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A New Approach in Joint Optimization of Maintenance Planning, Process Quality and Production Scheduling

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A B S T R A C T

Shop floor performance has great influence on performance of a manufacturing system. Traditionally, shop floor operational policies concerning maintenance scheduling, quality control and production scheduling have been considered and optimized independently. Anyway, these aspects of operations planning have an interaction effect on each other significantly and hereupon for improving the system performance; they need to be considered commonly. The main objective of this study is to provide a new approach in the quality control process. $\bar{x}$ control chart has been used in previous models, but in this study to improve the quality and increase the accuracy, cumulative sum control chart which is useful for detecting small changes by considering previous information of process is used and causes 5% improvement in objective function in the case that $\bar{x}$ control chart was used.

1. Introduction

Production scheduling, maintenance scheduling and process quality is some of the key operational policies, affecting the performance of any manufacturing system. Most production scheduling models, do not consider the effect of machine unavailability due to failure or maintenance activity. Similarly, maintenance planning models seldom consider the impact of maintenance on due dates to meet customer requirements.

An increasing number of researchers have recognized that there is a significant connection between product quality, process quality and equipment maintenance (Ben-Daya & Duffuaa, 1995), and integration of these may be beneficial to the organization [1]. Rahim (1993) jointly determined the optimal design parameters on an x-bar control chart and preventive maintenance (PM) time for a production system with an increasing failure rate [2]. Ben-Daya (1999), Ben-Daya and Rahim (2000) and Rahim (1994) investigated the integration of x-bar chart and PM, when the deterioration process during in-control period follows a general probability distribution with increasing hazard rate [3-5].

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This paper focuses on the joint consideration of production scheduling, maintenance scheduling and process quality with a new approach in the system monitoring. In order to improve the process quality and reduce the production defects we use CUSUM chart to control process quality.

The paper is organized as follows: in Section 2, the problem statement is discussed in detail. In Section 3, integrated cost model and numerical example are proposed. Section 4 provides a model for production schedule and compares it with joint model. Finally in section 5 the result of example is analyzed to highlight the importance of such joint considerations and new approach.

2. Statement of the problem

Consider a production system consisting of a single machine producing products of the same type with constant production rate (PR, items per hour) on a continuous basis (three shifts of 7h each, 6 days-a-week). Further, consider a single component operating as a part of machine with time-to-failure following a two parameter Weibull distribution [6]. Let the shape and scale parameters of the distribution be β and η respectively. In this paper, machine failure is considered in terms of failure mode (*FM*). It is assumed that whenever machine fails it leads to one of the following two consequences.

1. Failure Mode I (FM_1): leads to immediate breakdown of the machine.

2. Failure Mode II (FM_2): leads to reduction in process quality by shifting the process mean.

Failure Mode I (FM_1) is detected immediately as it brings the machine instantly to breakdown state. However, Failure Mode II (FM_2) is detected after a time lag through control chart mechanism. It is assumed that whenever the failure is detected, corrective actions are taken to restore the machine back to the operating conditions. Thus, (FM_1) results in an expected corrective maintenance cost comprising of cost of down time, cost of maintenance labor, and fixed cost of repair/restoration. However, Failure Mode II (FM_2) affects the functionality of the machine and causes the process to shift, resulting in an increase in the rejection rate, till it is detected. Thus (FM_2) in addition; also incurs the cost of lost quality. Preventive maintenance (*PM*) is carried out to reduce the unplanned down time cost. However, PM also consumes time and resources, which could otherwise be used for production. Preventive maintenance optimization is therefore done to strike a balance between cost of failure and cost of preventive maintenance [7].

Let us suppose the process quality can be evaluated by measuring one key quality characteristic of the finished product. Let *x* denote the measurement of this characteristic for a given product. It is assumed that is a normal random variable having mean μ and a standard deviation σ.

