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A cost-effective simulation algorithm for inspection interval optimization: An application to mining equipment

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ABSTRACT

In machinery maintenance policies, regular inspection intervals should be specified in such a way that the cumulative of direct and indirect financial consequences of maintenance activities should be minimized while supporting the functional health of system components. This study aims to develop a simulation algorithm, called the time-counter, to optimize inspection intervals. In the algorithm, uptime and downtime behaviors of the system components and production losses in the corrective repairs are considered random values. Delay time concept is regarded when estimating failure detection periods and deciding on the required maintenance type. In addition, the developed model is applied to two active draglines and their inspection intervals are optimized as 232 and 184 h for Dragline-1 and Dragline-2, respectively. The optimized values are observed to decrease the total maintenance costs by 5.9 and 6.2 percent for the given draglines, compared to the current interval of 160 h. The main novelties of the study are that (i) the proposed concept which allows for simultaneous assessment of system components in an incremental time span has not been proposed in the literature when deciding on optimal inspection intervals, (ii) it is the first initiative in inspection optimization of a mining machinery system, and (iii) it uses real datasets on lifetime, repair time, and financial values that are rarely observed in maintenance studies.

1. Introduction

Inspections are the integral parts of maintenance policies, especially in machine-based production cycles. These activities are generally performed in regular intervals to identify, examine, and recover potential abnormalities in working machinery systems. An inspection may entail various work packages such as: (i) visual inspection of system elements, (ii) preventive or corrective rectification of defects via repair or replacement activities, (iii) preventive replacement of predefined components in deterioration period, (iv) lubrication of friction-intensive locations in systems, and (v) overhauling of complex components. Inspections identify work packages covering the questions of whom, how, and how long for an effective implementation schedule. These maintenance activities allow decision-makers to reduce overall maintenance costs and to monitor functional efficiencies of system elements via taking precautions against failures that may take place during operations.

Although inspections provide benefits for sustainability of operations and longevity of system components, practicing them in short time intervals may lead to a frequent halt in operation. In this case, production losses due to excessive downtimes overcome the economic benefits of inspections. On the other hand, if time intervals between inspections are over-extended, this causes frequent failures of components during operations and initiates wear-out problems for working components. Resultant economic consequences of maintenance, once again, becomes a problematic issue. Therefore, inspection intervals should be determined so that the overall maintenance cost is minimized by including both direct and indirect considerations.

This paper proposes a simulation model for optimization of constant inspection intervals for a production system with multiple components, each of which has a random lifetime and random repair time over a predefined observation period. During the observation period, it is assumed that the following events can be performed for individual components within the system:

i. *Preventive Maintenance* – Component is maintained preventively in regular inspections in case the period of time between any defect arrival for the given component and its expected failure time overlaps any inspection duration.

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ii. *Corrective Maintenance* – Component is maintained correctively during operation in case the defect observable period is between any two inspection points and that it cannot be recognized during any inspection.
iii. *Do Nothing* – If a component is functionally healthy but any other operationally-dependent component fails during operation hours, the healthy components stop deteriorating during the random repair time of the failed one.

The proposed model is a simultaneous analysis of the events (i), (ii), and (iii) for each component in the system for each up-to-date time point which is incremented with small time intervals up to target observation period. The model is mainly motivated by solving time-dependent failures and the operation behaviors of large numbers of components with different operational dependency to obtain optimal inspection intervals. This research integrates a maintenance decision mechanism with delay-time concept with a cost minimization problem and performs a new time-incremental simulation algorithm to find out optimal inspection intervals. The second motivation of this paper is that the algorithm is applied to two massive draglines used in a coal mine and actual datasets gathered from the operations are introduced to the algorithm. In this way, this study offers an inspection interval optimization for a mining machinery for the first time where production is significantly correlated with machinery performance, and maintenance cost alone may add up to 40–50% of the total operating cost of machinery in a mine. In addition, a comprehensive reliability analysis is performed for the dragline components so that the lifetime and the maintenance characterization of an earthmover working in a demanding mining environment is revealed in detail for the first time.

This study covers five main sections. Following this introductory part, Section 2 gives a comprehensive literature review on the delay-time based inspection optimization and mining machinery maintenance. The originality of this paper is also discussed in this section. Section 3 presents the proposed simulation model. In Section 4, the developed model is applied to the draglines by using actual datasets to find out the optimal inspection intervals by minimizing the overall maintenance costs. Finally, the main conclusions derived from the study are given in Section 5.

