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Technical Paper

# A joint design of production run length, maintenance policy and control chart with multiple assignable causes

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A B S T R A C T

Although economic production quantity, statistical process monitoring and maintenance are three major concepts in process optimization of industrial environments, they have been often investigated separately in literature. Furthermore, in studies that consider these three concepts simultaneously, it is assumed that there is only one assignable cause in the production process. This simplified assumption is unlikely to occur in real production processes due to the usual complexity of manufacturing systems, which may lead to a poor performance in both economic and statistical criteria if the assignable cause originating the shift is different from the one anticipated at the design of the chart. To overcome these drawbacks, this paper develops an integrated model ofeconomic production quantity, statistical process monitoring and maintenance in the presence ofmultiple assignable causes. The particle swarm optimization algorithm is used to minimize the expected total cost per production cycle, subject to statistical quality constraints. Also, a comparative study is performed to illustrate the effect of considering multiple assignable causes on model's costs. Finally, a sensitivity analysis is conducted on the expected total cost per production cycle and process variable values to extend insights into the matter.



## 1. Introduction

Rapidly changing markets and the extension of product variety have increased the requirement for more complex equipment. To get the best output of expensive manufacturing processes, and to meet the quality challenge, equipment must be maintained in a suitable operating condition. This circumstance demands more effective maintenance policies. In this situation, the role of the equipment condition in controlling quantity, quality and cost of production becomes more evident and important than ever. Therefore, economic production quantity (EPQ), product quality, and maintenance are three interrelated problems. As mentioned earlier, there is a need for developing approaches that could capture the interdependence between these three main aspects of the modern manufacturing processes. Nevertheless, most of the researchers separately investigated three concepts of inventory, quality, and maintenance. For instance, Chen and Yang [4] presented a model for economic design control chart that only considers statistical properties of the process. Similar to this study, several other papers including Lee et al. [18] and Nenes et al. [23] studied economic design of control charts. Also, there are other papers such as Cheng and Chou [5], De la Torre Gutierrez and Pham [8], and Mehmood et al. [22] that applied control charts with considering special rules like Western Electric rules to detect out-of-control state.

Some of the researchers concentrated only on the maintenance issue. Several models were developed for various types of maintenance strategies. In this regard, Lee and Cha [16] implemented periodic preventive maintenance policies for a deteriorating repairable system. They studied detailed properties of the optimal policies that minimize the long-run expected cost. More recent studies about maintenance in industrial environments can be observed in Zhou et al. [34], and Nguyen et al. [24].

The integration of statistical process monitoring (SPM) and maintenance have attracted attention in recent years. In this regard, Linderman et al. [19] constructed a generalized analytic model that incorporates SPM and maintenance policy to minimize total expected cost. Zhou and Zhu [33] developed models that integrated maintenance activities with the design of control chart. They indicated that integrated models perform better than the two stand-alone models. Xiang [31] developed an integrated model of SPM and preventive maintenance (PM) for a manufacturing process that deteriorates according to a discrete-time Markov chain. Moreover, several other researches such as Yin et al. [32], Liu et al. [20], Le and Tan [15], investigated maintenance policy and statistical process monitoring concurrently.

Some other approaches integrated SPM and inventory issues. Most of these researches aimed to determine design parameters of control chart in a way that inventory and quality costsbe

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minimized. In this regard, Rosenblatt and Lee [28] presented a comparative study of continuous and periodic inspection policies in deteriorating production systems. They also investigated the effects of imperfect production on the optimal production cycle time. Makis and Fung [21] demonstrated the effect of machine failures on the optimal lot size and the number of samplings in a production cycle.

The widespread papers optimized production run-length and maintenance activities, simultaneously. Lee and Rosenblatt [17] conducted study on the joint problem of production planning and maintenance schedule. In this research, it is assumed that the process restoration cost depends on the existence shortages and the delay in detecting them. In another study, Wen et al. [30] suggested an EPQ model for a deteriorating system integrated with predictive maintenance strategy. Gan et al. [11] and Jiang et al. [13] are other studies that have been conducted in this context.

Although considering inventory concept in optimizing the production process has a significant role in reducing the manufacturing cost, very few papers in the literature of SPM and maintenance considered this issue. In this regard, Pan et al. [25] presented an integrated EPQ model based on a control chart for an imperfect production process. This model assumes that equipment goes to the out-of-control state because of only a single assignable cause. However, in the real situations, the process might go to an out-of-control state due to different assignable causes. Ben-Daya and Makhdoum [2] developed an integrated production and quality model under various preventive maintenance policies. This model similar to Pan et al. [25] assumes that only one type of assignable cause can occur during the production process. Moreover, this model designs control chart just based on economic criteria, ignoring statistical properties of the process. Rahim and Ben-Daya [27] is the other paper that has been proposed in this context. According to literature review Table 1 summarizes the characteristics of the existing researches in the literature.

