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Maintenance optimization using probabilistic cost-benefit analysis

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ABSTRACT

Over the recent decades, plant maintenance strategies have evolved from a corrective to a preventive approach. Also, deterministic models have been increasingly replaced by those based on reliability and risk, which are probabilistic. Approaches to obtaining the optimum maintenance interval have typically involved minimization of the total associated cost. The present work demonstrates an improved technique involving the maximization of reliability-based benefit-to-cost ratio (BCR), i.e., the ratio of potential monetary benefit that can accrue from an optimized preventive maintenance (PM) schedule to the costs incurred in implementing such a schedule. It is shown that the methodology can be used to optimize the PM schedule for process units whose reliability function is either exponential or follows a Weibull distribution. A sensitivity analysis has also been performed to demonstrate the effect of various model parameters on the benefit-to-cost ratio. The proposed approach constitutes an improvement over the cost minimization methodology reported in contemporary literature, and can even be extended to plant shutdown planning.

1. Introduction

Maintenance strategies have witnessed a paradigm shift over the recent decades from breakdown maintenance to more sophisticated strategies like condition monitoring and Reliability Centered Preventive Maintenance (RCPM). Plant safety/loss prevention is directly linked to the reliability of its operation. A robust maintenance program is necessary for the process industry as it deals with hazardous substances, often under severe operating conditions. Thus, plant managers and engineers today are faced with important preventive maintenance (PM) decisions aimed at integrated loss prevention. Preventive maintenance (PM) can help minimize the probability of losses due to accident situations and unscheduled failure of process units. The growing interest in reliability/risk-based PM and process safety management (PSM) is driven by the need to develop strategies that lead to an optimum safety vs. cost balance.

Quantitative approaches which link component deterioration to condition improvement by maintenance can help determine the effect of maintenance on reliability. A large number of papers have been recently published on the subject of optimizing maintenance through the use of mathematical models (Dey, 2004; Khan & Haddara, 2003a, 2003b; Montgomery & Serratella, 2002; Willcocks & Bai, 2000). Traditionally, optimal PM intervention schedules have been obtained using models, deterministic or probabilistic, which involves minimization of total costs incurred in relation to maintenance activities.

There are other objectives besides economics, which may influence preventive maintenance scheduling. For example, safety is an objective if combinations of equipment failures can cause a hazardous event, and if preventive maintenance can reduce the number of failures. In order to optimally trade-off multiple objectives, a single objective function needs to be constructed. This paper formulates a model to optimize the expected financial gain due to enhanced reliability deriving from PM against the costs incurred due to such an intervention.

Cost minimization has been the traditional objective in maintenance planning. Deterministic models (Vintr & Holub, 2003) on preventive maintenance optimization have established minima in costs based on operating cost parameters (repair, maintenance and acquisition). The use of deterministic methods, however, does not provide information about potential risk that results in non-optimal maintenance planning for process plants (Desjardins, 2002). Probabilistic models, on the other hand, use probability distributions to describe and represent natural variability and uncertainty in parameter, model and scenario (Bedford & Cook, 2001). Probabilistic models of scheduling preventive maintenance also minimize objective functions that reflect repair, replacement and PM costs (Zuo, Christianson, & Bartholomew-Biggs, 2006). The

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preventive maintenance interval is optimized when the increasing rate of corrective maintenance costs (with respect to time) equals the decreasing rate of preventive maintenance costs. Flexible maintenance intervals have been conceptualized by leveraging the step nature of the average change in reliability (with PM) over the service life of the component. Lapa, Pereira, and de Barros (2005) have used genetic algorithms to model flexible maintenance intervals for multi-component systems.

The present paper attempts to model PM using cost-benefit analysis (CBA). Our results show that while probabilistic PM cost minimization does not yield a definitive optimum for even the simplest of situation where a process unit has a constant failure rate; the CBA does show that an optimum PM interval can exist. Further, it is shown that units which typically undergo wear and tear during working life – pumps, compressors, turbines, etc. – and which show a Weibull type failure probability distribution are also amenable to CBA for obtaining optimal PM schedule. Lastly, we show that the benefit-to-cost ratio (BCR) is reasonably high in cases the PM and repair costs are less than 10% of the loss incurred due to an unscheduled breakdown.

2. Theory

The approach to PM optimization can be extended beyond cost minimization to a cost-benefit analysis. To solve for the optimal maintenance interval, a parameter benefit-to-cost ratio (BCR) may be defined. BCR is the ratio of the financial benefit (from increased reliability of a process unit) due to PM to the costs incurred due to maintenance interventions. Maximization of this ratio identifies the longest maintenance cycle that trades off the benefit from maintenance with the cost incurred to achieve an acceptable level of reliability of a process unit under maintenance.

Such an approach can be applied to any process unit. In the present paper, we illustrate it for units with (i) constant failure rate (faults/yr) and (ii) with a linearly increasing failure rate (faults/yr). While the former type of failure rate behavior is used for simple reliability analysis of a variety of process units, the latter type is usually applicable to units which undergo regular wear and tear (pumps, compressors, turbines).

