Available online at www.elixirpublishers.com (Elixir International Journal)

Mechanical Engineering

Elixir Mech. Engg. 65 (2013) 19919-19923

Elixir ISSN: 2229-712X

Optimal Replacement Policy for a Concrete Pump: A Case Study

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ARTICLE INFO

Article history:
Received: 29 October 2013;
Received in revised form:
2 December 2013;
Accepted: 10 December 2013;

Keywords
Maintenance,
Kay's Model,
Reliability Centered Maintenance,
Optimal replacement.

ABSTRACT

The dynamic behavior of infrastructure development has opened a wide area for research in construction management in general, and maintenance management in particular, globally. Ready mix concrete, which is mostly preferred nowadays, is loaded in a transit mixer, and is transported to the construction site. The concrete is delivered to the construction point by means of a concrete pump. Life of the concrete pump can be enhanced and hence capacity of the plantusing effective preventive maintenance. In this paper, optimal time for replacement for some critical components has been established using the approach of reliability centered maintenance. The paper includes the reliability assessment and the details of the effectiveness of maintenance on the system under investigation are reported in the paper.

Introduction

With the growing complexity of equipment and process and the magnitude of losses suffered in production due to breakdowns, today's management can no longer look upon maintenance as only a subsidiary function to production, but as one of the main tools of planned productivity, which must be effectively used to obtain the highest availability of production equipment commensurate with maintenance cost. The problems related to maintenance management have been attracting considerable attention from both researchers and practitioners, which is evident from the published literature.The dynamic behavior of infrastructure development has opened a wide area for research in construction management in general, and maintenance management in particular, globally. Ready mix concrete (RMC), which is mostly preferred nowadays, is loaded in a transit mixer, and is transported to the construction site. This method of mixing and transporting the RMC to a remote construction site has attracted the civil engineers. It is quite fast, efficient and above all clean. The concrete is delivered to the construction point by means of a concrete pump and its pipeline. Concrete Pump life is low due to the cement sludge that being handled makes the failure phenomenon time dependent and severe. In this paper, Reliability centered maintenance is applied to the concrete pump and effective maintenance policy is derived using a validated model.

Literature Review

In today's competitive world it is important and vital for making right maintenance decision. A number of models dealing with optimal maintenance policy have been published in literature.

Vaurio (1999) developed unavailability and cost models for periodically inspected and maintained units to minimize the cost rate by proper selection of optimal inspection interval using bisection procedure. Beichelt (2001) analyzed a policy for optimal scheduling replacement intervals of technical systems on the basis of maintenance cost parameter. The author validated the policies proposed using Rayleigh and Maxwell distributions. Schabe (1995) proposed a method to obtain optimal replacement time of a complex system based on the lifetime distribution function and repair cost of the components. Hipkin and Lockett (1995) surveyed literatures from 1976 to 1990 and presented an overview of optimal maintenance and replacement models. Wu and Croome (2005) suggested that in the reliability literature, maintenance time is usually ignored during the optimization of maintenance policies. In some scenarios, costs due to system failures may vary with time, and the ignorance of maintenance time will lead to unrealistic results. They developedmaintenance policies for such situations where the systemunder study operates iteratively at two successive states: up or down. Mariappan*et al*. (2008) developed a decision diagram that is capable of resolving collaborative decision. Failure processes can be effectively modeled as Weibull distribution with two parameters. As mentioned by Wayne (1985), using the Weibull parameters one can resolve maintenance policy between Breakdown maintenance (BDM) and Preventive Maintenance (PM). Nakagawa and Mizutani (2009) basically converted the usual maintenance models to finite maintenance models. The author considered three usual models of periodic replacement with minimal repair, block replacement and single replacement which are

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transformed to finite replacement models. The authors could derive appropriate replacement polices using analytical derivation and numerical computations.

Jos´e*et al* (2010) presented the architecture and implementation of a tool called preventive maintenance optimization software tool (PMOST), based on algorithms for the optimal scheduling of preventive maintenance (PM) tasks in semiconductor manufacturing operations. The authors demonstrated with the help of case studies that the results show significant improvements in consolidation of PM tasks.Ahmadi*et al*(2011) developed a cost rate function to identify the optimal frequency and interval for inspection of repairable components in aircraft undergoing ageing. The function also considered the cost associated with accidents caused by the occurrence of multiple failures. Li *et al*(2012) proposed a methodology to obtain the optimal scheduling for Preventive Maintenance using time-dependent reliability principles. They proposed an optimization algorithm that maximizes the time for Preventive Maintenance by improving the system reliability, so that the lifecycle cost stays below a specified target. Preventive Maintenance is performed at the time when the improved reliability falls below an acceptable target.