When the process is in-control, the process mean is at its target value. The process mean can instantaneously shift, due to machine failure or due to some external causes 'E' like environmental affects, operators' mistake, use of wrong tool, etc. The process is also restored if an external cause '*E*' is detected. After a shift the process is said to be out-of-control and the new process mean is given by: $\mu=\mu_0+\delta\sigma_0$, where δ is some non-zero real number. Usually, the failure which causes this shift is relatively subtle. Therefore, the cause of failure cannot be identified without shutting down the process and performing a close inspection of the equipment. The process also has to be restored similarly if an external cause '*E*' is detected.

A major disadvantage of a Shewhart control chart is that it uses only the information about the process contained in the last sample observation and it ignores any information given by the entire sequence of points. This feature makes the Shewhart control chart relatively insensitive to small process shifts, say, on the order of about 1.5σ or less.

CUSUM scheme is more efficient in detecting small shifts in the mean of a process. The analysis of ARL for CUSUM control chart shows better performance than Shewhart control chart when it is desired to detect the shifts in the mean of size 1.5 sigma or less. The CUSUM chart directly incorporates all the information in the sequence of sample values by plotting the cumulative sums of the deviations of the sample values from a target value.

For example, suppose that samples of size $n \geq 1$ are collected, and $\bar{x}_j$ is the average of the jth sample. Then if μ_0 is the target for the process mean, the cumulative sum control chart is formed by plotting the quantity:

$$C_i = \sum_{j=1}^{i} \left(\bar{x}_j - \mu_0 \right) \tag{1}$$

We note that if the process remains in control at the target value μ_0, the cumulative sum defined in equation (1) is a random walk with mean zero.

In some cases in detecting whether the control chart is random or not we may have problem. For solving this problem the V-mask control scheme is proposed by Barnard (1959). The V-mask is applied to successive values of the CUSUM statistic [8]:

$$C_i = \sum_{j=1}^{i} y_i = y_i + C_{i-1} \tag{2}$$

Where y_i is the standardized observation $y_i = (x_i - \mu_0)/\sigma$. A typical V-mask is shown in Figure 1. The decision procedure consists of placing the V-mask on the cumulative sum control chart with the point *O* on the last value of C_i and the line *OP* parallel to the horizontal axis. If all the previous cumulative sums, C_1, C_2,…, C_i lie within the two arms of the V-mask, the process is in control.

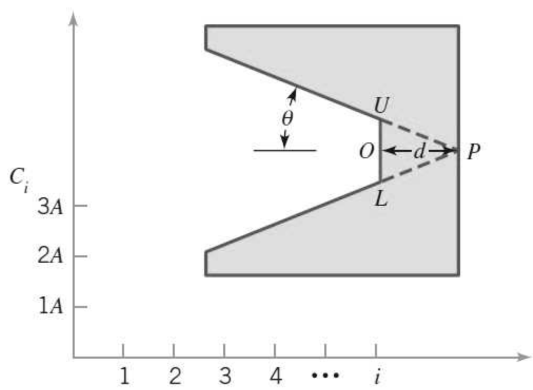

Figure 1. A typical V-mask

A method for designing the V-mask; i.e., selecting d and θ is [8]:

$$d = \left(\frac{2}{\delta^2}\right)\ln\left(\frac{1-\beta}{\alpha}\right) \tag{3}$$

$$\theta = \tan^{-1}\left(\frac{\Delta}{2A}\right) \tag{4}$$

Where 2α is the greatest allowable probability of a signal when the process mean is on target (a false alarm) and β is the probability of not detecting a shift of size d. If β is small, which is usually the case, then

$$d = -2\frac{\ln\alpha}{\delta^2} \tag{5}$$

3. Integrated approaches to maintenance and quality

While excessive maintenance results in unnecessary costs, inadequately maintained equipment may produce defective products resulting in large amount of rework and scrap costs. This has attracted attention of researchers for the joint consideration of maintenance and quality policies.

