (sampling interval)
- λ = Exponential parameter ($1/\lambda$ is the mean time to the occurrence of an assignable cause).
- C_0 = the cost of producing non-conformities/hour while the process is in-control.
- C_1 = the cost of producing non-conformities/hour while the process is out of control.
- ARL_0 = Average run length when the process is in-control state.
- ARL_1 = Average run length when the process is out of control state.
- $h - r$ = The expected time between a shift in the process(assignable cause) and the next sample, where $r = 1 - (1 + \lambda h)e^{-\lambda h}/\lambda(1 - e^{-\lambda h})$.
- E = expected time to sample and chart one item.
- $\gamma_1 = 1$ if production continuous during searches and 0 otherwise.
- $\gamma_2 = 1$ if production continuous during repair of the process and 0 otherwise.
- T_0 = Expected time to search a false alarm.
- T_1 = Expected time to discover the assignable cause.
- T_2 = Expected time to repair the assignable cause.
- $S = \frac{e^{-\lambda h}}{1 - e^{-\lambda h}}$ = Expected number of samples when process is under control.
- Y = Cost of investigate false alarm.
- W = Cost of locating and repairing an assignable cause.
- $\alpha = \frac{1}{ARL_0}$ = Probability of exceeding control limits when process is in-control state.
- $\beta = \frac{1}{ARL_1}$ = Probability of exceeding control limits when process is out of control state.
- δ = shift in the process average.

The strategy to compute the optimal sampling interval (h) and expected cost/hour for proposed CRSS-EWMA chart is discussed as follows.

2. Economic design of the proposed CRSS-EWMA chart

The Lorenzen-Vance model evaluates the economic performance of control charts. It considers:

- Sampling cost
- False alarm cost
- Investigation cost
- Production cost during out-of-control state

The Objective of the Lorenzen-Vance economic model is Minimize the expected cost per unit time. The expected monitoring cost per hour is computed using the Lorenzen-Vance economic cost model, which evaluates production, sampling, and investigation costs over the monitoring cycle.

2.1 Strategy to determine the sampling interval (h) for CRSS-EWMA

Step 1: Construct the CRSS sample using the circular ranking procedure and compute the observations used in the EWMA chart.

Step 2: Choose the set size (m), number of cycles (r) for CRSS, and the EWMA smoothing parameter (w). Fix the in-control average run length (ARL_0).

Step 3: Calculate the out-of-control average run length (ARL_1) for a specified shift in the failure rate.

Step 4: Specify the parameters of the economic cost model λ , C_0 , C_1 , a, b, Y, W , T_0 , T_1 , T_2 , E as given in equation (1)

Step 5: Compute the expected cost per hour for a given set of parameters as given in equation (1).

Step 6: Check the minimum value of expected cost per hour for a given set of parameters.

3. Automatic implantable cardioverter-defibrillators (AICDs)

An Automatic Implantable Cardioverter-Defibrillator (AICD) is a small implantable medical device used to monitor and correct life-threatening abnormal heart rhythms, especially ventricular Tachycardia (VT) and Ventricular Fibrillation (VF). These conditions can lead to sudden cardiac arrest, so continuous monitoring and immediate correction are critical. An AICD is surgically implanted under the skin near the upper chest, with electrode leads connected to the heart.

In-control ARL of 370 is maintained to compute the expected cost per hour for a sample size of 4. Both sets of parameters are considered to determine the optimal sampling intervals for the proposed CRSS-EWMA control chart used to monitor the reliability of Automatic Implantable Cardioverter-Defibrillators (AICDs). The lifetime of AICD devices is assumed to follow an exponential distribution. Expected cost is calculated for shifts in the process parameter of 0.25 and 0.5. Sample calculations to determine the optimal sampling interval h are given as follows. Various parameters for the proposed CRSS-EWMA control chart are considered as follows:

Sample size (n) = 4, CRSS set size (m) = 4, number of cycles (r) = 1, EWMA smoothing parameter (w) = 0.2, control limit coefficient (L) = 2.343. In-control average run length (ARL_0) = 370, shift in process parameter (δ) = 0.25.

