Computers & Industrial Engineering 98 (2016) 102–112

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Optimal maintenance policy for a system with preventive repair and two types of failures

Zhibin Zheng, Wenhui Zhou, Yanfang Zheng, Yongzhong Wu *

School of Business Administration, South China University of Technology, Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 30 July 2015
Received in revised form 31 March 2016
Accepted 2 May 2016
Available online 4 May 2016

Keywords:
Maintenance policy
Geometric process
Preventive repair
Failure repair
Average cost rate

ABSTRACT

Maintenance policy is one of the most critical issues in operations management. In reality, the proper functioning of productive systems is affected by so many complicated factors that even preventive repair cannot eliminate the possibility of system failures of different types. A cost-effective maintenance strategy is usually desired. In this paper, a geometric process maintenance model with preventive repair and two types of failures (repairable failure and unrepairable failure) is studied. A maintenance policy (T, N) is proposed, where preventive repair will be conducted when the successive operating time reaches T, and the system will be replaced by a new one when an unrepairable failure or the Nth repairable failure occurs. The optimal policy (T^*, N^*) is obtained such that the average cost rate (i.e., the long-run average cost per unit time) is minimized. The model is generalized to reflect three different types of maintenance systems. An algorithm is proposed to obtain the optimal policy (T^*, N^*). Numerical experiments are conducted to examine the impacts of system parameters on the optimal maintenance policy.

1. Introduction

The proper maintenance of productive systems is vital to ensure the normal operation of productive systems in various industries, including manufacturing, healthcare and power industries. It extends equipment life, improves equipment availability, retains equipment in proper condition and thus contributes to the overall performance of the company (Swanson, 2001; Waeyenbergh & Pintelon, 2002). The growing importance of maintenance management has generated increasing interests in academic research. In the past decade, maintenance and replacement problems have been studied extensively in the literature.

In the earliest studies of the maintenance problem, repair-replacement models were commonly considered as perfect repair models, which assumed that a failed system would be "as good as new" after repair. In practice, most systems cannot be considered "as good as new" after repair. Barlow and Hunter (1960) introduced a minimal repair model, in which minimal repair does not alter the aging of the system. Brown and Proschan (1983) considered the imperfect repair model, which involves two types of repair, i.e., perfect repair with probability p, and minimal repair with probability $(1 - p)$. Following the introduction of this model, relevant studies have been conducted by Park (1979), Phelps (1981), Block, Borges, and Savits (1985), and Kijima (1989). In reality, many systems are considered to be degenerative because of aging effects and accumulated wearing. This means that the successive operating time between failures monotonously decrease with the times of repair. Given this fact, Yeh (1988) and Lin (1988) presented the geometric process (GP) model to describe a degenerative system. This model proposed a new replacement policy N^*, in which the system would be replaced when failure occurs for N^* times. Thereafter, the GP model has been extensively applied to the maintenance problem for its capability in describing real maintenance data sets. Yeh (1992) and Yeh and Chan (1998) applied a GP model to fit three real data sets by using nonparametric and parametric methods. Lam, Zhu, Chan, and Liu (2004) used the GP model to analyze more real data sets. Through the analysis of the data of aircraft, computer, car and so on, they found that on average the GP model was the best model among four homogeneous and nonhomogeneous Poisson models for fitting these real data from a series of events. Subsequently, Tang and Lam (2006), Zhang and Wang (2007), Wang and Zhang (2009), and Finkelstein (2010) conducted further studies to extend the geometric process model.

All aforementioned models assume that a system has unique modes of failure. However, a system can have two or more failure modes in many circumstances. Some system failures can be classified based on causes. For instance, an electronic system may fail because of a short circuit or an open circuit. In a manual control

* Corresponding author.
E-mail address: okwyz@hotmail.com (Y. Wu).

http://dx.doi.org/10.1016/j.cie.2016.05.007
0360-8352/

system, a failure may be caused by a manmade mistake or machine trouble. Some system failures can be classified by severity. Lam, Zhang, and Zheng (2002) adopted a monotone process model to study a one-component degenerative system with $k+1$ states (k failure states and one working state). Their research showed that the studied system was equivalent to a geometric process repair model with a unique failure mode based on replacement policy in that both systems have the same long-run average cost per unit time and the same optimal policy. Furthermore, Zhang and Wang (2010) examined the same problem under optimal policy T. In some cases, slight failures can be easily fixed by a repairman. In other cases, serious failures are impossible to repair, or repairing them is not valid because of the extremely high cost. Recently, Wang and Zhang (2013) investigated the optimal replacement policy for a system with two types of failures, i.e., repairable and unrepairable failures, where unrepairable failure leads to an immediate replacement of the system.

