Comparison of Two Maintenance Policies for the Coordination of Decisions of Quality Control and Maintenance Planning

Hasan Rasay
Department of Industrial Engineering
Kermanshah University of Technology
Kermanshah, Iran.
H.Rasay@kut.ac.ir

Farnoosh Naderkhani
Concordia Institute of Information System Engineering (CIISE)
Concordia University
Montreal, Canada.
Farnoosh.naderkhani@concordia.ca

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Abstract— Recent increased enthusiasm towards mechanization and automation of production systems have resulted in interactions between maintenance management and statistical process control (SPC) as the main two major components of production systems. Consequently, different integrated models of maintenance and SPC have been developed to coordinate the decisions of these two components. In this paper, two maintenance policies are investigated for coordination of decisions of maintenance and SPC. A generic integrated mathematical model is developed and with simple modifications, the model can be employed to minimize the expected cost of the process unit time under each policy. Sensitivity analyses, comparative studies, and numerical examples are also provided.

Keywords—Quality control, Maintenance planning, Failure mechanism, Integrated model.

I. INTRODUCTION

Control charts as the powerful method of statistical process control (SPC) have been widely employed to maintain the stability of the production processes. On the other hand, maintenance is defined as a set of technical and administrative actions performed with the aim of retain the production system in operational states or restore them to the operational state. Widespread mechanization and automation increase the interactions between maintenance planning and statistical process control [1]. In many production processes, quality deterioration of produced items can be attributed to the poor maintenance condition of the production machines. Thus, evaluation of the quality characteristics of the process can provide partial information regarding the maintenance condition of the production machines [2-3].

Considering the above-mentioned points, different mathematical and simulation models have been developed in the literature of operation management with the aim of integration of the decisions of quality control and maintenance management. These models can be classified according to different characteristics. For example, in some integrated models, it is assumed that the process only has different operational states, i.e., in-control state and out-of-control state [4-5] while in some research, besides the operational states, the failure state is also considered for the system[6-7].

Regarding the type of the control chart in the integrated models of maintenance and quality, researchers have employed different types of them from a simple univariate $\bar{X}$ control chart to multivariate control charts and adaptive control charts. In some studies of integrated models, exponential distribution is assumed for the deterioration of the process or transition among the states of the system [8-9]. Assuming exponential distribution for failure mechanism facilitates the derivation of the models as the Markov chain properties can be applied. However, deterioration of many production systems does not follow exponential distribution. In these cases, some studies assume Weibull distribution [10-11]. Also, some studies have developed the models while a general continuous distribution is assumed for the process failure mechanism [5],[12].

In some studies focused on the integration of maintenance and SPC, it is assumed that after releasing a false alarm from the control chart, the process continues its operation without interruption, while in some other research, the integrated models are proposed assuming that having released a false alarm from the control chart, a specific maintenance action is conducted which terminates the production cycle. In this paper, a mathematical model is developed which optimizes the expected cost of the process per unit time. In particular, we concentrate the attention on two different maintenance policies. The model has a flexible structure so that by simple modifications, it can be easily applied to optimize the performance of the system under different policies. The rest of the paper is organized as follows: Section 2 introduces the problem and different maintenance policies implemented on the process during a production cycle. In Section 3, the models for two maintenance policies are derived. Section 4 presents numerical examples and sensitivity analyses. Finally, Section 5 concludes the paper.

II. PERFORMANCE OF THE PRODUCTION SYSTEM UNDER TWO DIFFERENT MAINTENANCE POLICIES

In this section, evolution of the production process during a production cycle under each maintenance policies is discussed.

2.1. Maintenance planning according to policy 1

Consider a production process that has two operational states: an in-control state denoted by state 0 and an out-of-control state denoted by state 1. The operation of the process in state 1 is undesirable, as in comparison with state 0, it leads to much more operational cost and also yields the higher quality costs. The time that the process spends in state 0 before transition to state 1, i.e., the process failure mechanism, follows a general continuous distribution function with non-decreasing failure rate.