$ARL_1 = 20.59$, $\lambda = 0.01$, $C_0 = 12.0$, $C_1 = 120.0$, $a = 0.5$, $b = 0.1$, $Y = 60.0$, $W = 22.4$, $\gamma_1 = 1$, $\gamma_2 = 1$, $T_0 = 0.5$, $T_1 = 2$, $T_2 = 2$, $E = 0.06$

Substituting the above values in equation (1),

$$\tau = 0.120, s = 416.167$$

$$\begin{aligned} &\text{Production Cost} = \\ &C_0/\lambda + C_1[-\tau + nE + h(ARL_1) + \gamma_1 T_1 + \gamma_2 T_2] = \\ &1200 + 120[-0.120 + 0.24 + 4.942 + 2 + 2] = 2,287.4 \end{aligned}$$

- Alarm and Repair Cost
 $= (sY/ARL_0) + W = (416.167 \times 60/370) + 22.4 = ₹89.89$
- Sampling Cost
 $= (a + bn)/h[(1/\lambda) - \tau + nE + h(ARL_1) + \gamma_1 T_1 + \gamma_2 T_2] = (0.9/0.24)(100 - 0.120 + 0.24 + 4.942 + 4) = 408.98$
- Cycle Time
 $= (1/\lambda) + [(1 - \gamma_1)sT_0/ARL_0] - \tau + nE + h(ARL_1) + T_1 + T_2 = 100 + 0 - 0.120 + 0.24 + 4.942 + 2 + 2 = 109.06 \text{ hours}$
- Total Expected Cost
 $= 2,287.46 + 89.89 + 408.98 = ₹2,786.33$

- Expected Cost per Hour $= 2,786.33 / 109.06 = ₹25.55/\text{hour}$
- The minimum expected monitoring cost is ₹25.55/hour, at the optimal sampling interval of 0.24 hour (₹25.557/hour at $h = 0.23$ and ₹25.554/hour at $h = 0.25$).

For the same parameters, the conventional EWMA chart requires $h = 0.17$ hour and costs ₹29.17/hour, so the CRSS-EWMA chart reduces the expected cost by 12.41 per cent while sampling less frequently. Expected cost per hour and sampling intervals are computed for sample sizes of 2 to 10 for shifts in the failure rate of 0.25 and 0.5 at the in-control ARL of 370. Table 1 shows the optimal sampling intervals (OSI) and expected cost per hour for various sample sizes and shifts, for both sets of parameters.

Parameter	Value	Description
Sample size (n)	4	Number of AICD devices monitored per inspection
Smoothing constant (w)	0.2	EWMA weight
In-control ARL	370	Average run length when device reliability is normal
Shift in failure rate (δ)	0.25	Change in AICD failure behaviour
Failure rate parameter	0.01	Exponential failure rate
Sampling cost coefficient a	0.5	Fixed inspection cost
Sampling cost coefficient b	0.1	Variable inspection cost
Investigation cost (Y)	60	Cost of analyzing device failure
Repair cost (W)	22.4	Device replacement/maintenance cost
Search time (T_0)	0.5	Time for false alarm investigation
Detection time (T_1)	2	Time to locate the device defect
Repair time (T_2)	2	Time to restore reliability
Sampling time per device (E)	0.06	Monitoring time

Table 1. Optimal sampling intervals for proposed CRSS-EWMA for various sample sizes

Sample Size (n)	ARL_0	Shift (δ)	ARL_1	OSI ₁ (hours)	EC ₁ (₹/hr)	OSI ₂ (hours)	EC ₂ (₹/hr)
2	370	0.25	54.59	0.14	29.543	0.33	91.025
2	370	0.5	20.29	0.22	24.504	0.43	71.657
3	370	0.25	31.33	0.19	27.041	0.41	82.307
3	370	0.5	11.58	0.30	22.916	0.57	64.907
4	370	0.25	20.59	0.24	25.548	0.51	76.588
4	370	0.5	8.04	0.39	22.138	0.71	61.481
5	370	0.25	14.90	0.30	24.606	0.61	72.783
5	370	0.5	6.19	0.46	21.700	0.85	59.529
6	370	0.25	11.53	0.35	23.982	0.71	70.185
6	370	0.5	5.07	0.54	21.432	0.99	58.331
7	370	0.25	9.37	0.41	23.553	0.81	68.362
7	370	0.5	4.33	0.61	21.259	1.12	57.564
8	370	0.25	7.89	0.46	23.249	0.91	67.054
8	370	0.5	3.79	0.68	21.145	1.25	57.061
9	370	0.25	6.82	0.51	23.029	1.02	66.097
9	370	0.5	3.39	0.75	21.068	1.39	56.726
10	370	0.25	6.02	0.57	22.867	1.12	65.389
10	370	0.5	3.07	0.82	21.016	1.52	56.500

