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An integrated model of statistical process control and maintenance based on the delayed monitoring

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ABSTRACT

This paper develops an integrated model of statistical process control and maintenance decision. The proposal of delayed monitoring policy postpones the sampling process till a scheduled time and contributes to ten-scenarios of the production process, where equipment failure may occur besides quality shift. The equipment failure and the control chart alert trigger the corrective maintenance and the predictive maintenance, respectively. The occurrence probability, the cycle time and the cycle cost of each scenario are obtained by integral calculation; therefore, a mathematical model is established to minimize the expected cost by using the genetic algorithm. A Monte Carlo simulation experiment is conducted and compared with the integral calculation in order to ensure the analysis of the ten-scenario model. Another ordinary integrated model without delayed monitoring is also established as comparison. The results of a numerical example indicate satisfactory economic performance of the proposed model. Finally, a sensitivity analysis is performed to investigate the effect of model parameters.

1. Introduction

With the increasing complexity of product system, the statistical process control (SPC) theory and maintenance decision are synthetically combined to establish an integrated model in various literatures to deal with the quality deterioration and failures of the equipment.

Apart from the complete equipment failure which causes heavy losses, the equipment cannot generate the deteriorating signal by itself. Sensors are allocated on the equipment directly or indirectly to collect process information and make guidance for the maintenance decision. There are also monitoring the process and sampling the products in real time to infer the equipment condition. These types of maintenance policies are known as condition-based maintenance. The engineers decide whether to maintain the equipment and what kind of maintenance should be taken in terms of the equipment condition. By inspecting, adjusting and replacing the system periodically, the failure rate of the equipment and the average cost are reduced. As a typical tool of SPC, the control chart is frequently used in practice. It depicts the distribution of the process parameter and predicts the tendency of these data. Therefore, once a change of the process mean is detected, alert signal will be generated to remind the engineers to take appropriate maintenance in case of more serious failure.

In this paper, we develop an integrated model of SPC and maintenance decision and take the delayed monitoring policy into account. A process producing single product with single equipment is assumed to operate in the in-control state when it begins. The control chart is employed to monitor the key quality characteristic of the product and will generate the alert signal as long as the mean value of quality characteristic shifts to the out-of-control state, which implies the probable deterioration of equipment. Once the production process operates in out-of-control state, both the failure rate of equipment and the production cost per unit time are supposed to be higher than that of the in-control state. Therefore, the predictive maintenance and the corrective maintenance are performed to deal with the true alert signal and the equipment failure, respectively. Additional preventive maintenance (also known as planned maintenance or schedule maintenance in some literatures) is only performed at a specific time to ensure the reliability of the equipment when neither failure nor alert signal occurs. Considering the relatively low hazard rate of equipment failure and quality shift during the preliminary period of production, the necessity of taking samples at an early age of the production process needs to be reconsidered. This paper proposes a delayed monitoring (DM) policy, which postpones sampling process till a scheduled time. The DM policy would reduce the total production cost by decreasing the frequency of

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sampling; however, it may also increase the total production cost by increasing the possibility of failure which occurs under the out-of-control state. Therefore, the DM policy deserves to be probed deeply when it is used in the integrated model. The introduction of DM policy increases the complexity of model analysis and contributes to ten different scenarios to describe the production process. Based on the reliability theory, this paper formulates the expression of the occurrence probability, the expected cycle time and the expected cycle cost for each scenario. Subsequently, a cost model aiming at minimizing the expected cost is established and solved by genetic algorithm.

This paper is organized as follows. In Section 2, the related literature on the integrating of SPC and maintenance policy is reviewed. Section 3 describes the assumption of the problem. In Section 4, the integrated model is developed and the cost function is analyzed in detail; a Monte Carlo simulation experiment is built to verify the integral calculation, and another integrated model without delayed monitoring is also built to compare with our model. In Section 5, the genetic algorithm is used to solve the model, the result comparison and sensitivity analysis are conducted. In the last section, the conclusion is drawn, and the tendency of further research is discussed.

2. Literature review

Quality control, maintenance policy, production planning and inventory management are important components of a manufacturing system. Effective integration of these components will give an industry a competitive edge in the market place [2]. Zhao and Wang [3] proposed the integrated model of production planning and maintenance.