Therefore, in order to indicate the benefits of integrating preventive maintenance and Statistical Process Control, a cost model has been reviewed that captures the costs associated with the manufacturing process which are affected by quality control policies and maintenance planning. Then, a numerical example is presented for illustration.

3.1. Integrated Cost Model

In this section we review a model that comprise of cost of poor quality, cost of sampling/inspection, cost of preventive maintenance, cost of downtime and fixed cost of repair/restoration. The expected total cost per unit time for the integrated model is written as [7]:

$$[ECPUT]_{M*Q} = \frac{E[C_{CM}]_{FM_1} + E[C_{PM}] + E[TCQ]_{process-failure}}{T_{eval}} \tag{6}$$

While $E[C_{CM}]_{FM_1}$ is the expected cost for minimal corrective maintenance due to (FM_1), $E[C_{PM}]$ is expected cost per preventive maintenance and $E[TCQ]_{process-failure}$ is the expected total cost of quality loss due to process failure. Optimal preventive maintenance interval (t_{PM}) and process control chart design parameters (n, h, k) are obtained by minimizing $[ECPUT]_{M*Q}$.

3.2. Numerical Example

Consider a single machine whose failure is assumed to follow a two parameter Weibull distribution with η=1000 and β=2.5 as the characteristic life and shape parameter respectively

[9]. Machine considered here is expected to operate for three shifts of seven hours each for 6 days in a week. The manufacturer has used CUSUM control chart to monitor the manufacturing process producing that product. Assuming that the process is characterized by an in-control state with process standard deviation of $\sigma = 0.01$ and a single assignable cause due to external failure is of magnitude $\delta_E = 1$ and let deviation due to machine failure be $\delta_{M/C}= 0.8$, which occurs randomly and results in a shift of process mean from μ_0 to $(\mu_0 + \delta_\sigma)$. Other parameters related to example are shown in Table 1.

Where (MT_{PM}) is the mean time to do preventive maintenance action with restoration factor (RF_{PM}) and (MT_{CM}) is mean time to corrective maintenance with restoration factor (RF_{CM}).

Table 1 : Relevant parameters for the illustrative example

Parameter Value	C_{FCPCM}	C_{Rej} (Rs/job)	C_f (Rs/h)	C_V (Rs/job)	C_F (Rs)	T_S (h)	$\delta_{M/C}$	δ_E
	10000	5000	1200	10	40	20/60	0.8	1
Parameter Value	C_{FCPPM} (Rs/component)	Labor cost (Rs/h of preventive m/c)	C_{lp} (Rs/job)	PR (Job/h)	T_{reset} (h)	T_1 (h)	T_0 (h)	C_{reset} (Rs/h)
	800	500	40	20	2	1	1	1500

The global optimization tool box of Maple 14 has been used to solve the optimization problem. By minimizing $[ECPUT]_{M*Q}$ in equation (6) the optimal values of decision variables ($n^*; h^*; k^*; t^*_{PM}$) are obtained [10].

Optimal values are as follows: $n^* = 23$, $k^* = 4.1$, $h^* = 6.5$, $t^*_{PM}= 211$ and the corresponding expected total cost of system per unit time is $[ECPUT]_{M*Q} = 197.39$.

4. Production Schedule Model

Consider a single machine that is required to process three batches of batch size 500 each. Other related parameters are given in Table 2. Following assumptions are made to solve the problem:

1. Job cannot be pre-empted by another job.
2. No failure of machine during the schedule.
3. Raw materials for all the batches are released at starting of the schedule.
4. All jobs in a batch are completed together upon the completion of the last job in the batch. The batch processing time is equal to the sum of the processing times of its jobs.

