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Approximate evaluation of average downtime under an integrated approach of opportunistic maintenance for multi-component systems

Hao Peng [a,*], Qiushi Zhu [b]

[a] Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing, China
[b] Vanderlande Industries, Veghel, The Netherlands

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ABSTRACT

Since the quality of after-sales services is becoming more and more important for users of capital goods, the average downtime per year becomes one of the key performance indicators of the systems. For multi-component systems, the average downtime per year is not only determined by the maintenance policies of individual components, but also can be saved by the joint maintenance decisions. Considering this dependency of system downtime, we proposed a unified opportunistic maintenance policy for systems under a mix of different individual maintenance policies (i.e., age-based, condition-based, and failure-based policies). Components can employ different maintenance policies. We developed approximation methods to evaluate the average downtime per year and a heuristic solution procedure to determine the interval length for the scheduled downs, the control limits or the age limits of components. The numerical study shows the accuracy of the approximation methods. Heuristic solutions are also obtained to demonstrate the use of our model.

1. Introduction

High-tech capital goods (e.g., oil-gas refineries, lithography machines, and baggage handling systems) nowadays become more and more important for production and services. Users of such advanced engineering systems usually require the systems to be available 24 h a day, 7 days a week. For instance, the lithography machines in chip factories are often the bottlenecks of the production lines, and run 24 h every day to create more chips. The downtimes of the lithography machines are very costly, i.e., millions of euros of reduced production output. The baggage handling system in a busy hub airport also works almost continuously to serve the flights. The out-of-service hours of the baggage handling system can result in delays of the flights, which is unacceptable for passengers. Hence, the average downtime per year becomes the key performance indicator of these advanced engineering systems (Timmermans, 2012; Trivedi, Kim, & Ghosh, 2013). While buying these advanced engineering systems, the tolerance level of the downtime per year will be specified by the users in the service contract to guarantee that the systems can run properly most of the time. The original equipment manufacturers (OEM) thus have to shift from a pure product-oriented strategy to a business strategy with a focus on the performances or services of the machines, in order to satisfy the customers' demand and increase the market share (Kim, Cohen, & Netessine, 2007). Due to this trend towards the so-called "performance-based logistics", the OEMs are motivated to evaluate the key performance indicators (e.g., average downtime per year) for the service schedules (e.g., maintenance schedule) and optimize the service schedules accordingly.

In this research for multi-component systems, we focus on the type of dependencies that the total downtime can be saved by jointly maintaining several components prone to failures. For example, if one failed component is maintained together with some other component prone to failure, the maintenance actions will be performed in a parallel way so that the total downtime is smaller than conducting the two maintenance actions sequentially; moreover, the setup time of production/services or the waiting time of maintenance resources can be reduced if several components can be repaired/replaced simultaneously, since only one setup or one delivery is needed. Thus, how to evaluate the key performance indicator (i.e., the average downtime per year) considering these dependencies is our research question for multi-component systems under different maintenance policies. We aim to build up a probability model to characterize the coordination of the different maintenance policies of multiple components so that the average downtime per year can be evaluated and minimized by optimizing the joint maintenance decisions.

* Corresponding author at: Zhongguancun east 55, 100190 Beijing, China.
E-mail address: penghao@amss.ac.cn (H. Peng).

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For single-component systems, the key performance indicators related to the expected downtime per year have been studied by many researchers (e.g., the average downtime per unit time, instantaneous availability, limit availability, or interval availability); see (Ebeling, 2009) for a brief introduction. For example, Christer and Lee (2000) revised the delay time model to evaluate the expected downtime per unit time, by including the downtimes in the calculation of the expected number of failures over an inspection period. Jiang, Kim, and Makis (2013) investigated the structure of the optimal control policy that maximizes the long-run expected availability under partial observations. van Dijkhuizen and van der Heijden (1999) maximized the interval availability, instead of the usual limiting availability, to determine the optimal preventive maintenance policy. For order-driven manufacturing systems, the interval availability is often seen as a more appropriate performance measure.

For multi-component systems, Monte Carlo simulation is one approach to evaluate system downtimes or availabilities, e.g., Marquez, Heguedas, and Iung (2005) provided a case study of cogeneration plants. Faulin, Juan, Serrat, and Bargueno (2008) proposed the use of discrete-event simulation as an efficient methodology to obtain estimates of availability functions in time-dependent real systems. The systems can present multiple states, dependencies among failure/repair times or non-perfect maintenance policies. Naseri, Baraldi, Compare, and Zio (2016) modeled the time-dependent effects of environmental conditions on the system availability of oil and gas processing facilities. Due to the complexity of the problem, direct Monte Carlo simulation was used. It is worth noting that a calendar-based preventive maintenance policy was considered, which is similar to our case. Borgonovo, Marseguerra, and Zio (2000) presented a Monte Carlo approach for the evaluation of plant maintenance strategies and operating procedures under economic constraints. A model of obsolescence is introduced to evaluate the convenience of substituting a failed component with a new, improved one.