OSI₁, EC₁ = Optimal sampling interval and expected cost/hour for the first set of parameters

OSI₂, EC₂ = Optimal sampling interval and expected cost/hour for the second set of parameters

The results indicate that the optimal sampling interval in Table 1 depends on the sample size and the shift in the failure rate of AICD devices. Larger shifts and larger samples give shorter ARL_1 values, and

therefore longer optimal sampling intervals and lower expected cost: when each sample is more likely to signal, the chart can sample less often. Under the first set of parameters, the optimal sampling interval increases from 0.14 to 0.82 hour and the expected cost decreases from ₹29.54 to ₹21.02 per hour as n increases from 2 to 10. Under the second set, where assignable causes are more frequent and sampling is costlier, the optimal sampling intervals are longer (0.33 to 1.52 hours)

and the expected cost is higher (₹56.50 to ₹91.03 per hour). The EWMA control chart effectively detects small changes in AICD failure behaviour. Thus, the proposed CRSS-EWMA monitoring framework provides an economically efficient method for surveillance of the reliability performance of Automatic Implantable Cardioverter-Defibrillators.

Comparison of CRSS-EWMA and conventional EWMA control charts

The economic design of the proposed CRSS-EWMA control chart has been compared with the economic design of the RSS-EWMA control chart for monitoring the reliability of Automatic Implantable Cardioverter-Defibrillators (AICDs). The expected cost per hour and optimal sampling intervals are computed for different sample sizes and shifts in the failure rate, with both charts designed for $ARL_0 = 370$. The comparison results are presented in Tables 2 and 3.

First set of parameters

$$\lambda = 0.01, C_0 = 12, C_1 = 120.0, a = 0.5, b = 0.1, Y = 60.0, W = 22.4, \gamma_1 = 1, \gamma_2 = 1, T_0 = 0.5, T_1 = 2, T_2 = 2, E = 0.06.$$

Second set of parameters

$$\lambda = 0.05, C_0 = 12, C_1 = 120.0, a = 5.0, b = 1.0, Y = 90.0, W = 35.0, \gamma_1 = 1, \gamma_2 = 1, T_0 = 0.5, T_1 = 2, T_2 = 2, E = 0.10.$$

Table 2. Comparison of Expected Cost between CRSS-EWMA and RSS-EWMA (First Set of Parameters)

n	ARL_0	δ	OSI_p (CRSS)	OSI_e (RSS)	EC_p (₹/hr)	EC_e (₹/hr)
7	370	0.25	0.41	0.25	23.553	27.828
7	370	0.5	0.61	0.41	21.259	23.502
8	370	0.25	0.46	0.28	23.249	27.596
8	370	0.5	0.68	0.45	21.145	23.429
9	370	0.25	0.51	0.30	23.029	27.423
9	370	0.5	0.75	0.49	21.068	23.393
10	370	0.25	0.57	0.33	22.867	27.294
10	370	0.5	0.82	0.52	21.016	23.381

OSI_p = Optimal sampling interval of CRSS-EWMA chart
 OSI_e = Optimal sampling interval of RSS-EWMA chart
 EC_p = Expected

cost/hour of CRSS-EWMA chart
 EC_e = Expected cost/hour of RSS-EWMA chart

Table 3. Comparison of Expected Cost between CRSS-EWMA and RSS-EWMA (Second Set of parameters)

n	ARL_0	δ	OSI_p (CRSS)	OSI_e (RSS)	EC_p (₹/hr)	EC_e (₹/hr)
2	370	0.25	0.33	0.33	91.025	97.154
2	370	0.5	0.43	0.39	71.657	77.476
3	370	0.25	0.41	0.38	82.307	93.094
3	370	0.5	0.57	0.48	64.907	73.126
4	370	0.25	0.51	0.43	76.588	90.382
4	370	0.5	0.71	0.56	61.481	70.779
5	370	0.25	0.61	0.49	72.783	88.468
5	370	0.5	0.85	0.65	59.529	69.418

The performance of the CRSS-EWMA control chart is compared with the conventional EWMA control chart using the optimal sampling interval and expected cost per hour. From the results in Tables 2 and 3, it can be observed that the expected cost per hour (EC_p) of the CRSS-EWMA chart is smaller than the expected cost per hour (EC_e) of the conventional EWMA chart for every sample size and shift in the failure rate. For example, in Table 2, the expected costs 23.553, 23.249, 23.029 and 22.867 (CRSS-EWMA) at $\delta = 0.25$ are smaller than 27.828, 27.596, 27.423 and 27.294 (RSS-EWMA). Similarly, in Table 3, the CRSS-EWMA costs 91.025, 82.307, 76.588 and 72.783 at $\delta = 0.25$ are lower than the corresponding EWMA costs 97.154, 93.094, 90.382 and 88.468.