The process is monitored as follows: at specific time points such as $(t_1,t_2,\dots,t_{m-1})$ which are the decision variables of the model, n units of the produced items of the process are selected and a suitable quality characteristic (characteristics) is (are) measured and then a suitable statistic is calculated. This statistic is plotted on a desired control chart. If the statistic falls within the control limits of the control chart, the process will continue its operation without any interruption. If the statistic falls outside the control limits, an alarm is issued from the control chart. After that, an investigation is performed on the system to verify this alarm. If the investigation concludes that the chart signal is incorrect (i.e., the process is in state 0), the process continues its operation without any further interruptions, but if the investigation concludes that the chart signal is correct, a reactive maintenance (RM) is implemented.

At the end of the production cycle (at time point t_m), there is no sampling from the produced items; but only the maintenance inspection is applied to determine the true state of the process. If the maintenance inspection indicates that the system is in the in-control state at t_m, then a preventive maintenance (PM) is conducted, but if the maintenance inspection indicates that the system state is out-of-control at tm then RM is applied. Based on the descriptions presented so far, three scenarios are possible for the evolution of the process during a production cycle.

Scenario 1: The process remains in state 0 until tm, hence, PM is conducted at tm.

Scenario 2: The Process shifts to state 1 before t_{m-1} , and an alarm is released from the control chart in one of the remaining inspection periods. Thus, RM is implemented and the process is renewed.

Scenario 3: The process shifts to state 1 before t_m , but the control chart cannot release this state. In other words, no alarm indicating the out-of-control state of the process is issued by the control chart in the remaining inspection periods. Hence, at tm, after the maintenance inspection, the true state of the process is identified, and RM is conducted. Thus, in this policy, a production cycle terminates because of PM or RM actions.

2.2 Maintenance planning according to policy 2

The main difference of this policy with policy 1 is as follows: it is assumed that if the control chart issues a false alarm in one of the inspection time points, a compensatory maintenance (CM) action is conducted on the process. Accordingly, in each production cycle, four scenarios may occur:

Scenario 1: The process remains in state 0 until tm and no alarm is released from the control chart in the previous inspection periods. Hence, PM is conducted on the process at t_m.

Scenario 2: While the process is operating in state 0, a false alarm is released from the control chart. Hence, CM is implemented, and the process is renewed.

Scenario 3: The Process shifts to state 1 before t_{m-1}, and an alarm is released from the control chart in one of the remaining inspection periods. Thus, RM is implemented, and the process is renewed.

Scenario 4: The process shifts to state 1 before t_m, but the control chart cannot release this state. In other words, no alarm indicating the out-of-control state of the process is issued by the control chart in the remaining inspection periods. Hence, at tm, after the maintenance inspection, the true state of the process is identified, and RM is conducted.

Accordingly, in this policy, a production cycle of the process starts in state 0 and is terminated due to implement one type of the maintenance actions (RM, PM or CM).

III. COST OPTIMIZATION FOR INTEGRATED MODEL BASED ON FIRST POLICY

According to the assumptions presented in Section 2.1, the mathematical model of integration of maintenance and quality control is developed for the first proposed policy.

The process monitoring described in the previous section can be considered as a renewal reward process consisting of the stochastic and independent identical cycles. E[T] and E[C] are defined as the expected cycle length of a production cycle and the expected cost of a production cycle, respectively. Hence, the expected cost of the process per time unit (ECT) can be obtained using the following formula:

$$ECT = \frac{E[C]}{E[T]} \tag{1}$$

Now, consider a single arbitrary inspection interval such as (t_{i-1},t_i). Given the state of the process which is identified immediately after the inspection at t_{i-1} , three different configurations can be considered as follows:

Configuration 1: The process is in state 0 at t_{i-1} and remains in this state until t_i. The occurrence probability of this case is as follows:

$$P\left(a_{t_{i-1}}\right) = P\left(t > t_i | X_{t_{i-1}} = 0\right) = \frac{\bar{F}(t_i)}{\bar{F}(t_{i-1})}\,. \tag{2}$$

Note that $F(t)$ is the cumulative distribution function (c.d.f) of the process failure mechanism and $\bar{F}(t_i) = 1 - F(t_i)$.

