Computers & Industrial Engineering 108 (2017) 192–198

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Availability and maintenance modelling for systems subject to multiple failure modes

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ARTICLE INFO

Article history:
Received 8 October 2016
Received in revised form 11 April 2017
Accepted 16 April 2017
Available online 21 April 2017

Keywords:
Availability analysis
Multiple failure modes
Renewal process
Optimal inspection

ABSTRACT

The availability and optimal maintenance policies of a competing-risk system undergoing periodic inspections are studied in this paper. Specifically, a repairable system with a working state and M failure modes is considered. Each failure mode has a random failure time. When the system fails from the ith $(i = 1, 2, \ldots, M)$ failure mode, corresponding corrective repair is performed which takes a random time Y_i $(i = 1, 2, \ldots, M)$. Some analytical results on the instantaneous availability and the steady-state availability for the system are derived. The model is then utilized to obtain the optimal inspection interval that maximizes the system steady-state availability or minimizes the average long-run cost rate. A numerical example for Remote Power Feeding System is presented to demonstrate the application of the developed approach.

1. Introduction

In most researches, failure models are investigated concentrating on single failure mode. However, in practice, as the system configuration and the failure states of units are becoming more diverse, the modelling of systems with multiple failure modes is drawing increasing attention (see, for example, Cha, Lee, & Mi, 2004; Levitin, Zhang, & Xie, 2006; Liu, Xie, Xu, & Kuo, 2016; Song, Coit, Feng, & Peng, 2014; Tian, Zuo, & Huang, 2008; Zheng, Zhou, Zheng, & Wu, 2016; Zhu, Fouladirad, & Berenguer, 2016). For systems that suffer multiple failure modes, competing failure may occur and any of them can cause system failure. For example, consider a network of electronic units (Long, Xie, Ng, & Levitin, 2008; Zhang, 2004). When a unit is in the state of short circuit (open circuit failure), the corresponding corrective repair (CR) time distribution may not be identical. Some systems, such as those in chemical industry and nuclear power station, have soft failures and hard failures. In these cases, the repair and cost implications of those failure modes are different.

As important performance indices of systems, availability analysis has always been a hot topic in the field of reliability engineering. Availability analysis for systems with single failure mode has been extensively explored in the literature. Related literatures can be found in Barlow and Proschan (1981), Sharma and Misra (1988), Cui and Xie (2001), etc. Although a complex system can fail in more than one way, existing availability models rarely consider multiple failure modes. In competing-risk systems, for different failure modes, the corresponding CR times may obey different distributions which results in the changes in the availability or other performance indices of the system. The conventional assumption in system availability analysis that a system only has one failure state is not adequate in applications. Combined with the classical theory of competing risks (Crowder, 2001), what distinguishes the proposed model from others is that multiple failure modes are naturally incorporated.

For systems suffering from hidden failures, to improve the system availability, an inspection policy is usually adopted to detect whether a failure has occurred or not (see, e.g., Cui, Zhao, Shen, & Xu, 2010; Berrade, Scraf, Cavalcante, & Dwight, 2013). Based on the intervals between successive inspections, two types of inspections have been considered in literature, namely: periodic inspection and non-periodic inspection. The common practice in applications is to apply periodic inspection which is easier to schedule.

Many literatures have investigated periodic inspection due to its feasibility. Most early works on periodic inspection focus on steady-state availability and a few literatures investigate the instantaneous availability of periodically-inspected systems. Sarkar and Sarkar (2000) studied the instantaneous availability and steady-state availability for an inspection-based system. Cui and Xie (2005) did a similar work by considering random downtime caused by repair. Tang, Lin, Banjevic, and Jardine (2013) investigated the availability of a periodically inspected

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http://dx.doi.org/10.1016/j.cie.2017.04.028
0360-8352/

Nomenclature

FM	failure mode	T	inspection interval
CR	corrective repair	τ	minimum inspection interval
RPFS	Remote Power Feeding System	N	number of performed inspections before a system failure occurs in a renewal cycle
M	number of failure modes	N_I	number of performed inspections in a renewal cycle
X_i	failure time of the ith failure mode $i = 1,2,\ldots,M$	L	uptime of the system in a renewal cycle
$F_i(x)$	distribution function of X_i, $i = 1,2,\ldots,M$	D	downtime of the system in a renewal cycle
$f_i(x)$	probability density function of X_i, $i = 1,2,\ldots,M$	S	length of a renewal cycle
Y_i	repair time of type i failure, $i = 1,2,\ldots,M$	C_I	each inspection cost
$G_i(y)$	distribution function of Y_i, $i = 1,2,\ldots,M$	C_f	penalty cost rate during system downtime
$g_i(y)$	probability density function of Y_i, $i = 1,2,\ldots,M$	C_{R_i}	CR cost rate of the ith failure mode
p_i	probability that the system fails from the ith failure mode	C	total cost in a renewal cycle

system considering non-negligible down time. This paper considers a periodically inspected repairable system with a working state and M failure modes. Each failure mode has a random failure time. When the system fails from the ith $(i = 1,2,\ldots,M)$ failure mode, corresponding CR is performed which takes a random time Y_i $(i = 1,2,\ldots,M)$. The instantaneous availability and steady-state availability for systems with multiple failure modes are obtained.