From Tables 2 and 3, it can be observed that the economic design of the proposed CRSS-EWMA control chart performs better than the conventional EWMA control chart for all sample sizes and shifts con-

sidered. This reduction in expected cost occurs because Circular Ranked Set Sampling provides more informative observations than simple random sampling, with PRE increasing from 133.3 per cent at $n = 2$ to 341.4 per cent at $n = 10$. As a result, the CRSS-EWMA chart detects shifts in the reliability behaviour of AICD devices more quickly: for example, at $n = 7$ and $\delta = 0.25$, ARL_1 is 9.37 for CRSS-EWMA against 24.71 for EWMA. This gives a shorter out-of-control period and reduced production loss. The CRSS-EWMA chart also has longer optimal sampling intervals than the EWMA chart (for example, 0.41 against 0.25 hour at $n = 7$ and $\delta = 0.25$), so it needs fewer samples per hour. Therefore, the proposed CRSS-EWMA control chart provides an economically efficient monitoring scheme for detecting reliability shifts in Automatic Implantable Cardioverter-Defibrillators.

4. Discussion

The performance of the proposed CRSS-EWMA control chart is compared with the conventional EWMA control chart using optimal sampling intervals and expected cost per hour. The results show that the CRSS-EWMA chart provides a lower expected cost per hour than the conventional EWMA chart for all sample sizes and shifts in the failure rate. Under the first set of parameters (Table 2, $n = 7$ to 10), the saving ranges from ₹2.24 to ₹4.43 per hour, a reduction of 9.54% to 16.22%. Under the second set of parameters (Table 3, $n = 2$ to 5), the saving ranges from ₹5.82 to ₹15.69 per hour, a reduction of 6.31% to 17.73%. For an AICD monitoring system that runs continuously (8,760 hours per year), this is roughly ₹19,600 to ₹38,800 per year under the first set and ₹51,000 to ₹1,37,400 per year under the second set for each monitored stream, and the saving grows in proportion to the number of device lots or production streams being monitored.

The savings increase with the sample size, in line with the increase in PRE, and under the first set it is larger for the smaller shift (15.36% to 16.22% at $\delta = 0.25$ against 9.54% to 10.12% at $\delta = 0.5$), because small shifts take longer to detect and the out-of-control cost dominates. The CRSS-EWMA chart also needed longer optimal sampling intervals than the conventional EWMA chart (by 0.16 to 0.30 hr under the first set and 0 to 0.20 hr under the second set). Together with its lower cost, this indicates that the more informative CRSS observations allow earlier detection of an increase in the device failure rate with less frequent sampling. In practice, earlier detection means that a batch of devices whose reliability is degrading can be identified and investigated sooner, so that corrective action can start earlier. The optimal sampling intervals became longer as the sample size and shift size increased, in line with the smaller ARL_1 values for larger samples and larger shifts.

5. Conclusion

This study developed an economic design of the EWMA control chart based on Circular Ranked Set Sampling (CRSS) for monitoring the reliability of Automatic Implantable Cardioverter-Defibrillators (AICDs), whose lifetimes follow an exponential distribution. The optimal sampling intervals were obtained by minimizing the expected cost per hour under the Lorenzen-Vance unified cost model at a fixed in-control ARL of 370.

The proposed CRSS-EWMA chart gave a lower expected cost per hour than the conventional EWMA chart in every combination of sample size ($n = 2$ to 10) and shift ($\delta = 0.25, 0.5$) considered, with savings of 9.54% to 16.22% under the first set of parameters and 6.31% to 17.73% under the second set in Tables 2 and 3. In the numerical example ($n = 4, \delta = 0.25$), the minimum expected cost is ₹25.55 per hour at an optimal sampling interval of 0.24 hr, against ₹29.17 per hr for the conventional EWMA chart. In summary, the CRSS-EWMA chart is an economically efficient and statistically sound alternative to the RSS-EWMA chart for the reliability monitoring of implantable cardiac devices.

