Reliability Engineering and System Safety 157 (2017) 54–63

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

A review on condition-based maintenance optimization models for stochastically deteriorating system

Suzan Alaswad [a,*], Yisha Xiang [b]

[a] College of Business, Zayed University, Abu Dhabi, UAE
[b] Department of Industrial Engineering, Lamar University, Beaumont, TX 77710, USA

ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form
4 August 2016
Accepted 15 August 2016
Available online 20 August 2016

Keywords:
Condition-based maintenance
Preventive maintenance
Stochastic deterioration
Maintenance optimization
Inspection

ABSTRACT

Condition-based maintenance (CBM) is a maintenance strategy that collects and assesses real-time information, and recommends maintenance decisions based on the current condition of the system. In recent decades, research on CBM has been rapidly growing due to the rapid development of computer-based monitoring technologies. Research studies have proven that CBM, if planned properly, can be effective in improving equipment reliability at reduced costs. This paper presents a review of CBM literature with emphasis on mathematical modeling and optimization approaches. We focus this review on important aspects of the CBM, such as optimization criteria, inspection frequency, maintenance degree, solution methodology, etc. Since the modeling choice for the stochastic deterioration process greatly influences CBM strategy decisions, this review classifies the literature on CBM models based on the underlying deterioration processes, namely discrete- and continuous-state deterioration, and proportional hazard model. CBM models for multi-unit systems are also reviewed in this paper. This paper provides useful references for CBM management professionals and researchers working on CBM modeling and optimization.

1. Introduction

Industrial organizations are continuously seeking new strategies to improve the effectiveness of their operations. Maintenance optimization and the selection of maintenance strategies play an important role in the effectiveness of any industrial system's operation. Maintenance actions can be generally classified into two categories: corrective maintenance and preventive maintenance (PM). Traditionally, PM takes the form of system overhaul or unit replacement based on elapsed time, which is often referred to as time-based maintenance (TBM). TBM schedules are typically determined based on a probabilistic model of system failure. In recent years, condition-based maintenance (CBM) has received much attention in the maintenance research community. Unlike TBM policies that are developed based on historical failure data, CBM is a maintenance approach that emphasizes on combining data-driven reliability models with sensor data collected from monitored operating systems to develop strategies for condition monitoring and maintenance. The goal of CBM is to reduce unnecessary maintenance actions and eliminate the risks associated with preventive maintenance actions. Rapid development of computer based monitoring technologies (e.g., advanced sensors) has further facilitated CBM practices.

The literature on the use of mathematical modeling for the purpose of analyzing, planning, and optimizing TBM is abundant. Reviews on TBM can be found in [1–7]. In contrast, CBM has only received increasing attention recently, and only a few survey papers have considered CBM models extensively. The majority of existing CBM survey papers limits the scope within the diagnostic and prognostic methods and algorithms. For example, Jardine et al. [8] review recent studies and developments in CBM with emphasis on models, algorithms, and technologies for data acquisition and data processing. Peng et al. [9] divide the prognostic models into four categories: physical model, knowledge-based model, data-driven model, and combination model, and review various techniques and algorithms by this category. Ahmad and Kamaruddin [10] present an overview of time-based and condition-based maintenance in industrial applications, and summarize the most recent condition monitoring techniques. Shin and Jun [11] review CBM approach and address several aspects of CBM, such as definition, advantages and disadvantages, related international standards, procedures and techniques. Despite the recent rapid development of sensor technology that

* Corresponding author.
E-mail addresses: suzan.alaswad@zu.ac.ae (S. Alaswad), yxiang@lamar.edu (Y. Xiang).

http://dx.doi.org/10.1016/j.ress.2016.08.009
0951-8320/

Nomenclature

CBM Condition-based maintenance
CBPM Condition-based predictive maintenance
DTMC Discrete-time Markov chain
HMM Hidden Markov model
IG Inverse Gaussian
PHM Proportional hazard model
PM Preventive maintenance
POMDP Partially observed Markov decision process
SMDP Semi-Markov decision process
SPC Statistical process control
TBM Time-based maintenance

facilitates CBM, there exists increasing pressure on reducing unnecessary inspection and/or PM actions and the associated costs incurred from additional data collection, documentation, and analysis through optimal design of CBM policies. Therefore, mathematical modeling and optimization of CBM has become a major concern to operations and maintenance managers, and a review in this particular area is now more relevant. This paper aims at providing a review on CBM literature with emphasis on mathematical modeling approaches, and providing useful references for CBM management professionals and researchers working on CBM planning.