In many industries, the preventive repair or preventive maintenance (a scheduled and regular machine maintenance practice) is commonly adopted. By detecting the potential problem of the system, preventive repair could extend system lifetime, availability and reliability. Morimura (1969) studied various types of preventive repair policies. Zhang (2002) investigated the optimal replacement policy N^* for a geometric process repair model with "as good as new" preventive repair. The author determined the replacement policy N^* while assuming that the cycle time of preventive repair T was fixed. Furthermore, Lam (2007) examined a combination policy (T,N) for a GP maintenance model with preventive repair. In this paper, the proposed model also determines the optimal cycle for preventive repair instead of replacement policy N. Recently, Wang and Zhang (2014) examined an optimal bivariate policy (T,N) for a GP maintenance model with inspections and preventive repair in which failures are detected only by periodic inspections.

Lam (2007) proposed a practical combination policy (T^*,N^*) for the GP maintenance model with preventive repair. However, this model does not consider the case of unrepairable failure. In reality, both repairable and unrepairable failures may occur in most systems. Hence, considering both repairable and unrepairable failure types in the GP model system is reasonable and appropriate. A repair-replacement policy that considers both failure types should be investigated.

In this paper, the optimal repair-replacement policy for a degenerative system with preventive repair and both repairable and unrepairable failures is studied. The GP model is used to describe the degenerative characteristics of the system. In the proposed maintenance policy, the system will be repaired when a repairable failure occurs and be replaced with a new system when an unrepairable failure or the Nth repairable failure occurs. In addition, preventive repair is conducted when the successive operating time reaches T. The optimal maintenance policy (T^*,N^*) is determined to minimize the long-run average cost per unit time.

The remaining of the paper is organized as follows. Section 2 describes the problem and the proposed GP maintenance model in details, followed by the analysis of the model in different cases in Section 3. In Section 4, an algorithm for achieving the optimal maintenance policy is proposed, with which some meaningful theorems are obtained and discussed. Numerical examples are conducted and discussed in Section 5. Finally, the paper concludes in Section 6.

2. The GP maintenance model

For the ease of exposition, we first summarize all the notations and symbols adopted in Table 1.

Table 1
Notations and symbols.

X_n^i	Potential successive operating time of the system after $(i-1)$th preventive repair in the nth period
Y_n^i	The ith preventive repair time in the nth period
Z_n	Failure repair time in the nth period
X_τ	Total operating time in the τth replacement cycle
Y_τ	Total preventive repair time in the τth replacement cycle
Z_τ	Total failure repair time in the τth replacement cycle
W_τ	Replacement time in the τth replacement cycle
a	The ratio parameter of geometric process (GP) $\{X_n^1;\ n=1,2,\ldots\}$ $(a \geqslant 1)$
b_1	The ratio parameter of geometric process (GP) $\{Y_n^1;\ n=1,2,\ldots\}$ $(0<b_1\leq 1)$
b_2	The ratio parameter of geometric process (GP) $\{Z_n;\ n=1,2,\ldots\}$ $(0<b_2\leq 1)$
λ	Expectation of X_1^1
β	Expectation of Y_1^1
η	Expectation of Z_1
ω	Expectation of W_τ
T	Cycle time of preventive repair
N	Number of repairable failures
p	Probability of repairable failure
q	Probability of unrepairable failure
p_f	Probability of the successive operating time shorter than T
q_f	Probability of the successive operating time longer than T
r	System working reward per unit time
c_0	The basic replacement cost of the system
c_1	Cost rate (cost per unit time) of preventive repair
c_2	Cost rate of failure repair
c_3	Variable replacement cost per unit time
M_n	Total number of preventive repairs in the nth period
F_τ	Total number of failures (including repairable and unrepairable) until an unrepairable failure occurs in the τth replacement cycle
$C(T,N)$	Long-run average cost per unit time given policy (T,N)

2.1. Problem description

This paper considers a new productive system, which yields working reward per unit time during the course of operation. Due to wear and tear, environment influence and other factors, system failures may occur, some of which are repairable while the others are unrepairable. The probability of the repairable failure is p and the probability of the unrepairable failure is $q=1-p$.

To deal with these two types of failures and improve the reliability of the system, three different types of maintenance are adopted.

- Preventive repair. Preventive repair is a routine practice and may involve inspections, measurements, adjustments, and minor parts replacement in order to postpone failure from occurring. The cost rate(cost per unit time) of preventive repair is c_1.
- Failure repair. Failure repair is conducted when a repairable failure occurs. Failure repair often involves changing of certain damaged parts to restore functionality of the system. The cost rate of failure repair is c_2.
- System replacement. When a failure occurs, the system may also be replaced by a new and identical one. The replacement cost consists of two parts, i.e., the fixed cost c_0 to purchase a new system and the variable cost which is proportional to the replacement time at rate c_3.

A maintenance policy (T,N) is proposed and studied, in which a preventive repair is performed when the successive operating time reaches T, and the system is replaced by a new one when an unrepairable failure or the Nth repairable failure occurs. It is noted that if a failure occurs before a scheduled preventive repair, the preventive repair will be postponed to the time when another cycle time T