2. Literature review

2.1. Inspection interval optimization with delay-time concept

The delay-time concept introduced by Christer (1973) is extensively utilized in the literature to determine optimal inspection intervals of the systems. This concept considers the two-stage failure process as a summation of two successive periods: The first one is between the start-up time of the component and the defect arrival time and the other one, called delay time, is from the defect arrival time to the expected failure time if the defect is not rectified (Wang & Banjevic, 2012). In the literature, the main effort for the delay-time concept has been given to building mathematical models under certain assumptions. These models have heavily concentrated on the systems with (i) single component, (ii) a major failure mode or (iii) a single failure rate (Berrade, Scarf, Cavalcante, & Dwight, 2013; Berrade, Scarf, & Cavalcante, 2015; Christer, 1991; Flage, 2014; Jia & Christer, 2002; Li, He, Yan, Hu, & Cheng, 2015; Okumura, Jardine, & Yamashina, 1996; Ramadan, 2016; Van Oosterom, Elwany, Çelebi, & Van Houtum, 2014; Wang, 2009, 2011, 2013; Wang & Wang, 2015; Wang, Zhao, & Peng, 2014; Yang, Ma, & Zhao, 2017; ; Wang, Wang, & Peng, 2017). There are comparatively fewer numbers of models working on the systems with (i) multi-component, (ii) multi-failure mode or (iii) multi-defect.

In more detail, Zhao, Chan, Roberts, and Madelin (2007) tried to maximize reliability of components with the multi-defect arrival by regarding non-constant inspection intervals. The non-homogenous Poisson process was used to define the defect arrival rate and minimal repair was assumed. Aven (2009) considered a monotone safety system with multi-components to develop an inspection plan by using the delay time concept via minimizing long run unit cost induced by inspections and component replacements in failures and inspections. Wang, Banjevic, and Pecht (2010) presented a delay time model for multi-component systems where components were regarded individually but also in harmony to league together within a subsystem or system. This model allowed for the identification of more than one failure mode for each component. Optimal intervals were obtained by minimizing total cost in a renewal cycle. Wang (2012) used the delay-time concept in a joint model to find out the optimal inspection intervals and to develop a spare part inventory plan for the systems holding large amounts of identical component. Wang, Carr, and Chow (2012) proposed a dynamic model for the inspection policy of multi-component systems where technological improvements in the systems may require non-constant inspection intervals. The model's objective function was developed in such a way that either of cost, downtime and reliability could be selected as the optimization criterion. Taghipour and Banjevic (2012) proposed two models to optimize the inspection interval of a complex system with components subjected to hard and soft failures. In a research by Jodejko-Pietruczuk and Werbińska-Wojciechowska (2014), the effect of accuracy of delay-time estimation on block inspection policy for a three-component k-out-of-n system was simulated by assuming three different probability functions for the delay time values. Liu et al. (2015) proposed a model to achieve optimal inspection intervals of a n-component parallel system by minimizing long-term cost.

Besides the mathematical contributions, the delay-time approach has also been applied to various specific systems such as automotive vehicles (Scarf & Majid, 2011), wind turbines (Andrawus, Watson, Kishk, & Gordon, 2008), metallurgical systems (Christer, Wang, Baker, & Sharp, 1995; Christer, Wang, Sharp, & Baker, 1998), marine systems (Arthur, 2005; Christer & Lee, 1997; Emovon, Norman, & Murphy, 2016; Pillay, Wang, Wall, Ruxton, & Loughran, 2004; Wang & Majid, 2000), civil engineering structures (Cavalcante, Alencar, & Lopes, 2017; Christer, 1988; Redmond et al., 1997), and other mechanical systems (Leung & Kit-Leung, 1996; Martinez, Lara, Pascual, & Droguett, 2015).

2.2. Maintenance researches on mining equipment

Mining is the extraction of economically-valuable minerals from the earth's crust by using different surface and underground application techniques. Thousands of large pieces of equipment with different capacities and service types are employed at mine sites to satisfy the row material demand of various industries. More particularly, surface mines dominate most of the mining equipment population all over the world. More than 70,000 pieces of equipment in 1400 large surface mines with a total market value of USD 150 billion is expected to be used in the surface mining operations worldwide. The given population can be examined in detail in Table 1 (The data was retrieved from The Parker Bay Company, 2017).

Equipment availability is the primary concern of sustainable operations in both surface and underground mines since mining production rate and operating cost are significantly correlated with equipment performance. Here, maintenance expenditure alone is expected to add up to 40–50% of the total operating cost of equipment. Inefficient maintenance policies may increase this amount as well as interrupt production plans. Therefore, it is vital for mines