The model developed in this work is an extension of that due to Lapa et al. (2005), which itself is a generalized form of the model proposed earlier (Lewis, 1996). Let C_m and C_r, respectively, be the costs of planned preventive maintenance and unplanned replacement/repair. The total cost, C_T, referred to the component's operation during the interval from the beginning of its operation and the time it suffers the first maintenance $T_m(1)$, indicated by the superscript index $(0 \rightarrow 1)$, is given by:

$$C_T^{0\rightarrow 1} = C_m^{0\rightarrow 1} R[T_m(1)] + C_r^{0\rightarrow 1}[1 - R[T_m(1)]]. \tag{1}$$

Generalizing this concept to the other intervals, a conditional probability $R[t/T_m(1)]$ may be defined; this represents the probability of the system to survive till time t, given that it did not fail until $T_m(1)$. If t_α is the time period until the component's failure, this is given by:

$$R[t|T_m(1)] = P\{t_\alpha > T_m(1) + t | t_\alpha > T_m(1)\} \tag{2}$$

$$R[t|T_m(1)] = \frac{R[t + T_m(1)]}{R[T_m(1)]}. \tag{3}$$

Using $t = T_m(2) - T_m(1)$ for interval $(1 \rightarrow 2)$ we get,

$$C_T^{1\rightarrow 2} = C_m^{1\rightarrow 2}\left[\frac{R[T_m(2)]}{R[T_m(1)]}\right] + C_r^{1\rightarrow 2}\left[1 - \frac{R[T_m(2)]}{R[T_m(1)]}\right]. \tag{4}$$

Generalizing for the 'ζ' number of intervals between maintenance interventions, the last one $(\zeta + 1)$ between the last maintenance intervention and the end of the service life (T_{ser}), we get:

$$C_T^{0\rightarrow T_{ser}} = \sum_{j=1}^{\zeta} C_m^{(j-1)\rightarrow j}\left[\frac{R[T_m(j)]}{R[T_m(j-1)]}\right] + C_r^{(j-1)\rightarrow j}\left[1 - \frac{R[T_m(j)]}{R[T_m(j-1)]}\right] + C_r^{\zeta\rightarrow T_{ser}}\left[1 - \frac{R[T_m(ser)]}{R[T_m(\zeta)]}\right]. \tag{5}$$

Assuming 'N' maintenance interventions over the entire service life, the total cost incurred due to maintenance for the entire equipment life is:

$$C(T) = \sum_{j=1}^{N}\left[C_m \frac{R(jT)}{R\{(j-1)T\}} + C_r\left\{1 - \frac{R(jT)}{R\{(j-1)T\}}\right\}\right]. \tag{6}$$

Let $R(t)$ be a general reliability function for an equipment and let the equipment be restored to an *As Good As New* (AGAN) condition after every PM intervention. For the jth maintenance interval, i.e., $(j-1)T \rightarrow jT$, the average difference in the reliability of the equipment *with* and *without* PM is given by:

$$\Delta R_m^{(j)}(T) = \frac{\int_0^T R(t)dt}{\int_0^T dt} - \frac{\int_{(j-1)T}^{jT} R(t)dt}{\int_{(j-1)T}^{jT} dt}. \tag{7}$$

Thus, the average difference in the two reliability functions for the entire life time of the process unit is (Fig. 1):

$$\Delta\overline{R_m}(T) = \frac{1}{N}\sum_{j=1}^{N} \Delta R_m^{(j)} \tag{8}$$

$$N = \left[\frac{T_{ser}}{T}\right] [x] \text{denotes greatest integer} \le x. \tag{9}$$

If C_{inc} be the cost incurred due to lost production and other financial losses due to process unit breakdown, the benefit $B(T)$ derived from periodic PM for the entire equipment life is:

$$B(T) = C_{inc} \cdot \Delta\overline{R_m}(T). \tag{10}$$

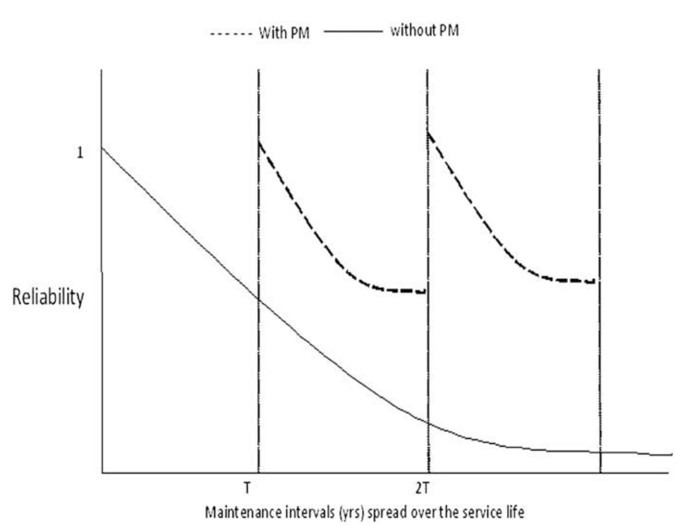

Fig. 1. Reliability vs. time for a single component with and without PM.