Opportunistic maintenance of production systems subject to random wait time and multiple control limits

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ABSTRACT

A variety of production systems experience unavoidable production wait time due to the exhaustion of raw materials or lack of demand, which provides extra opportunities for the execution of maintenance activities. In this article, we propose a novel condition-based maintenance strategy for a production system whose production waits arrive according to the homogeneous Poisson process. The system undergoes gradual degradation, which ultimately results in soft failures (capacity reduction). To ensure a flexible and cost-effective maintenance allocation, opportunistic maintenance (during production waits) and regular maintenance are schemed simultaneously along with two separate control limits. The applicability of the proposed strategy is validated by a case study on a crystallizer casting machine. The result illustrates that the proposed maintenance strategy is more cost-effective compared with several classic/advanced strategies.

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1. Introduction

Most production systems in industry (e.g., a canning line, a steel production machine, a flexible automated manufacturing system) suffer from unexpected failures, which may cause tremendous economic losses due to the reduction of product qualities and outputs [27]. For this reason, preventive maintenance is of particular importance, since it allows timely detections and removals of pending failures [20,23]. Nevertheless, executions of preventive maintenance activities usually require the stoppage of production systems, and probably result in expensive downtime costs. On the other hand, production waits may arise due to the exhaustion of raw materials, lack of demands etc. [13]. It offers opportunities for low-cost maintenance activities via the sufficient utilization of unavoidable production stoppage time. Therefore, an elaborate combination of preventive and opportunistic maintenance is able to capture the superiorities of both maintenance types from the perspective of cost reduction.

Opportunistic maintenance models have been extensively reviewed in the literature [30]. Generally, these models are formulated within two main frameworks, i.e., time-based maintenance (TBM) and condition-based maintenance (CBM) [12]. The former framework decides the acceptance criterion of an opportunistic maintenance based on the age threshold [17]. In other words, opportunistic maintenance is accepted only when the age of the system exceeds a pre-determined threshold. The latter framework performs opportunistic maintenance based on the measurement of the current system condition [35]. For instance, if a system is found defective or wear-out at an inspection or its degradation level exceeds a pre-determined level, an opportunistic maintenance is accepted.

A number of opportunistic maintenance models have focused on failure-based opportunities in multi-component systems, where maintenance opportunities of a component are offered by internal factors, i.e., failures of other components. Within the TBM framework, a state-of-the-art review of opportunistic maintenance (random maintenance) was provided by Nakagawa [16]. Zhu et al. [38] introduced a multi-level strategy scheduling both regular and opportunistic replacement simultaneously. Within the CBM framework, Valadimire et al. [2] investigated optimal maintenance policies for multi-component systems with periodic and opportunistic inspections. Qiu et al. [22] formulated availability and maintenance modelling for systems subject to multiple failure modes.

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On the other hand, maintenance opportunities triggered by external factors have also attracted considerable attention [33,34]. Such factors are usually unavoidable for production/manufacturing systems, which could arise from various sources, e.g., production buffers, raw material shortage and harsh environmental conditions [1,6,24]. Excellent works about external opportunistic maintenance were conducted by Pan and Zuo [9,39,40], which applied selective maintenance to binary systems, series–parallel systems and multi-state system under various operational conditions. Similar maintenance models were also observed in Nakagawa et al. [17], where both periodic and opportunistic inspection policies are summarized. Notice that, a common assumption for external opportunities is that they arrive according to a Poisson process, either the homogenous or the non-homogenous type. For instance, Li et al. [13] proposed an age-based replacement strategy considering production waits arriving according to homogenous Poisson process (HPP). Cavalcante et al. [3,4] established opportunistic maintenance models for a single component with HPP opportunity occurrences. Furthermore, the non-homogenous opportunity arrival cases were studied in the one-cycle opportunistic maintenance models proposed by Ba et al. [1] and Yang et al. [36].

Most existing opportunistic maintenance models due to external factors are time-based. Such models are suitable for systems whose deterioration paths are not evident or condition information is not available. Nevertheless, nowadays the deterioration states of more and more production systems become measurable thanks to the rapid development of monitoring technology, which enables the arrangement of condition based maintenance. This motivates us to investigate a novel opportunistic maintenance strategy for a deteriorating production system whose inspection and replacement opportunities are provided by external factors (random production waits). Such opportunistic maintenance is different from opportunistic maintenance of multi-component systems from two aspects: (a) the maintenance cost formulation could be realized by the analytical approach instead of simulation: (b) the maintenance plan is arranged according to the age of the system (age-based) instead of calendar time (block-based).