It may be noted that these are generally the assumptions made for many scheduling/sequencing problems for which models have been attempted in the past [11, 12]. The objective is to obtain the batch sequence that minimizes the cost per unit time of the schedule $(CPUT)_S$. $(CPUT)_S$ can be calculated as [7]:

$$(CPUT)_S = \frac{\text{Total penalty cost due to batch delay} + \text{Total raw material inventory carrying cost}}{\text{Schedule completion time}} \quad (7)$$

Penalty cost is incurred only when a batch is delayed beyond its due date. Penalty cost for a batch can be calculated as [7]:

$$\text{Batch penalty cost} = (\text{batch completion time} - \text{batch due date}) \cdot p_i \quad (8)$$

As it is assumed here that the raw material for all the batches are released at the starting of the schedule, raw material for a batch is carried until it starts processing, i.e., for the duration of the processing and setup time of all the previous batches (if any) and the setup time of the current batch. Hence the inventory carrying cost is calculated based on the whole batch size for this period. Secondly, during the processing of a batch, raw material of the batch depletes at a constant rate and therefore the inventory carrying cost is calculated for this period also based on the average inventory (half the batch size).

Table 2 : Production parameters

Batch	*Processing time in minutes per job*	*Batch size*	*Setup time in h*	*Total processing time (h)*	*Due date (h)*	*Penalty cost/h/batch (Pi) (in h)*	*Carrying cost/job/h*
1	6	500	3	53.0	100	75	1.71
2	3	500	1	26.0	50	50	1.71
3	2	500	2	18.66	40	45	1.71

To obtain the optimal production schedule a total enumeration method is used. In the present problem for the three batches, a total of 3! batch sequences are possible. These batch sequences are shown in Table 3. Table 3 also shows the $(CPUT)_S$ value for all the six possible sequences. It is clear from Table 3 that sequence [B2-B3-B1] gives minimum cost per unit time of the production schedule $(CPUT)_S$ and so the same is selected as optimal sequence.

Table 3: Calculation for all possible sequences

Batch sequence	Completion time			Tardiness Penalty			Penalty Cost	Inventory Cost	$(CPUT)_S$
	Batch 1	Batch 2	Batch 3	Batch 1	Batch 2	Batch 3			
[B1-B2-B3]	53	79	98	0	29	58	4045	11407	158
[B1-B3-B2]	53	98	72	0	48	32	3808	12248	164
[B2-B1-B3]	79	26	98	0	0	58	2595	9654	125
[B2-B3-B1]	**98**	**26**	**45**	**0**	**0**	**5**	**210**	**8742**	**92**
[B3-B1-B2]	72	98	19	0	48	0	2383	11336	140
[B3-B2-B1]	98	45	19	0	0	0	0	9583	98

4.1. Joint Production And Maintenance Schedule Model

When the optimal schedule obtained in Section 4 is implemented on shop floor, it may get interrupted due to scheduled optimal preventive maintenance interval obtained in Section 3.1.

In order to implement both the policies, it is necessary to combine the maintenance interval on the optimal batch sequence. It is assumed that the machine cannot be stopped for PM until all the jobs in a batch are completed.

The objective of combining these two policies is to determine the optimal production sequence for which the Cost Per Unit Time of joint consideration is minimized. However, the problem of integration is complicated by the fact that tardiness values for the jobs are stochastic, since the machine may or may not fail during processing of a job and PM decisions affect the probability of machine failure. The CPUT for joint consideration of production and maintenance schedule can be expressed as:

$$(CPUT)_{S*(M*Q)} = \frac{\text{Total penalty cost due to batch and maintenance delay} + \text{Total raw material inventory carrying cost}}{\text{Schedule completion time}} \tag{9}$$

The total penalty cost due to batch and maintenance delay can be calculated as follows (details can be seen in Pandey, Kulkarni, & Vrat, 2010):