Configuration 2: The process is in state 1 at t_{i-1} and remains in this state until t_i. The occurrence probability of this case is as follows:

$$P\left(b_{t_{i-1}}\right) = P\left(X_{t_i} = 1 | X_{t_{i-1}} = 1\right) = 1 \tag{3}$$

Configuration 3: In this case, the process is in state 0 at t_{i-1} but at time point t $(t_{i-1}<t<t_i)$, the process transits to stat 1. The occurrence probability of this case is as follows:

$$P(c_{t_{i-1}}) = P(t_{i-1} < t < t_i | X_{t_{i-1}} = 0) = 1 - P(a_{t_{i-1}}) \quad (4)$$

Let define $P^0_{t_i}, P^1_{t_i}$ as the probability of operation of the process in state 0 or 1 immediately after the inspection at t_i, respectively. $P^0_{t_i}$ is computed as follows:

$$P^0_{t_i} = \bar{F}(t_i); i = 1,2,\dots,m. \quad (5)$$

Also, for $i = 1,2,\dots,m-1, P^1_{t_i}$ is given by this recursive formula:

$$P^1_{t_i} = \beta\left[P^1_{t_{i-1}} \times P(b_{t_{i-1}}) + P^0_{t_{i-1}} \times P(c_{t_{i-1}})\right] = \beta\left[P^1_{t_{i-1}} + P^0_{t_{i-1}} \times P(c_{t_{i-1}})\right], \quad (6)$$

where β represents the probability of type II error. The sum of the two terms inside the square brackets is the probability of the process operation in state 1 just before the inspection at t_i. Also, if the process is in state 1 before the inspection at t_i ,with the probability of β, the control chart cannot detect the out-of-control state, and the process will continue its operation in state 1 after the inspection performed at t_i.

It is assumed that all the maintenance actions are perfect, thus, the following equation holds true at the start of each production cycle:

$$P^0_0 = 1;\ P^1_0 = 0 \quad (7)$$

Eq. 7 states that the process is always in the in-control state at the start of a production cycle. Based on the notations and assumptions introduced so far, E[C] in Eq. 1 is given by the following equation:

$$E[C] = W_0 E[T_0] + W_1 E[T_1] + W_{QC} E[QC] + W_I(E[\alpha] + 1) + W_{PM} P_{PM} + W_{RM} P_{RM}, \quad (8)$$

where W_1 is the expected operation cost of the process per unit time when the process is in state i for i={0,1} such that $W_1 > W_0$. W_{QC} is the cost of sampling. W_I is the inspection cost. W_{PM} and W_{RM} represent preventive and reactive maintenance cost, respectively. $E[T_0]$ and $E[T_1]$ represent expected time that the process operates in state 0 and state 1 in a production cycle, respectively. $E[QC]$ is the expected numbers of sampling inspection in a production cycle. Finally, P_{PM} (4) and P_{RM} denote the probability of termination of a production cycle due to the preventive and reactive maintenance actions, respectively.

Similarly, expected cycle length is given by:

$$E[T] = E[T_0] + E[T_1] + Z_I(E[\alpha] + 1) + Z_{PM} P_{PM} + Z_{RM} P_{RM}, \quad (9)$$

where Z_I, Z_{PM} and Z_{RM} represent expected inspection, preventive and reactive time.

Now, we proceed to compute each term in Eqs. 8 and 9. If T^i_0 is defined as the expected time length that the process operates in state 0 within interval (ti-1,ti), then E[T0] can be computed as follows:

$$E[T_0] = \sum_{i=1}^{m} T^i_0, \quad (10)$$

(6)

such that for $i = 1,2,\dots,m, T^i_0$ is calculated as follows:

$$T^i_0 = P^0_{t_{i-1}}\left[\frac{\bar{F}(t_i)}{\bar{F}(t_{i-1})}(t_i - t_{i-1}) + \int_{t_{i-1}}^{t_i} \frac{f(t)}{\bar{F}(t_{i-1})}(t - t_{i-1})dt\right]. \quad (11)$$

This equation is derived considering the fact that if the process is in state 0 at t_{i-1} and scenario a occurs, then the process operates in state 0 in the whole of the interval. On the other hand, if scenario c occurs, the time length that the process operates in state 0 is $t - t_{i-1}$.