Model to Derive Maintenance Policy

The model developed by Kay (1976) offers considerable scope to derive maintenance decisions. The schedule maintenance is to mitigate the failure of machinery, during its assigned operating time by means of scheduled overhauls. One of the criteria by which the effectiveness of PM can be addressed is via cost rate. In this particular studywe need optimal schedule for minimizing the cost rate.

Notations

f (t)	: Probability density function (pdf) of Time to failure
R (t)	: Reliability function
M	: Mean Time Between Failures (MTBF)
BDM	: Breakdown maintenance
PM	: Preventive maintenance
m	: Mean Time To Repair (MTTR) or Mean maintenance time, in case of BDM
m_s	: MTTR, Mean maintenance time of PM
T	: Scheduled period
T*	: Optimal schedule
$\overline{T}$	: Mean time between two consecutive PMs
h(t)	: Hazard rate function
c	: Maintenance cost per unit time for BDM
c_s	: Maintenance cost per unit time for PM
C	: Average effective maintenance cost rate for BDM
C_s	: Average effective maintenance cost rate for PM
α	$= \frac{\overline{T}}{M} \leq 1$
γ	$= m_s/m \leq 1$
δ	$= c_s/c \leq 1$
μ	$= m/M \leq 1$
β	: Shape parameters of Weibull distribution
θ	: Scale parameter of Weibull distribution
σ	: Standard deviation
RMC	: Ready mix concrete

Equations for cost rate have been derived in respect of preventive and breakdown maintenance.

Average effective maintenance cost rate for BDM

$$C = \frac{cm}{M + m} \tag{1}$$

Average effective maintenance cost rate for PM

$$C_s = \frac{c_s m_s R + cm(1 - R)}{\overline{T} + m_s R + m[1 - R]} \tag{2}$$

For cost rate of PM to be lesser than that of BDM

$$C_s < C$$

Hence for the given criterion preventive maintenance to be attractive $C_s < C$. The following conditions have been derived using the above criterion, to ensure that the preventive maintenance scheduled in time T is to offer minimum cost of maintenance than that of breakdown maintenance.

$$\alpha = \frac{1}{\theta\Gamma\left(1+\frac{1}{\beta}\right)} \int_0^T e^{-\left(\frac{t}{\theta}\right)^\beta} dt \qquad (3)$$

$$\alpha > 1-kR(T) \qquad (4)$$

Where, $k = (1-\delta\gamma) + \gamma\mu(1-\delta)$

As failure processes can be safely modeled as Weibull distribution, (3) can be evaluated after Weibull analysis on the data collected. As the integrand in (3) is transcendental but real valued analytic function, a graphical approach would be more feasible to evaluate the finite integral. Equation (4) resolves into α-curve and a straight line [1-k.R(T)], which is equivalent to [(1-k)+kF(T)]. These two components are superimposed as shown in Figure 1 which is obtained using a code written in MATLAB, Version 7.0. This diagram is referred to as "Decision diagram". From (4), it is clear that for any given value of β, if the point of intersection leaves a significant part of α-curve on its right side then PM is preferable. Since the straight line1-k.R(T) resolves the decision, hereafter, the straight line will be referred to as "decision line". 1-k.R(T) will have its Y-intercept as (1-k) and passes through (1, 1) which is common to α curve and the decision line. Either the point of intersection between α curve and the decision line, or the point of the maximum gap between α curve and the decision line will offer the initial value for the optimal period.

Selection of Optimality

The iterative mechanism developed by Mariappan et al. (2008)picks up the initial T* value from the decision diagram and then terminates the iteration when no further improvement is possible in T*. The iterative formula is expressed in Equation (5).