The two interrelated research areas, SPC and maintenance have been investigated extensively and contributed to the development of integrated model in recent years with applying the theory of SPC and reliability engineering simultaneously. Ben-Daya and Duffuaa [4] are among the earliest researchers who began to notice the strong link between maintenance and quality. Tagaras [5] put forward an economic model that incorporates both process control and maintenance procedures. Ben-Daya [6] and Cassady and Bowden [7] preliminarily proposed to integrate the SPC and the PM and tentatively introduced the $\overline{X}$ control chart in conjunction with an age-replacement PM policy. Ben-Daya and Rahim [8] and Lee and Rahim [1] further studied the effect of maintenance on the economic design of $\overline{X}$ control chart. Linderman and McKone-Sweet [9] developed a generalized analytic model that coordinates SPC and planned maintenance and consists of three scenarios. Based on these studies, researchers develop the integrated model on aspect of optimization objectives, control chart selection, maintenance policy, failure mechanism, monitoring strategy, probability distribution etc.

The widely used economic design of control chart (see [10,11]) aims at minimizing cost or maximizing profit, its advantage is that it quantifies all related cost into the designing of control chart and is consistent with the enterprise interest. Woodall [12,13] pointed out the weakness of the economic design for its large number of false alarms or insensitivity to quality drift. The statistical design model aims at improving the detection performance of the control chart by optimizing the average run length without considering the economic cost. To balance economic effect and statistical performance, researchers studied the multi-objective economic-statistical design of the control chart in [14–16]. In this paper, we propose the economic model with employing the delayed monitoring method, which could, to a certain extent, reduce the number of samplings and false alarms during the in-control state.

Studies above mainly emphasize the deteriorating process shifting to the out-of-control condition, the failure caused by stochastically sudden shock of the equipment and the followed reactive maintenances are out of their consideration. Grall and Bérenguer [17] investigated the analytical model of a condition-based inspection/replacement policy for a stochastically and continuously deteriorating system. Deloux and Castanier [18] considered a system with two failure mechanisms: cumulative deterioration failure and stress-failure. Mehrafrooz and Noorossana [19] presented an improved integrated model with six scenarios. In their model, the time of shift to an out-of-control condition and the time of equipment failure are assumed to be two different random variables. Panagiotidou and Nenes [20] and Wu and Wang [21] improved the integrated model in terms of the monitoring method and they replaced the traditional static fixed-parameter (Fp) Shewhart control chart by employing an adaptive variable-parameter (Vp) Shewhart control chart with PM to monitor process mean. Kuo [22] and Xiang [23] formulated the deterioration process as a discrete-time Markov chain and jointly optimized the integrated model of SPC and maintenance.

Some of these studies assumed that the time of quality shift and of equipment failure followed exponential distribution, which featured with constant failure rate. Zhou and Zhu [24], Charongrattanasakul and Pongpullponsak [25] further stressed the increasing hazard rate of the process failure mechanism in the integrated model of SPC and maintenance. Panagiotidou and Tagaras [26] proposed a general integrated model characterized by multiple distinct operational states and a failure state, the time of shift from the normal operational state to an inferior one and the times to failure are random variables following Weibull distribution. Panagiotidou and Tagaras [27] presented an economic model for the optimization of PM in a production process with two quality states, and three alternative distribution types were used to describe the failure mechanism in all quality states: Weibull, Gamma and Truncated Normal.

The Shewhart $\overline{X}$ chart is one of the most frequently used control charts for its effectiveness and convenience when coping with the step shift or large shift of process mean. The gradual shift and the small shift due to tool-wear have been investigated together with SPC in [28,29], and various types of control charts like EWMA and CUSUM have been proposed to cope with a small shift [30]. Multivariate SPC chart is also selected by some researchers. Yang and Rahim [31] derived a Hotelling T^2 control chart to deal with a process involving a Weibull shock model with an increasing failure rate. Wu and Makis [15] considered the χ^2 chart for a condition-based maintenance application and pointed out that the Multi-EWMA chart and Multi-CUSUM chart were some possible future research directions as well. Beside the process mean, Mehdi and Nidhal [32] proposed to depict the non-conforming units rate chart to identify the process condition.

The intervention maintenance after an out-of-control signal is usually assumed to be perfect and can restore the equipment to as-good-as-new condition. In practice, the imperfect maintenance responding to the out-of-control signal is quite common. There are researchers who extend the maintenance strategy including but not limited to minimal maintenance. Panagiotidou and Tagaras [33] developed an economic model for the optimization of maintenance procedures in a production process with two quality states and combined two types of maintenance: the minimal maintenance that upgrades the quality state of the equipment without affecting its age and the PM that fully upgrades the equipment to the as-good-as-new condition. Moreover, Panagiotidou and Tagaras [34] proposed a combined monitoring-maintenance model comprising three different maintenance strategies: perfect PM, perfect CM and minimal maintenance, which avoids production under poor conditions and costs less than perfect maintenance.