The probability that the machine fails while *k*th batch is getting processed can be determined using the Weibull probability distribution as follows [9]:

$$\varphi_k = F\left(p_{[k]}+\bar{a}[k-1] \middle| \bar{a}[k-1]\right) = 1 - \exp\left[-\left(\frac{p_{[k]}+\bar{a}[k-1]}{\eta}\right)^{\beta} + \left(\frac{\bar{a}[k-1]}{\eta}\right)^{\beta}\right] \qquad k = 1,2,\dots, m \tag{10}$$

$$\bar{\varphi}_k = 1 - \varphi_k \tag{11}$$

The completion time for a job is a discrete random variable that depends on: (1) the age of the machine prior to decision making; (2) the processing time for batches; (3) the time to complete PM and the PM decisions; and (4) the repair time and the probability of machine failure during batches. Let $C_{[k]}$ denote the completion time for the *k*th batch. Then:

$$C_{[k]} = MT_{PM} \cdot \sum_{k=1}^{m} y[k] + \sum_{k=1}^{m} p[k] + M_{[k]} \qquad k = 1,2,\dots, m \tag{12}$$

Let $N_k = \{1, 2, \dots, k\}$, and let N_{Kq} denote a subset of N_k containing q elements. Then, $M_{[k]}$ is a discrete random variable having the following probability mass function

$$\pi[kq] = \Pr\{M[i] = q \times MT_{CM}\} = \sum_{N_{k,q}} \prod_{I \in N_{k,q}} \varphi[k] \prod_{I \notin N_{k,q}} \bar{\varphi}[k] \qquad q = 0,1,\dots, k \tag{13}$$

For all k = 1, 2, . . ., m, let

$$C[k] = (MTTR)_{PM} \cdot \sum_{k=1}^{m} y[k] + \sum_{k=1}^{m} p[k] + q \times MT_{CM} \qquad q = 0,1,\dots, k \tag{14}$$

Let $\Theta_{[k]}$ denote the tardiness of the *k*th batch, $k = 1, 2, \dots, m$. Note that $\Theta_{[k]}$ has $k + 1$ possible values,

$$\theta_{[k,q]} = \max\left(0, C_{[k,q]} - d_{[k]}\right) \tag{15}$$

$$E\left(\Theta_{[k]}\right) = \sum_{q=0}^{k} \theta_{[k,q]} \cdot \pi_{[k,q]} \tag{16}$$

Therefore, the total penalty cost incurred due batch tardiness is given as

$$(TPC)_{\text{batch tadiness}} = \sum_{k=1}^{m} p_{[k]} E\left(\Theta_{[k]}\right) \tag{17}$$

Where $d_{[k]}$ and $P_{[k]}$ are the due date and penalty cost for the *k*th batch respectively. Table 4 shows the calculations of $(CPUT)_{S\times(M\times Q)}$ for all the four possible locations of PM for the given batch sequence.

Table 4: Optimal solution obtained from integration example result

Batch sequence	Location of PM	$(\text{CPUT})_{S\times(M\times Q)}$
[B1-B2-B3]	PM is performed before first batch	134
[B1-B3-B2]	PM is performed before first batch	128
[B2-B1-B3]	PM is performed before second batch	126
[B2-B3-B1]	**PM is performed before second batch** (in this case it is batch 1 i.e. B3)	**96**
[B3-B1-B2]	PM is performed before second batch	101
[B3-B2-B1]	PM is performed before first batch	118

5. Conclusions

In this paper, an attempt has been made to review the literature dealing with integration of three aspect of production planning functions i.e., production scheduling, maintenance scheduling and quality control, and propose a model to improve the previous models.

According to the results obtained in previous models [7, 9], the objective function when we use x-bar control chart is equal to 108. But by using the CUSUM control chart because of its ability to detect small changes the value of objective function becomes 96. In the other words, using CUSUM control charts reduce the costs resulting from loss of goodwill and batch rejection for the manufacturer. Therefore joint optimization model with cumulative sum control chart results in an average improvement of approximately 85% compared to independent models. Depending on the nature of the manufacturing system, the average saving may be different but still it can be very substantial.

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