An effective maintenance policy plays a critical role in mitigating the risk of system failure. It is interesting to see that multiple failure states systems have been gradually taken into account optimal maintenance modelling (Sharma & Misra, 1988; Sheu, Griffith, & Nakagawa, 1995; Levitin & Lisnianski, 2001; Levitin, 2002; Liu et al., 2016; Rai & Bolia, 2014; Dietrich & Kahle, 2016; Shang, Si, & Cai, 2016; Zhu et al., 2016). Many authors consider the cost associated with maintenance as a key factor in their work and choose a cost objective function (Peng, Feng, & Coit, 2009; Shi & Zeng, 2016; Tian & Liao, 2011). On the other hand, for certain complex systems, such as control systems in nuclear power station and satellite systems, system availability is much more important than upkeep cost. Optimal maintenance policy maximizing availability has been studied extensively such as reported in Bernguer, Grall, Dieulle, and Roussignol (2003) and Khatab, Ait-Kadi, and Rezg (2014). In this paper, we consider both availability and cost, and develop optimal maintenance policies by either maximizing system steady-state availability or minimizing average long-run cost rate. Based on the two performance measures, we compare the two maintenance policies.

In this paper, the results on system availability and optimal maintenance policies are derived, which can be readily applied to many systems experiencing multiple failure modes. We demonstrate the developed availability models and optimal maintenance policies for systems with multiple failure states considering a Remote Power Feeding System (RPFS). RPFS is one of the core technologies of the deep seafloor observatory network and is playing an increasingly important role in many critical fields (Barnes, Best, & Zielinski, 2008; Kojima & Asakawa, 2004). The issue of multiple failure modes is a critical problem that RPFS has experienced. Few studies have been conducted that analyze the availability and maintenance policy for RPFS.

The contribution of this paper is twofold. Firstly, we investigate the instantaneous availability and steady-state availability of a periodically inspected system with multiple failure modes. Secondly, the optimal inspection policies maximizing the steady-state availability or minimizing the long-run average cost rate is investigated. The application of the results in this paper in illustrated through RPFS.

The remainder of this paper is organized as follows: Section 2 describes the periodically inspected system with multiple failure modes. In Section 3, the instantaneous availability and steady-state availability are analyzed. Section 4 considers the optimal inspection interval maximizing system steady-state availability or minimizing the average long-run cost rate. We demonstrate the developed model through a numerical example in Section 5 and provide conclusions in Section 6.

2. System description

The specific assumptions used for availability analysis and maintenance modelling are summarized as follows.

(1) Initially, a new system with one working state is put into operation. The system failure can be classified into M mutually exclusive failure modes. For example, for a typical integrated digital communication system, screen display failure and antenna failure are the two main failure modes of the system (Liu et al., 2013).
(2) Each failure mode has a theoretical failure time denoted by X_i $(i = 1,2,\ldots,M)$ with distribution function $F_i(t)$, density function $f_i(t)$ and failure rate function $\lambda_i(t)$. Additionally, X_i $(i = 1,2,\ldots,M)$ are independent.
(3) Failures can be detected only at the time of inspection. Inspections are assumed to be instantaneous, perfect and non-destructive. If the system fails from the ith failure mode, corresponding perfect CR takes a random time of length Y_i $(i = 1,2,\ldots,M)$, with distribution function $G_i(y)$ and density function $g_i(y)$. Y_i $(i = 1,2,\ldots,M)$ are mutually independent random variables.
(4) The CR cost rate of the ith failure mode is C_{R_i} $(i = 1,2,\ldots,M)$. The cost of an inspection is C_I. The downtime penalty cost rate is C_f.
(5) A renew cycle is defined as a time interval between the installation of a new system and the completion of the first CR or a time interval between two consecutive completions of CRs.

A possible sample path of the system is illustrated in Fig 1. As shown in Fig. 1, the inspection interval length is T. The system fails from failure mode 2 between the third inspection and the fourth inspection, and it remains idle and no CR is taken until the fourth inspection. Corresponding CR takes a random time Y_2. On completion of the CR, the system is renewed. The time interval between the installation of the system and the completion of the first CR is called Cycle 1 while the time interval between the completion of the first CR and the completion of the second CR is Cycle 2.

Hence the maintenance costs in a renewal cycle are associated with inspections, CR and downtime. Then we focus on deriving