Maintenance at pre-planned schedule times considering opportunistic replacement

Y.R. Melo*, C.A.V. Cavalcante*, R.S. Lopes* and P.A. Scarf**

**Departamento de Engenharia de Produção, Universidade Federal de Pernambuco, Brazil*

***Cardiff Business School, Cardiff University, UK*

e-mail address: [author name]@random.org.br

Abstract. In this paper, we examine the impact of opportunities on systems that are maintained periodically. In a fleet of systems, such as a wind farm, an irregularity in one can serve as an opportunity for others, allowing maintenance actions to be carried out at a lower cost. In this context, we propose a maintenance policy with two phases. In the first phase there are inspections, and in the second phase, only corrective maintenance is carried out. Our main idea is to introduce flexibility to phase two, whereby opportunistic replacements may be carried out. Besides the fact that any action can be taken at predefined fixed times, we also consider defaulting which is the impediment to perform maintenance actions related to the limit of resources available or any external event. The proposed model is based on the delay time concept, where a single component system has three states: good, defective and failed. The system operates in both the good and the defective state. The defective state is only observable by inspection. The purpose of this study is to provide some insights for the decision-maker related to best practice when a system is accessible only at pre-planned, fixed times, where a default can occur, and installation problems can affect the reliability of the system and significantly change its expected life. The results of the numerical study show that the proposed policy has advantages when opportunities offer a less expensive means of preventive replacement and are frequent. For the benefit of the maintenance manager, especially when facing large logistic costs, maybe it is more interesting to be aware of what to do, when opportunities happen, than follow a restricted sequence of inspections.

1. Introduction

Decisions about maintenance actions are an essential part of the management of industrial facilities. Maintenance activities must consider the technical characteristics of the system. The maintenance planning can be related to inspection, repair, and replacement to improve the system's performance, and these actions involve high costs. Among the maintenance actions, an important policy is the inspection of the systems.

Inspection policies aim to detect a defective condition in a system and to be able to repair the defect before a failure occurs. The ideal condition would always detect the defect and avoid failures. The critical point is to determine when the system is in the defective state. A concept called delay-time was proposed by (Christer, 1999) to a mathematical modeling of the time from the identifiable defect to the failure point.

Since the delay-time concept was developed, several advances have been proposed in the literature, such as considering uncertainty in the quality of inspection (imperfect inspection) (Zhang et. al, 2021; Scarf and Cavalcante, 2012), considerations about opportunities (Cavalcante et. al, 2018), risk considerations (Silva & Lopes, 2018), environmental considerations (Jones et al. (2009)), postponed (Berrade et. al, 2017), spare parts (Wang, (2011); Zahedi-Hosseini et. al, 2017), among others as shown in the review paper (Jonge & Scarf, 2020). Practical applications of delay-time inspection found excellent results in different contexts, such as mining (Gölbaşı & Demirel, 2017), carbon black factory (Jones et. al, 2010), marine machinery (Emovon et. al, 2016), concrete structures (Redmond et. al 1997), gearboxes (Leung & Kit-leung, 1996), fishing vessel (Pillay et. al, 2001).

Opportunistic maintenance is a strategy that aims to consider the opportunities that arise to carry out an action to improve system condition (Cavalcante et. al, 2018). Opportunistic actions have a lower cost because the system is already stopped for some reason, such as failure in another component or issues related to production management.

The critical factor in the opportunity policy is to determine when an opportunity should be considered for maintenance action. If the action for opportunity maintenance occurs in advance it will have a cost and will not be effective because the system is not defective. On the other hand, if management does not consider the

opportunity and the system is defective, it will not act at a lower cost. Ideally, the management needs to consider opportunities that occur within the defect range. The big challenge is that there is uncertainty about when opportunities occur and uncertainty about the degradation of the system.

This paper proposes a hybrid maintenance policy combining inspection and replacement maintenance actions with opportunities to explore low-cost opportunistic replacement. In this policy, we propose to study a window of opportunities. The practical motivation to consider a window of opportunities is to explore more flexible planning in systems where logistical costs are high and access for maintenance must be planned, like offshore systems or underwater systems. In these systems, special types of tools are required to support maintenance inspections, such as vessels, cranes, submersible vehicles. For this, we consider that inspection visits occur at fixed intervals. Another motivation is modelling uncertainty in the realization of the planned action (default). The remainder of this paper is structured as follows. The proposed model is presented in section 2. The discussion on the results and on the sensitivity analysis are established in section 3 and the final considerations are discussed in section 4.