To fill research gaps and overcome the above-mentioned drawbacks, this study integrates the concepts of SPM, maintenance and inventory in a unified model. It aims to minimize the expected total cost (ETC) of production process subject to statistical constraints. The ETC contains the inventory holding, ordering, maintenance, sampling and quality control costs. Moreover, the proposed model in contrast to the other approaches in this field considers non-uniform sampling in a way that integrated failure rate over all sampling intervals would be the same value. Also to make the model more adapted to real manufacturing situation, the process under consideration can go to out-of-control state due to several types of assignable causes.

The rest of this paper is organized as follows: In the next section, the problem will be defined in detail. The Section 3 represents the proposed model for the joint design of production run length, maintenance policy and control chart with multiple assignable causes. In the Section 4, solution approach is explained. The Section 5 which is called experimental results consists of three sub-sections: (1) numerical example, (2) comparative study and (3) sensitivity analysis. Finally, in Section 6 conclusions and further perspectives are given based on the obtained results in the numerical example.

## 2. Problem definition

Traditional EPQ models focus on inventory issueand make decisions based on storage and ordering costs with this assumption that the manufacturing process is perfect, which means quality defect and machine deterioration never happen. However, a perfect manufacturing process rarely can be found in real industrial environments. A production system often begins its operation in an in-control state and after a period of time, shifts to an out-of-control state due to machine deterioration, fatigue and etc. Consequently, the quality loss cost that is imposed to the manufacturer extremely increases because of producing more non-conforming outputs.

This paper investigates an imperfect manufacturing process, which includes two states: (1) in-control state and (2) out-of-control state. A Shewhart X-bar control chart is used to monitor a quality characteristic with an alert signal to inform operators when the process shifts to the out-of-control state. The manufacturing process starts operating in the in-control state and one type of assignable cause may occur during the cycle time. An assignable cause happens due to the process nature, machine failure, operator errors, undesirable materials and so on that ultimately leads to shifting process to the out-of-control state. In contrast to most of existing approaches, the suggested model integrates economic production quantity, statistical process monitoring and maintenance in the presence of multiple assignable causes. Furthermore, the proposed model sets sampling intervals in a way that integrated failure rate over all sampling intervals would be the same value.

The imperfect process that mentioned earlier consists of three possible scenarios. These scenarios are introduced based on situations that may occur for a production run. Scenario1 happens if production process always remains in an in-control state from the beginning of the production cycle until the end. When scenario1 occurs, aplanned preventive maintenance is implemented at the end of the production cycle. Scenario 2 is a situation in which process shifts during production cycle to an out-of-control state and control chart detects this shift before conducting the planned preventive maintenance. In scenario 2, a corrective maintenance (CM) is required to restore the process to as-good-as-new situation. Scenario 3 is similar to scenario 2 with this difference that control chart can't detect the shift to the end of the production cycle. In many situations, the alarm wouldn't be issued at the exact time of shift in the quality characteristic due to a delay in signaling the change by the control chart. In this scenario at the end of the production cycle, when PM activity is conducted, the shift is identified and then PM activities are replaced with CM ones. The graphical representation of three scenarios is presented in Fig. 1 briefly.

### 2.1. Notations

Before developing the proposed model mathematically, the notations used to formulate the problem are presented in Table 2. As demonstrated in Table 2, notations are divided into three parts: indices, decision variables and parameters.

### 2.2. Assumptions and definition

The considered assumptions in the proposed model are as follows:

1. Each cycle of the process starts in the in-control state.

2. The time before occurrence of the $i^{th}$ assignable cause follows a Weibull distribution which the probability density function (PDF) is given by $f_i(t) = \lambda_i \nu t^{\nu-1} e^{-\lambda_i t^{\nu}} t$, $\lambda_i > 0$, $\nu \geq 1$, $i = 1, \ldots, s$ and the hazard rate is $r_i(t) = \lambda_i \nu t^{\nu-1}$.

3. The time before occurring first of any assignable cause follows a Weibull distribution with the shape parameter $\nu$ and the scale parameter $\lambda_0$, where $\lambda_0 = \sum_{i=1}^{s} \lambda_i$.This equation is proved in Appendix A.

$$f_0(t) = \lambda_0 \nu t^{\nu-1} e^{-\lambda_0 t^{\nu}} \quad (1)$$

4. If there is no alert signal after the $k^{th}$ sampling interval, a preventive maintenance is performed on the systemat the end of the $(k+1)^{th}$ interval. An alert signal in the $j^{th}$ interval $(0 < j < k)$, indicates that the process has been shifted to the out-of-control state.