If T^i_1 is defined as the expected time length that the process operates in state 1 within interval

(t_{i-1}, t_i) then $E[T_1]$ is computed as follows:

$$E[T_1] = \sum_{i=1}^{m} T^i_1 \quad (12)$$

while T^i_1 is obtained as follows:

$$T^i_1 = P^0_{t_{i-1}}\left[\int_{t_{i-1}}^{t_i} \frac{f(t)dt}{\bar{F}(t_{i-1})}(t_i - t)dt\right] + P^1_{t_{i-1}}(t_i - t_{i-1}). \quad (13)$$

Derivation of Eq. 13 is similar to Eq. 11.

If P^i_{RM} is defined as the probability of conducting RM just after the inspection at t_i, then P_{RM} is obtained as follows:

$$P_{RM} = \sum_{i=1}^{m} P^i_{RM}, \quad (14)$$

while P^i_{RM} is computed as follows:

$$P_{RM}^{i} = (1-\beta)\left[P_{t_{i-1}}^{1} + P_{t_{i-1}}^{0}\int_{t_{i-1}}^{t_i}\frac{f(t)dt}{\bar{F}(t_{i-1})}\right]. \quad (15)$$

The sum of the two terms inside the brackets is the probability of process operation in state 1 just before the inspection at time t_i. Also, if the process is in state 1 before the inspection at t_i, with the probability of $1-\beta$, the control chart detects the out-of-control state and RM is implemented.

Since, there is no sampling inspection in the last inspection period, i.e., only the inspection is performed at time point t_m, thus P_{RM}^{m} can be computed as follows:

$$P_{RM}^{m} = P_{t_{m-1}}^{1} + P_{t_{m-1}}^{0}\int_{t_{m-1}}^{t_m}\frac{f(t)dt}{\bar{F}(t_{m-1})}. \quad (16)$$

We assume that the production cycle terminates due to the performance of one of the following maintenance actions: RM or PM. The probability of termination of a production cycle due to the performance of RM is computed previously. The probability of termination of a production cycle due to the performance of PM is as follows:

$$P_{PM} = 1 - P_{RM}. \quad (17)$$

If P_{QC}^{i} is defined as the probability of performing the sampling inspection at the end of interval (t_{i-1}, t_i), then E[QC] is given by the following equation:

$$E[QC] = \sum_{i=1}^{m-1} P_{QC}^{i}, \quad (18)$$

Such that

$$P_{QC}^{i} = P_{t_{i-1}}^{0} + P_{t_{i-1}}^{1}. \quad (19)$$

Note that, the sum of the two terms in the right-hand side of Eq.19 is not necessarily equal to one. It is possible that a production cycle is terminated before reaching to time point t_{i-1} due to performance of RM. Finally, the expected number of false alarms within a production cycle is given by:

$$E[\alpha] = \sum_{i=1}^{m-1} P_{\alpha}^{i} \quad (20)$$

where P_{α}^{i} is the probability of false alarm at time point t_i which can be computed as follows:

$$P_{\alpha}^{i} = \alpha \times \bar{F}(t_i). \quad (21)$$

This completes the calculation for the long-run expected average cost for the first policy.