The popularity of CBM in the research community and industrial applications relies heavily on the development of stochastic deterioration models. We refer readers to Si et al. [12] and Ye and Xie [13] for reviews on degradation-based reliability models. The choice of the stochastic process that best describes the deterioration greatly influences the decision of the CBM strategy. In the literature, when the system condition is directly observable, stochastic deterioration models are usually classified based on whether deterioration states are discrete or continuous. For some systems that operate in dynamic environments, deterioration is caused by multiple factors referred to as covariates. For such systems, proportional hazard model (PHM) is commonly used to model the multivariate failure models. In this paper, we classify CBM models based on the three aforementioned classes: discrete, continuous, and PHM (see Fig. 1). Under this classification, we review existing CBM models for both single- and multi-unit systems.

The remainder of the paper is organized as follows. Section 2 reviews the CBM optimization models based on inspection quality, inspection frequency, optimization criteria, maintenance degree, and optimal design. Sections 3 and 4 review the mathematical modeling of CBM for single- and multi-component deteriorating systems, respectively. Finally, Section 5 concludes the paper with some future CBM research directions.

2. Condition-based maintenance modeling

The objective of CBM is typically to determine a maintenance policy that optimizes system performance according to certain criteria (i.e. cost, availability, reliability, etc.). The design of CBM policies has mainly focused on (1) inspection schedule and (2) preventive maintenance threshold. This section reviews the CBM optimization models based on inspection quality, inspection frequency, optimization criteria, maintenance degree, and optimal design.

2.1. Inspection quality

In practice, the majority of CBM models assume perfect inspections, i.e. each inspection reveals the exact state of the system without error. However, it is more realistic to assume that inspections are imperfect and may not detect failure states. Examples of studies that consider imperfect inspection can be found in CBM literature. Badıa et al. [14] propose an inspection policy to detect failures of a single-unit system subject to several hidden causes of failure, and assume that the probability of non-detection of a failure during an inspection depends on the failure cause. Lam [15] presents a CBM model for a deteriorating system in which the states of the system can be only diagnosed by non-perfect inspections. That is, an inspection is associated with probability of detection and probability of false alarm. Zequeira and Bérenguer [16] extend the previous models by classifying inspections into three types of inspections: perfect (detect without error all system failures), partial (detect without error only type I failures), and imperfect inspections (detect with error only type II failures) which may give false-positive results for other failure types. He et al. [17] present a special case of the model presented in [16] with no partial inspections are allowed. Berrade et al. [18,19] consider a similar approach in which inspection process is subject to error, and false positives and false negatives are possible.

Modeling imperfect inspection based on such inspection error classification is usually arbitrary because inspection error

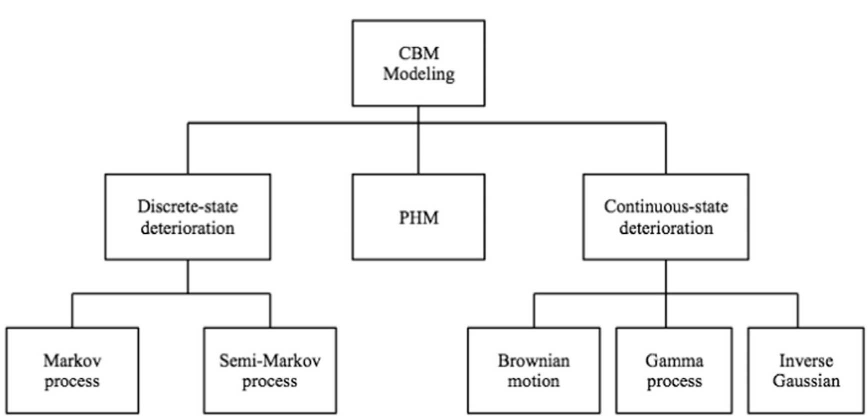

Fig. 1. CBM stochastic deterioration models.