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An integrated framework for mode failure analysis, delay time model and multi-criteria decision-making for determination of inspection intervals in complex systems

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ABSTRACT

This paper aims to propose a framework for the definition of an inspection policy with three main elements: evaluation of failure modes (MF) of a system, selection of the criteria that best represent each dimension of failure modes and a process for determining inspection actions through a multi-criteria approach. The proposed modeling consists of determining the inspection interval for each mode of failure, considering that the MF has different consequences under different criteria. To meet this goal, first, the system and its respective failure modes are identified. Then, the consequences of the MF are classified according to a logical decision diagram that assists the decision-maker in identifying the criteria to be used in modeling, which may vary between cost, downtime, safety, environmental, quality and reputation, selecting among them the one (s) that best represent each mode of failure. Finally, the inspection intervals are determined for each MF using a multiple-criterion decision analysis (MCDA). By applying the framework proposed in a subsystem of a thermoelectric plant, it was possible to determine the inspection interval for each failure mode. Through the proposed model, it was possible to introduce a broad view of the decision problem and to focus attention on the failure modes that have the greatest impact.

1. Introduction

The definition of an inspection policy is one major challenge for maintenance managers in complex systems. In order to aid inspection decisions, Christer (1976) proposed the delay-time concept, which represents the time interval between the occurrences of a defect in the system to failure. If an inspection occurs during this interval, the defect can be detected and a breakdown avoided.

The delay-time models can be divided into two categories: models for complex systems and models for a single component, where the first refers to a system with different components and failure modes and the second to a single component subject to a single mode of failure (Christer, 1999).

In complex systems, inspection has an important role to play in maintenance. This occurs because, in most of these systems, failures do not occur immediately and are characterized by a process in which failure is preceded by a defect (Ferreira et al., 2013).

Wang (2008) highlights that for delay-time modeling in complex systems, an approximation is made so that the arrivals of defects of all components are grouped. It is then also necessary to assume that the delay-time of all the defects follows an identical distribution. For some systems this may not be true, and MF may have different distributions and impacts depending upon different criteria.

As highlighted by Jones et al. (2009), it is important to apply techniques to identify critical failures, failure modes and the chances of failure occurring in order to make inspection decisions. A technique commonly used for this purpose is Failure Mode and Effect Analysis (FMEA), which considers systems to be composed of different failure modes, each with different consequences (Stamatis, 2003).

In this sense Andrawus et al. (2008) used a hybrid model between FMECA (Failure Modes, Effect and Criticality Analysis) and the delay-time model to evaluate the failure characteristics of a wind turbine subsystem. Inspection intervals for critical turbine subsystems are determined in order to minimize cost. These subsystems are characterized according to failure modes.

Emovon et al. (2016) presented a methodology that integrates multicriteria decision analysis (MCDM) with a delay-time model for the determination of inspection intervals in marine machinery systems. With this approach, decision criteria (cost, downtime and reputation) are modeled.

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Table 1
Contribution of different authors according to the optimization criteria.

	Author	Year	Cost	Down Time	Reliability	Safety	Environmental impact	Profit	Reputation
1	Cai et al.	2007	X						
2	Akbarov et al.	2008	X						
3	Aven & Castro	2008	X			X			
4	Wang	2008	X	X					
5	Andrawus et al.	2008	X						
6	Jones et al.	2009	X	X			X		
7	Wang	2009	X					X	
8	Ferreira et al.	2009	X	X					
9	Hu et al.	2009	X						
10	Wang	2011	X						
11	Cavalcante et al.	2011	X	X					
12	Cunningham et al.	2011		X					
13	Lu and Wang	2011		X					
14	Wang et al.	2011			X				
15	Wang	2012	X	X	X				
16	Lu et al.	2012	X						
17	Wang et al.	2013	X						
18	Ferreira et al.	2013	X	X					
19	Oosterom et al.	2014	X						
20	Flage	2014	X						
21	Wang et al.	2014	X						
22	Lopes et al.	2015	X						
23	Nazemi & Shahanaghi	2015		X					
24	Yang et al.	2015	X						
25	Liu et al.	2015	X						
26	Yang	2016	X						
27	Emovon et al.	2016	X	X					X
28	Ramadan	2016	X	X					
% Of the criteria used			85,71%	39,29%	7,14%	3,57%	3,57%	3,57%	3,57%

Ramadan (2016) presented a bi-objective optimization model to determine the number of inspections in repairable systems with a finite life. Consideration was given to the availability of the components and the total cost of maintenance.

A brief summary of the literature for the last ten years about delay-time modeling with the main criteria used is presented in Table 1.

In the publications shown in Table 1, seven criteria were found, with different denominations. Among the most common criteria, cost was referenced in 24 articles (85.71%), and downtime in 11 (39.29%). The number of papers using at least one of these two criteria represents 96.43% of the total. The other criteria were used with less frequency, criteria reliability in 7.14% of the total. The criteria of safety, environmental impact, profit and reputation appeared at frequencies 3.57% each. It is possible to emphasize that only 25% of the analyzed papers considered two optimization criteria, while 11% used three criteria. This is probably due to the increasing complexity of modeling when the number of criteria increases. Another point that can be observed is that only one article employed classification of the systems according to their modes of failure.

Therefore, it is possible to highlight that in the literature related to delay-time, little attention has been given to the use of more than three criteria in the inspection modeling and the classification of systems according to failure modes. The relevance of delay-time modeling within maintenance management justifies the need for a methodological framework to analyze these points together.

Given this context, this paper proposes a method to assist maintenance managers in setting the interval between inspections, with consideration given to the criteria of cost, downtime, safety, environmental impact, quality and reputation that best represent each Failure Mode (MF), and to the process of determining the optimum inspections through the use of a multicriteria approach. These three elements together constitute a new proposal for defining inspection policy.

This paper is divided as follows: Section 2 describes the framework for determining the inspection intervals for each failure mode, in Section 3 the results are found for a case study in a thermoelectric plant, and section 4 offers the conclusion.

2. Proposed framework to define the inspection interval

The following notations were used:

T Interval between inspections
h Delay-time
m Numbers of failure modes in the system
θ_m Redundancy factor for failure mode m
β_m Shape parameter of the distribution *delay-time*, *f(h,m)*
$\varnothing_m$ Scale parameter of the distribution *delay-time*, *f(h,m)*
r_m Probability of a defect present at an inspection to be identified
k_m Rate of arrival of defects related to failure mode m
Cb_m Cost of breakdown due to each failure mode m
Ci_m Inspection cost related to each mode of failure m
Cir_m Cost of inspection repair related to each mode of failure m
Db_m Average downtime related to breakdown due to each failure mode m
D_m Average downtime related to inspection due to each failure mode m
Rb_m Impact of reputation related to breakdown to each failure mode m
Ri_m Impact of defect on reputation related to each failure mode m
EA_m Environmental impact of breakdown related to each failure