IV. COST OPTIMIZATION FOR INTEGRATED MODEL BASED ON SECOND POLICY

In this policy, expected cost per time unit (ECT) can be obtained from Equation 1, while $E[C]$ and $E[T]$ are computed based on the following equations:

$$E[C] = W_0 E[T_0] + W_1 E[T_1] + W_{QC} E[QC] + W_{PM} P_{PM} + W_{RM} P_{RM} + W_{CM} P_{CM} + W_I, \quad (22)$$

and

$$E[T] = E[T_0] + E[T_1] + Z_{PM} P_{PM} + Z_{RM} P_{RM} + Z_{CM} P_{CM} + Z_I \quad (23)$$

If P_{CM}^{i} is defined as the probability of performing CM just after the inspection at t_i, then P_{CM}, the probability that a production cycle is terminated due to the CM, is given by this equation:

$$P_{CM} = \sum_{i=1}^{m} P_{CM}^{i} \quad (24)$$

While P_{CM}^{i} is computed as follows:

$$P_{CM}^{i} = \bar{F}(t_i)(1-\alpha)^{i-1}\alpha \quad (25)$$

In this policy, the following equation holds for computing $P_{t_i}^{0}$:

$$P_{t_i}^{0} = \bar{F}(t_i)(1-\alpha)^{i}; i = 1,2,\dots,m-1 \quad (26)$$

Each production cycle terminators due to the effect of PM, CM or RM. Eq. 14 computes the termination probability of a production cycle due to the effect of RM. Thus, probability of termination a production cycle due to PM is as follows:

$$P_{PM} = 1 - P_{CM} - P_{RM} \quad (27)$$

The other equations of subsection III is valid to compute the terms of Eqs. 22 and 23.

V. NUMERICAL EXAMPLE

This example is selected from Reference [3]. A manufacturer producing nonreturnable glass bottles which are designed to package a carbonated soft drink beverage. The manufacturer used X-bar control chart for the process monitoring. When the process is in the in-control state, the quality characteristic follows a normal distribution with the mean and variance of μ_0, σ^2, respectively. In the out-of-control state, the mean of the process shifts to $\mu_1 = \mu_0 + \delta\sigma$, while the variance of the process remains unchanged. Also, δ indicates the magnitude of the shift, and it is assumed to be constant. The thickness of the bottles is an important quality characteristic. Suppose that the thickness of the bottle in the in-control state is 10mm and a single assignable cause leads to a shift in the mean of the process with the magnitude of $\delta = 1$.

For the X-bar chart, the probability of type I and type II errors are given by:

$$\alpha = 2\Phi(-k);\ \beta = \Phi(k - \delta\sqrt{n}) - \Phi(-k - \delta\sqrt{n}) \quad (28)$$

Where $\Phi(.)$ indicates the cumulative distribution function (c.d.f) of the standard normal distribution. Also, the process failure mechanism is based on a Weibull distribution with shape parameter $v = 2$ and mean $\mu = 20$ hours. In the analyses of this section, it is assumed that sampling inspections are conducted at equidistant intervals denoted as (h). The other parameters of the process are illustrated in Table 1. In this table, W_f and W_v are the fixed and variable sampling cost respectively. Thus, W_{QC} for n units is $W_f + n \times W_v$.

Table 1. The parameters of the process

parameter	δ	W_f	W_v	W_I	W_0	W_1	W_{RM}	W_{PM}	W_{CM}
value	*1*	*10*	*0.1*	*100*	*10*	*200*	*3000*	*2000*	*1000*

parameter	Z_I	Z_{RM}	Z_{PM}	Z_{CM}
value	0.3	1	0.8	0.6

Table 2. The results of the optimization

Decision variables	h	k	n	m	t_m	ECT
Policy 1	3.9	2.8	25	9	35.1	161.29
Policy 2	3.6	2.8	24	10	36	161.05