Compared with Monte Carlo simulation, analytical methods can save the computation times significantly. Trivedi et al. (2013) reviewed analytic modeling techniques such as non-state-space models, state-space models, and hierarchical models to evaluate average system downtime or system availability, with case studies applying these methods from Motorola, Cisco and Sun Microsystems. Average downtime (in minutes per year) has been used as a performance indicator for the Cisco router case and Sun Microsystems case. Cochran, Murugan, and Krishnamurthy (2001) presented a generic Markov model to reduce the computational effort of availability evaluation. The method was used and compared with a Petri-net simulation in a case study of a reactor regenerator system in a Fluid Catalytic Cracking Unit in a petroleum refinery. Raje, Olaniya, Wakhare, and Deshpande (2000) assessed the availability of a critical pumping system of the Crude Distillation Unit of a refinery using a three-state Markovian model. If the maintained system evolves according to a semi-Markov process, Bloch-Mercier (2000) identified the optimal preventive maintenance policy to maximize the stationary availability. Csenki (1994) derived the joint availability of a system modelled by a semi-Markov process, which is defined as the probability of the system being functional in both t and $t + x$. Wang and Pham (2006) investigated the availability of the series system whose components are subject to imperfect repair, correlated times to failure and repair. The shut-off rules are optimized. de Smidt-Destombes, van der Heijden, and van Harten (2004) analyzed the availability of a k-out-of-N system with identical components considering the spare part stock level, the maintenance policy and the repair capacity. Maintenance is initiated when the number of failed components exceeds some critical level. Kreimer and Mehrez (1998) computed the availability of a real-time queueing system when both service and maintenance times are exponentially distributed. Du, Cui, and Lin (2016) obtained the closed-form expressions of four availability indexes using the technique of aggregated stochastic process. In most of the above works, the type of downtime dependencies among components has rarely been considered, which refers to the savings on the total downtime by joint maintenance decisions; see (Do, Vu, Barros, & Berenguer, 2015 and Tsai, Wang, & Tsai, 2004).

If we do not consider downtime as a key performance indicator, many works have been done recently to propose maintenance policies for degrading systems. Alaswad and Xiang (2017) reviewed the latest works of condition-based maintenance. Ahmadi and Fouladirad (2017) maximized the expected gain of a deteriorating production system under random inspections. Verbert, De Schutter, and Babuska (2017) proposed a new strategy for timely maintenance planning in multi-component systems. Lee and Cha (2016) considered periodic preventive maintenance policies and assumed that the failure process between two PMs follows a new counting process which is a generalized version of the nonhomogeneous Poisson process. Zhou, Lin, Sun, and Ma (2016) optimized a maintenance policy of a parallel-series system considering both stochastic and economic dependence among components as well as limited maintenance capacity. El Hajj, Castanier, Schoefs, and Yeung (2016) constructed a degradation model for maintenance of reinforced concrete structure subjected to cracking. Liu, Xie, and Kuo (2016) analyzed the system reliability subject to shared constant or cumulative loads.

Our research differs from the existing works by considering a mixture of different maintenance policies (i.e., age-based policy, condition-based policy and failure-based policy) for multi-component systems. The coordination of maintenance actions under the different policies has rarely been discussed in the literature. However, for a complex engineering system in practice, different maintenance policies are employed for different components due to the diverse characteristics of components. For example, some electronic parts (e.g., circuit board, current adapter) are under the failure-based maintenance policy (FBM), since their failure times follow exponential distributions. For parts that have increasing failure rates, the age-based maintenance policy (ABM) is often employed. If the conditions of parts can be measured easily, the condition-based maintenance policy (CBM) is often used. We proposed a unified opportunistic maintenance framework for such kind of multi-component systems under mixed maintenance policies. In this framework, when the degradation level of a CBM component exceeds its control limit, we will take the first appeared (scheduled/unscheduled) opportunity from other components and jointly maintain this CBM component with other components. Similarly, when the age of an ABM component exceeds its age limit, we will take the appeared opportunity to conduct joint maintenance on this ABM component. The average long-run downtimes per year for components and system are approximately evaluated and minimized by optimizing the control limits for CBM components and the age limits for ABM components.

The outline of this paper is as follows. The problem description and formulation are given in Section 2. In Section 3, approximation methods are proposed to evaluate the expected downtime of a multi-component system under a mix of different maintenance policies. Based on the approximation models, in Section 4, a heuristic solution procedure is given to minimize the expected downtime. In Section 5 numerical study is performed to check the accuracy of the approximation models. The heuristic solutions of the optimization model are also presented in Section 5, as well as a sensitivity analysis.