The degradation behavior of the production system in this paper is characterized by the inverse Gaussian (IG) process. This process is chosen because of its nice mathematical property, explicit physical meanings and flexibility in incorporating environmental effect and explanatory variables [7,8]. To acquire sufficient degradation information of the system, two categories of condition monitoring (CM) are arranged simultaneously. On one hand, opportunistic monitoring (OM) (during production waits) could take maximum advantage of production stoppage time. On the other hand, regular monitoring (RM) [15,28] is schemed for a better manipulation of the CM frequency, since the arrival rate of production waits is usually uncontrollable.

The majority of existing CBM models investigated a single control limit for single-component production systems [18,29,37]. On the other hand, a multi-level control limit setting was seldom addressed in literature. Liao et al. [14] provided two types of control limits for a continuously monitored degrading system subject to a condition-based availability limit policy. Analogously, Rafiee et al. [25] applied a two-level control limit setting to a degradation-threshold–shock (DTS) model. Nevertheless, the lower control limits addressed in the above-mentioned models were defined as imperfect repair limits. In contrast, the two-level control limit setting in this article arises from the hybrid monitoring strategy. Specially, the control limit at an OM (production wait) is defined as the opportunistic limit, whereas the control limit at a RM is defined as the regular limit. Compared with a single threshold setting, this two-level setting ensures more flexible maintenance resource allocations and more sufficient utilizations of unavailable system downtime, and thus incurs a lower maintenance cost. As far as we know, such a monitoring and control limit strategy has not been investigated in condition-based maintenance of production systems.

The main contributions of this paper to the maintenance engineering are as follows.

- A novel condition-based maintenance strategy incorporating regular and opportunistic maintenance is introduced for a production system based on its operation and degradation characteristics;
- Two levels of CMs as well as control limits are simultaneously schemed to enable a flexible and cost–effective maintenance resource allocation;
- The superiority of the proposed maintenance strategy is validated by its comparison with some classical/advanced strategies;
- A case study on a crystallizer casting machine is presented to illustrate the applicability of the maintenance model, which is based on the real data collected from a crystallizer manufacturing factory.

The rest of the paper is organized as follows. Section 2 introduces the production system and the detailed maintenance strategy. Section 3 formulates the cost model based on the maintenance strategy. Section 4 provides three classic/advanced maintenance strategies for comparison. Section 5 presents a case study on a crystallizer casting machine to illustrate the application of the strategy. Section 6 provides some final remarks.

**Notations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>CBM</td>
<td>Condition-based maintenance</td>
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<tr>
<td>CM</td>
<td>Condition monitoring</td>
</tr>
<tr>
<td>OM</td>
<td>Opportunistic monitoring</td>
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<tr>
<td>RM</td>
<td>Regular monitoring</td>
</tr>
<tr>
<td>$T$</td>
<td>RM interval</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Length of total i regular monitoring intervals, $i = 0, 1, \cdots$</td>
</tr>
<tr>
<td>${N(t), t \geq 0}$</td>
<td>Arrival process of production waits following homogenous Poisson process</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Intensity of ${N(t), t \geq 0}$</td>
</tr>
<tr>
<td>$S$</td>
<td>Random time duration between two successive production waits</td>
</tr>
<tr>
<td>$H(t)$</td>
<td>Cumulative distribution function (CDF) of S</td>
</tr>
<tr>
<td>${X(t), t \geq 0}$</td>
<td>Degradation process characterized by the inverse Gaussian (IG) process</td>
</tr>
<tr>
<td>$L_f$</td>
<td>Threshold of the degradation-based failure</td>
</tr>
<tr>
<td>$L_r$</td>
<td>Regular control limit, $0 &lt; L_r &lt; L_f$</td>
</tr>
<tr>
<td>$L_o$</td>
<td>Opportunistic control limit, $0 &lt; L_o &lt; L_f$</td>
</tr>
<tr>
<td>$$nor$</td>
<td>Production rate at the normal state</td>
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