2. Development of the model

X	Defect arrival time
F_X	Defect arrival time distribution
β_i	Weibull distribution shape parameter for subpopulation i
η_i	Weibull distribution characteristic parameter for subpopulation i
m	Mixing parameter
H	Delay time
F_H	Delay time distribution
l	Inverse of the mean of the delay time distribution
μ	Opportunity arrival rate
p	Default probability
s	Time between visits
K	Number of inspections in a renewal cycle (decision variable)
W	Time window for arrival of opportunities (decision variable)
M	Number of visits in a renewal cycle (decision variable)
ci	Inspection cost
cp	Cost of preventive replacement during an inspection or at the end of the cycle
cf	Corrective replacement cost
co	Preventive replacement cost in an opportunity
cd	Downtime cost per unit time
$EC(K, W, M)$	Expected cost of a renewal cycle
$EV(K, W, M)$	Expected length of a renewal cycle
$CR(K, W, M)$	Cost rate

Table 1. Notation

In this study, it is considered a single component system composed by the union of a component and a socket that results in an operational function (Ascher & Feingold, 1984) that must present itself in one of its three states during any visit made to it. They are: good, defective or failed, where we can see that when the system is in good condition, it will be operating on a regular basis, but it is also proposed that in the defective state the system continues to function normally, requiring a maintenance action, known as inspection, to differentiate from the good state, with the purpose of avoiding an evolution from the defective state to the failed state (Christer, 1999). The system is subject to bad installation that provides a mixed population of weak and strong components. The main reason to consider that in this paper is that the maintenance actions in high seas can undergo sudden changes in climatic conditions, enabling the possibility of introducing errors in the installation of the component. Such errors have repercussions in the alteration of the time of arrival of defect, which can be anticipated. X is the time of arrival of defect, which is related to a mixture of distribution (2.1), since there are two different populations of components, a weak and a strong one, where $f_1(x)$ and $f_2(x)$ are Weibull distributions.

$$f_x(x) = mf_1(x) + (1 - m)f_2(x) \quad (2.1)$$

When the system is already in a defective state, it evolves to failure. The duration of the system in a defective state is given by the random variable H , which is related to an exponential distribution. Opportunities are modeled using a Poisson distribution with an arrival rate. The opportunities are independent of X and H , which are statistically independent from each other.

The presented model in this paper considers that maintenance actions can only be carried out through visits, which happens at pre-specified periods (Cavalcante et al, 2020) or at opportunities that arise in the system. In general, we can consider that the policy has two main phases and a sub-phase within the second one.

The first phase can be named inspection phase, and as the name suggests, it is the one intended for system inspections to find out its real state. It is proposed that from the beginning of the cycle until the end of the first phase, K inspections should be carried out, being s the period between one inspection and another. Thus, the first phase is the period $[0, Ks]$. In this first phase, preventive replacements can occur, when the component is in the defective state in one of the effective inspections (that is, the one that does not have a default) and corrective replacements can occur when a component fails between the period of two effective inspections.

The second phase can be called the correction phase. Inspections cease from the time Ks and thus begins this second phase, which lasts until the end of the cycle given by the M -th visit, so the second phase is the period $[Ks, Ms]$. Unlike the first phase, visits do not serve to distinguish the state of the system between the good and defective states, but between the good and the failing state, since the failed state can be observed without the need of inspection. In addition, there is a subphase within the second phase that occurs through the opening of the window of opportunities given by Ws , which also continues until the end of the cycle (Ms). This subphase of opportunities is the period $[Ws, Ms]$. This second phase comprises replacements in three different ways: Corrective replacement, which is carried out when the system is in a failed state in one of the effective visits; Preventive replacement when the system reaches the age limit (Ms); And preventive replacement when there is an opportunity, which can be named as opportunistic replacement. In these last two cases, we consider that it is not possible to have default.

The maintenance policy discussed in this paper considers the cost rate (long run cost per unit time), $CR(K, W, M)$, as a decision criterion, which can be found by dividing the expected cost by the expected cycle length (Ross, 1996). Thereby, we seek the value of the decision variables that return a minimized cost rate, as shown in the mathematical modeling in (2.2).

$$\begin{aligned} \text{Min } CR(K, W, M) &= \frac{EC(K, W, M)}{EV(K, W, M)} \\ \text{subject to:} \\ W - K &\geq 0 \\ M - W &\geq 0 \end{aligned} \quad (2.2)$$

3. Results and discussion

This section presents the results of the model's application. All parameters considered are shown in Table 2, as well as the obtained optimum policy. Our purpose here is to investigate the advantages in terms of cost that the window of opportunities brings to the scenario we presented in this paper. We consider the cost of preventive replacement as our unit cost and all the other costs are related to that one, such as corrective replacement cost, opportunistic replacement cost, downtime per unit time cost, and inspection cost.

Table 2 presents at the first row the other base parameters. The interval between visits is the unit of time, which is equal to the shape parameter of the weak population. All costs are per event, excluding the cost of downtime, which is per unit of time that the system is not in its operational state, this cost can be associated with the loss of power generation of the turbine.