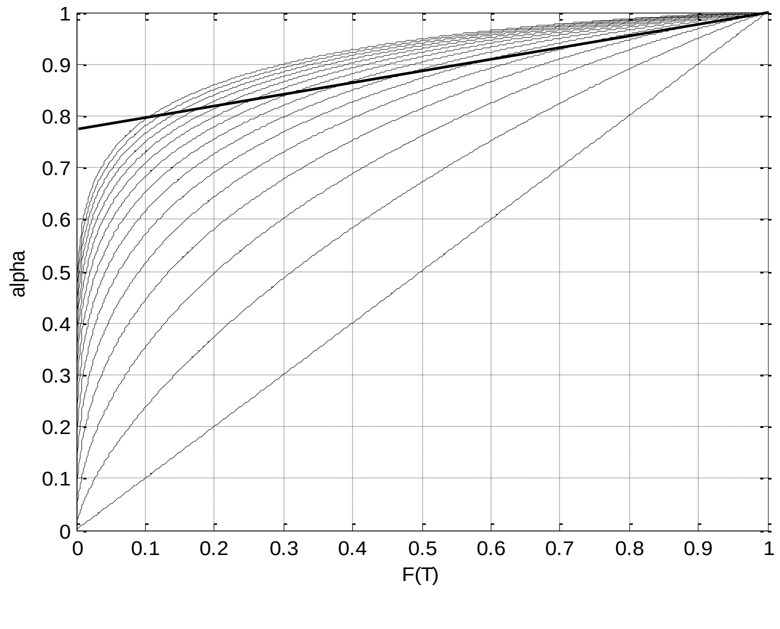

Figure 1: Decision diagram

$$T_{i+1}^* = \theta \left\{ \frac{\theta}{\beta M k} \right\}^{\frac{1}{\beta-1}} \left\{ \frac{[1-kR(T)]}{\alpha} \right\}_i^{\frac{1}{\beta-1}} \qquad (5)$$

Procedure

1) By carrying out appropriate FMEA critical parts have been identified.
2) Reliability assessment is carried out for the identified critical parts.
3) Labour cost, downtime cost (cost due to non-operation of the pump), part cost for each part are obtained.
4) From the cost data, establish k.
5) Obtain shape parameter from Weibull analysis.
6) With the values of k and β, enter decision diagram and find the initial value of T*.
7) Apply the iterative formula expressed in Equation (5) and get the optimal schedule for PM.

Table 1: C_s values for various critical elements

Parts	Cost			Total cost, C_s (Rs./hr)
	Labour cost (Rs./hr)	Downtime cost (Rs./hr)	Part cost (Rs.)	
Gate valve	113	650	12376	13139
Formless rings	113	650	2000	2763
Ram	75	650	2370	3095
Shell (set of two)	113	650	6630	7393
Piston assembly	113	650	3500	4263
Plunger cylinder	113	650	7500	8263

In case of breakdown of a critical part, the pump has to be brought back to the plant for replacement. Towing cost, as obtained from the company records is Rs. 4.5 per km. The site under observation was found to be 10 km from the plant.
Total towing cost = (10+10) * 4.5 = Rs. 90

Along with the part which has failed, some other parts have to be replaced, which wear out due to the failure of the part under consideration. Also, the downtime cost due to non-operation of the pump must be considered.

Hence the maintenance cost per unit time for breakdown maintenance (C) includes:

1. Part cost
2. Replacement cost per hour
3. Downtime cost per hour
4. Towing cost
5. Cost of additional parts which are replaced

But, (Part cost) + (Replacement cost per hour) + (Downtime cost per hour) = C_s

$$\therefore C = C_s + (\text{Towing cost}) + (\text{Cost of additional parts which are replaced}) \qquad (6)$$

Results and Discussions

The six critical components chosen are Gate valve, Formless rings, Ram, Shell, Piston assembly and Plunger cylinder. Sample calculations are carried out on failure data available for a part called formless rings as mentioned in Table 2.

Table 2: Failure data for formless Rings

i	Time to failure (TTF)	F(t)
1	24	0.0476
2	40	0.0952
3	48	0.1429
4	56	0.1905
5	80	0.2381
6	88	0.2857
7	96	0.3333
8	120	0.3809
9	128	0.4286
10	176	0.4762
11	178	0.5238
12	192	0.5714
13	196	0.6190
14	198	0.6667
15	216	0.7143
16	224	0.7619
17	240	0.8095
18	244	0.8571
19	256	0.9048
20	264	0.9524
21	272	1.0

Weibull analysis gave the parameters $\beta = 2.9$, $\theta = 180$.
The cost data: C_s = Rs. 2763
Obtaining values of C = Rs. 2853, $\delta = 0.968$, $m_s = 4$ hrs; $m = m_s + 1$ hr for towing = 5 hrs
$\gamma = 0.8$, $\mu = 5/(180*0.9) = 0.03$, $k = (1-\delta\gamma) + \gamma\mu(1-\delta) = (1-0.968*0.8)+0.8*0.3(1-0.968) = 0.23$

Applying the procedure discussed above, the decision is to go for PM with the optimum schedule T* = 236.5hrs. Similarly, the decision whether to go for PM or not is done using the decision diagram. These values and decisions are reported in Table 3.

Table 3: Optimal schedules for critical components

Parts	Optimum time for replacement (t*) (hrs)
Gate valve	394.6
Formless rings	236.5
Ram	339.3
Shell	150.1
Piston assembly	352.6
Plunger cylinder	PM is not preferred

Conclusions

Reliability centered maintenance is applied to the concrete pump. Using a validated model the effective maintenance policy was derived. The whole procedure involves data collection, analysis, FMEA. Thus the whole paper illustrates how to practically obtain optimal schedule for PM and whether or not PM programme is preferable. The values obtained have proved to be time and cost effective on the field.

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