References

- Lucas JM, Saccucci MS. Exponentially weighted moving average control schemes: Properties and enhancements. *Technometrics*. 1990;32(1):1-12.
- Montgomery DC. *Introduction to statistical quality control* (6th ed.). John Wiley & Sons. 2009.
- Lorenzen TJ, Vance LC. The economic design of control charts: A unified approach. *Technometrics*. 1986;28(1):3-10.
- Linderman K, Love TP. Economic and economic-statistical design of MEWMA control charts. *Journal of Quality Technology*. 2000;32(4):410-421.
- Prajapati DR, Mahapatra PB. An economical comparison of proposed $\bar{X}$ chart with MEWMA chart. *International Journal of Quality & Reliability Management*. 2010;27(4):475-485.
- Amiri A, Moslemi A, Doroudyan MH. Robust economic and economic-statistical design of EWMA control chart. *The International Journal of Advanced Manufacturing Technology*. 2015;78:511-523.
- Katebi M, Pourtaheri R. An economic-statistical design of the Poisson EWMA control charts for monitoring nonconformities. *Journal of Statistical Computation and Simulation*. 2019;89(15):2813-2830.
- Lee MH, Khoo MBC, Haq A, Chew X. Economic-statistical design of the variable sampling interval Poisson EWMA chart. *Communications in Statistics Simulation and Computation*. 2023;52(5):2139-2150.
- Lucas JM, Saccucci MS. Exponentially weighted moving average control schemes: Properties and enhancements. *Technometrics*. 1990;32(1):1-12.
- Linderman K, Love TP. Economic and economic-statistical design of MEWMA control charts. *Journal of Quality Technology*. 2000;32(4):410-421.
- Lorenzen TJ, Vance LC. The economic design of control charts: A unified approach. *Technometrics*. 1986;28(1):3-10.
- Montgomery DC. *Introduction to statistical quality control* (8th ed.). Hoboken, NJ: John Wiley & Sons; 2019.
- Prajapati DR, Mahapatra PB. An economical comparison of proposed $\bar{X}$ chart with MEWMA chart. *International Journal of Quality & Reliability Management*. 2010;27(4):475-485.
- Rafiei N, Asadzadeh S, Niaki STA. Multi-objective design of risk-adjusted control chart in healthcare systems with economic and statistical considerations. *Communications in Statistics – Simulation and Computation*. 2021;52(7):2667-2684.
- Sarwar MA, *et al.* A novel EWMA-based adaptive control chart for industrial process monitoring. *Scientific Reports*. 2024;14.
- Hunter JS. The Exponentially Weighted Moving Average. *Journal of Quality Technology*. 1986;18:203-210.
- Lu CW, Reynolds MR Jr. EWMA control charts for monitoring the mean of autocorrelated processes. *Journal of Quality technology*. 1999;31(2):166-188.
- Lucas JM, Saccucci MS. Exponentially Weighted Moving Average Control Schemes: Properties and Enhancements. *Technometrics*. 1990;32(1):1-12.
- Patil GP, Sinha AK, Taillie C. 5 Ranked set sampling. *Handbook of statistics*. 1994;12:167-200.
- McIntyre GA. A method for unbiased selective sampling, using ranked sets. *Australian journal of agricultural research*. 1952;3(4):385-390.
- Samawi HM, Muttlak HA. Estimation of ratio using rank set sampling. *Biometrical Journal*. 1996;38(6):753-764.
- Patil GP, Sinha AK, Taillie C. Ranked set sampling: a bibliography. *Environmental and Ecological Statistics*. 1999;6:91-98.
- Tiwari N, Chandra G, Nautiyal R. Ranked Set Sampling: A Review with New Initiative on Extreme Ranked Set Sampling. 2019.
- Lorenzen TJ, Vance LC. The economic design of control charts: A unified approach. *Technometrics*. 1986;28(1):3-10.

How to cite this article: Kaviyarasu DV, Inbarasi M. Enhancing EWMA chart using CRSS for cost models: application to implantable cardioverter-defibrillator monitor. *International Journal of Statistics and Applied Mathematics*. 2026;11(10):44-48. doi: <https://www.doi.org/10.22271/math.2026.v11.i10a.2716>