	Cases	Parameters														Optimum policy			
		η_1	β_1	η_2	β_2	m	p	l	s	cp	cf	ci	cd	co	μ	K	W	M	CR(K,W,M)
Base parameters	0	1	3	10	3	0.2	0.2	0.5	1	1	4	0.1	2	0.5	0.25	2	4	8	0.2931
Sensitivity analysis	1	1	3	10	3	0.2	0.2	0.5	1	1	4	0.1	2	0.5	0	2	N/A	7	0.3300
	2	1	3	10	3	0	0.2	0.5	1	1	4	0.1	2	0.5	0.25	0	3	7	0.1862

3	1	3	10	3	0.2	0.4	0.5	1	1	4	0.1	2	0.5	0.25	2	4	8	0.3089
4	1	3	10	3	0.2	0	0.5	1	1	4	0.1	2	0.5	0.25	2	4	8	0.2770
5	1	3	10	3	0.2	0.2	0.5	0.5	1	4	0.1	2	0.5	0.25	3	9	17	0.2945
6	1	3	10	3	0.2	0.2	0.5	2	1	4	0.1	2	0.5	0.25	1	2	4	0.3262
7	1	3	10	3	0.2	0.2	0.5	1	1	4	0.5	2	0.5	0.25	0	3	9	0.3391
8	1	3	10	3	0.2	0.2	0.5	1	1	7	0.1	2	0.5	0.25	2	4	7	0.3734
9	1	3	10	3	0.2	0.2	0.5	1	1	4	0.1	2	0.7	0.25	2	5	8	0.3093
10	1	3	10	3	0.2	0.2	0.5	1	1	4	0.1	2	0.5	0.1	2	4	7	0.3144
11	1	3	10	3	0.2	0.2	0.5	1	1	4	0.1	2	0.5	0.5	2	5	10	0.2715

Table 2. Results and sensitivity analysis

When comparing the base case with case 1, we can see that the inclusion of opportunities in the system is really useful, it causes an increase in the life cycle of the component and at the preventive age of replacement (M_s). Another observation we can make is that as there are no opportunities coming in case 1, the optimum value for W is indifferent for any value (from K to M). This happens because, as there is no opportunity, establishing an opportunity window has no practical effect. In addition, the increase in opportunities in the system also reduces the cost rate. Those phenomena can be seen in the comparison of the base case with cases 1, 10 and 11. In fact, when the opportunities are more frequent and cheaper, the tendency is to wait for the opportunity during a longer period of time, which corresponds to postpone significantly the preventive replacement M_s , in order to make the opportunity window greater. The sensitivity analysis also indicates that the probability of default does not change the optimal maintenance policy, as we can see in the comparison of the base case with cases 3 and 4. Nevertheless, we can also analyze in these cases that the cost rate increases as there is a greater probability of a lack of spare parts or undesirable conditions for carrying out a maintenance action, which is a default.

We can observe that when there are no components within the weak subpopulation, that is, the mixing parameter is null, the optimal maintenance policy returns that the inspection maintenance action is not necessary ($K=0$). Another very important parameter for our maintenance policy is the interval between visits. It is not a variable decision, but it takes into account a context where the resources allocated to the maintenance of the system are limited in order to restrict the periods which visits can be made to the system. In the sensitivity analysis carried out through Table 2, we can see that as the visits become less frequent, that is, the interval between visits to the system increases, the policy tends to have fewer inspections (base case, case 5, case 6), as well as tending to decrease in general the absolute value of visits in which the transitions between the phases and sub-phase are carried out. The costs related to each maintenance action within the policy in this paper have a huge impact in defining the best policy. The increase in any of the costs directly reflects the increase in the policy's cost rate. In addition, we have to notice that the increase in inspection costs leads to a reduction in the number of inspections and a greater opening in the window of opportunity (case 7). In addition, the increase in the opportunity cost leads to a decrease in the window of opportunity (case 9). This is a very important result, since the logistic cost in offshore wind turbines is one of the greatest challenges to be overcome, thus the indication that opportunities exist and they cost less than a preventive maintenance, may influence the maintenance manager to turn the opportunities more effective, than to base the plan in individual inspections.

Figure 1. For maintenance policy, cost-rate versus (1) threshold for opportunities W , (2) age for preventive replacement M for different values of total number of inspections K .

We can see through an analysis shown in Figure 2 that the cost rate of the maintenance policy described in this article is way more sensitive to the total number of inspections scheduled to be carried out within a life cycle, than for the other variables, taking into account the base case for analysis. This explains why the optimal policies of the sensitivity analysis carried out in Table 2 vary considerably the other maintenance policy decision variables (threshold of opportunities W and age for preventive replacement M), without varying the total number of inspections within a renewal cycle for the different parameters presented. The increase in the cost rate when the total number of inspections is varied in a period can be greater than 9% for both scenarios in Figure 2. In the variation of threshold of opportunities and preventive age of replacement for different values of the total number of inspections this fact can be observed when comparing $K = 0$ to $K = 1$.