The results of the optimization for both policies are shown in Table 2. As the data of Table 2 shows, there is a limit difference between the performances of the two polices. According to policy 1, a sample with size 25 should be taken from the process evert 3.9 hours. The mean of the sample is plotted on an x-bar control chart with coefficient 2.8 for the control limit. Maximum duration of a production cycle is 35.1 hours and after that the process is inspected and the appropriate maintenance actions, i.e. PM or RM, should be conducted. This policy leads to minimize the expected cost per time unit which is 161.29. According to Table 2, maximum duration of production cycle in policy 2 is 36 which is a bit more than the one in policy 1. It is worthwhile to note that in optimization of the models we stipulate that the average run length (ARL) of the control chart in control state should be bigger than 150. This constraint guaranties suitable statistical properties for the control chart. Table 3 shows the results of some sensitivity analyses. The results of change in some main parameters are illustrated in this table. For example, the table shows that an increase of the mean time to shift the process from state 0 to 1 (μ) from 20 to 40 leads to a decrease in ECT while the values of m and t_m increases. The effect of change in the magnitude of the shift (δ) from 1 to 2 is a significant decrease of sample size (n) and a slight decrease in ECT. The main effect of increasing W_0 from 10 to 20 is increase of h (interval of sampling) and ECT. Regarding the comparison of two policies, generally speaking, the table shows that the difference between the performances of these two polices is negligible. This result is justifiable due the fact that a constraint is placed for the ARL of the control chart in optimization the models, i.e., ARL of the control chart in control state should be bigger than 150. The results of further numerical examples show that relaxing this constraint leads to significant difference between the performances of the process under each policy.

VI. CONCLUSION

In this paper, a mathematical model is developed for the integration of the decisions of maintenance planning and quality control in a production system with two operational states. The model is derived assuming a general continuous random variable for failure mechanism of the process. Also, the model has versatile features and with simple modifications it can be employed for different maintenance policies. More specifically, two maintenance policies are considered. The main difference of these two policies is as follows: in the second policy, it was assumed that having released a false alarm from the control chart, a compensatory maintenance action is conducted which terminates the production cycle, while in the first policy, during a production cycle, if a false alarm issues from the control chart, the process continues its operation without any further maintenance interruption. Comparison studies and numerical and sensitivity analyses are also provided. According to the comparative studies, difference between the performances of the process under each policy is not significant.

Table 3. The result of a sensitivity analysis for some important factors of the integrated model

	δ=1				δ=2			
	W_0=10		W_0=20		W_0=10		W_0=20	
	Policy 2	Policy 1	Policy 2	Policy 1	Policy 2	Policy 1	Policy 2	Policy 1
20	$ECT = 161.05$ $h = 3.6$ $k = 2.8$ $n = 24$ $m = 10$ $t_m = 36$	$ECT = 161.29$ $h = 3.9$ $k = 2.8$ $n = 25$ $m = 9$ $t_m = 35.1$	$ECT = 169.68$ $h = 4$ $k = 2.8$ $n = 24$ $m = 9$ $t_m = 36$	$ECT = 169.89$ $h = 4.4$ $k = 2.8$ $n = 25$ $m = 8$ $t_m = 35.2$	$ECT = 160.53$ $h = 3.3$ $k = 2.8$ $n = 7$ $m = 11$ $t_m = 36.3$	$ECT = 160.77$ $h = 3.5$ $k = 3.1$ $n = 8$ $m = 10$ $t_m = 35$	$ECT = 169.23$ $h = 3.9$ $k = 2.8$ $n = 7$ $m = 9$ $t_m = 35.1$	$ECT = 169.44$ $h = 3.9$ $k = 3.1$ $n = 8$ $m = 9$ $t_m = 35.1$
40	$ECT = 92.36$ $h = 3.1$ $k = 2.8$ $n = 24$ $m = 22$ $t_m = 68.2$	$ECT = 92.62$ $h = 3.2$ $k = 2.8$ $n = 25$ $m = 21$ $t_m = 67.2$	$ECT = 101.70$ $h = 3.3$ $k = 2.8$ $n = 24$ $m = 21$ $t_m = 69.3$	$ECT = 101.95$ $h = 3.4$ $k = 2.8$ $n = 25$ $m = 20$ $t_m = 68$	$ECT = 91.74$ $h = 2.9$ $k = 2.8$ $n = 7$ $m = 24$ $t_m = 69.6$	$ECT = 91.96$ $h = 3$ $k = 3.3$ $n = 9$ $m = 23$ $t_m = 69$	$ECT = 101.10$ $h = 3$ $k = 2.8$ $n = 7$ $m = 23$ $t_m = 69$	$ECT = 101.32$ $h = 3.1$ $k = 3.3$ $n = 9$ $m = 22$ $t_m = 68.2$

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