4. Final considerations

In this paper we propose a hybrid maintenance policy with opportunistic replacement, when inspection and failure finding actions only can take place at pre-planned schedule time, is . Where s is the interval between two successive pre-planned scheduled times. The consideration of the existence of opportunity is quite relevant, because in the regime of maintenance only at pre-planned schedule times, those opportunities could be used as a positive point, especially if we consider a fleet of systems, such as a wind farm. When dealing with systems with a high logistical cost, this consideration can have a large financial impact, since we consider that the interoccurrence in one system can provide an opportunity to another one and the spare parts are already close to the system under study. In the context of offshore wind turbines, the spare parts would be on the vessel in the sea.

Defaulting might be very realistic in the kind of context brought up earlier. We can consider that the location of some offshore wind turbines may provide more adverse weather conditions, which can be associated with more default for these systems, since generally it is not possible to provide maintenance action under these conditions. Consequently, other turbines near to them, or on the route of them, may have more opportunities. Those considerations can improve the performance of the system, since when we deal with opportunistic replacements it means that scheduled visits for preventive replacement become less and less necessary, as the optimal policy takes advantage of the financial advantage brought by the opportunities.

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References

- Ascher H, Feingold H (1984) *Repairable Systems Reliability: modeling, inference, misconceptions and their causes* (p. 232), New York: M. Dekker.
- Berrade MD, Scarf PA, Cavalcante CA (2017) A study of postponed replacement in a delay time model. *Reliability Engineering & System Safety* **168**, 70-79.
- Cavalcante CA, Lopes RS, Scarf PA (2018) A general inspection and opportunistic replacement policy for one-component systems of variable quality. *European Journal of Operational Research* **266**(3), 911-919.
- Cavalcante CA, Lopes RS, Scarf PA (2021) Inspection and replacement policy with a fixed periodic schedule. *Reliability Engineering & System Safety* **208**, 107402.
- Christer AH (1999) Developments in delay time analysis for modeling plant maintenance. *Journal of the Operational Research Society* **47**(11), 1406-1409.
- Da Silva JG, Lopes RS (2018) An integrated framework for mode failure analysis, delay time model and multi-criteria decision-making for determination of inspection intervals in complex systems. *Journal of Loss Prevention in the Process Industries* **51**, 17-28.

- De Jonge B, Scarf PA (2020) A review on maintenance optimization. *European Journal of Operational Research* **285**(3), 805-824.
- Emovon I, Norman RA, Murphy AJ (2016) An integration of multi-criteria decision making techniques with a delay time model for determination of inspection intervals for marine machinery systems. *Applied Ocean Research* **59**, 65-82.
- Golbasi O, Demirei N (2017) A cost-effective simulation algorithm for inspection interval optimization: an application to mining equipment. *Computers & Industrial Engineering* **113**, 525-540.
- Jones B, Jenkinson I, Wang, J (2009) Methodology of using delay-time analysis for a manufacturing industry. *reliability engineering & system safety* **94**, 111-124.
- Jones B, Jenkinson I, Yang Z, Wang J (2010) The use of bayesian network modelling for maintenance planning in a manufacturing industry. *Reliability Engineering & System Safety* **95**(3), 267-277.
- Leung F, Kit-Leung M (1996) Using delay-time analysis to study the maintenance problem of gearboxes. *International Journal of Operations & Production Management* **16**, 98 - 105.
- Pillay A, Wang J, Wall AD & Ruxton T (2001) A maintenance study of fishing vessel equipment using delay-time analysis. *Journal of Quality in Maintenance Engineering* **7**(2), 118-128.
- Redmond DF, Christer AH, Rigden SR, Burley E, Tajelli A, Abu-Tair A (1997) O.R. modelling of the deterioration and maintenance of concrete structures. *European Journal of Operational Research* **99**(3), 619-631.
- Ross, S (1996) *Stochastic processes*. New York: Wiley.
- Scarf PA, Cavalcante CAV (2012) Modelling quality in replacement and inspection maintenance. *International Journal Productions Economics* **135**, 372–381.
- Wang W (2011) A joint spare part and maintenance inspection optimization model using the delay-time concept. *Reliability Engineering & System Safety* **96**, 1535-1541.
- Zahedi-Hosseini F, Scarf PA & Syntetos A (2017) Joint optimization of inspection maintenance and spare parts provisioning: a comparative study of inventory policies using simulation and survey data. *Reliability Engineering & System Safety* **168**, 306-316.
- Zhang F, Shen J, Liao H, Ma Y (2021) Optimal preventive maintenance policy for a system subject to two-phase imperfect inspections. *Reliability Engineering & System Safety* **205**, 107254.