International Journal of Performability Engineering, Vol. 9, No. 3, May 2013, pp. 273-285.
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Printed in India

Opportunistic Actions for Subassemblies of a Reciprocating Compressor: An LCC Based Approach

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(Received on May 14, 2012, revised on August 10, 2012)

Abstract: In this paper, an opportunistic maintenance approach has been studied on a reciprocating compressor, which consists of series connected structure. When the system is down, either under corrective or preventive maintenance, the opportunity to replace even preventive non-failed subassemblies is considered. The optimization of opportunistic action depends upon the failure cost, which again depends upon the minimum cost of opportunistic action. The impact of opportunistic maintenance on the Life Cycle Cost (LCC) of a reciprocating compressor has been simulated. The case study result shows the reduction of INR 12,541,750 in LCC of a reciprocating compressor and ensures the required level of operational availability, when the opportunistic maintenance is incorporated in its traditional maintenance approach.

Keywords: *Opportunistic maintenance, mechanical system, LCC, availability*

1. Introduction

Mechanical systems (like machine tool, engine, compressors, *etc*.) start deteriorating, in general, with the passage of time; to upkeep them in the operational state, appropriate maintenance actions are required. Maintenance improves the system performance by reducing the number of catastrophic failures. The aim of maintenance is to sustain the system performance over and above the desired level but at minimum possible cost, so as to achieve the operational objective(s) of the maintenance, in general, and of the system in particular.

Maintenance for a mechanical system comprises of actions like inspection, corrective, preventive and overhaul including opportunity maintenance that was first coined by Radner and Jorgenson [1] and McCall [2]. Opportunistic maintenance refers to a kind of preventive action, in which the necessary maintenance action for non-failed components/subassemblies is carried out at opportunities when the system is down, either correctively or preventively. Thus, whenever a system is taken for maintenance of any kind, there may be an opportunity to do maintenance of its other components, which have not failed, but their scheduled maintenance is due shortly. It can enhance the system performance through preventing random breakdowns by availing the opportunities of maintaining the non-failed component, during planned and/or unplanned maintenance activity.

The opportunistic maintenance decisions depend upon the maintainability, the available time, failure cost and maintenance cost, *etc*. The maintenance cost can be estimated from the cost incurred in different activities like corrective, preventive, overhauls and opportunistic; that do contribute in systems' Life Cycle Cost (LCC). The maintenance cost may get affected by failures which can be reduced by incorporating the opportunistic actions during planned and unplanned maintenance activities. However, the execution of opportunistic action on non-failed component(s) may be carried out, when its execution time is less than or equal to the available downtime. Therefore a trade-off

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between maintenance activities and operational objectives is required to have a minimum LCC with an assured level of system performance.

The objective of this paper is to incorporate the opportunistic maintenance action in a particular schedule of preventive action for a multi-subassemblies system subjected to high downtime losses and economic dependence. In this work, an attempt has been made to study the effect of opportunistic maintenance on the LCC of a reciprocating compressor that consists of 19 subassemblies; connected in series and are subjected to random failures over their operating span. The subassemblies are replaced/repaired on failure, and at the same time, the opportunities for preventive maintenance on other subassemblies that are due are also undertaken. The LCC model for the reciprocating compressor is developed, and minimized on the basis of optimized opportunistic maintenance action while ensuring the required level of operational availability. One of the three alternatives of opportunistic actions i.e. 'Do Nothing' (N), 'Repair' (r) and 'Replacement' (R) are chosen to study their effect on the LCC. The optimization of opportunistic action for a particular subassembly is based on its criticality of failure; which further depends upon the minimal cost of the opportunistic alternatives among the possible ones.

In the next section, the relevant literature, particularly dealing with opportunistic maintenance is presented. Section 3 presents the mathematical models for LCC and availability of the system. In Section 4, the proposed approach is illustrated by a case study, which explains the formulation and verifies the convergence of the solution procedure. Section 5 concludes the work and suggests the future scope of research.

Notation

a	Restoration factor
A	Operational Availability
C_{aqi}	Acquisition cost of ith subassembly in the system
C_{fix}	Fixed cost to carrying out each maintenance action, which includes the costs of material required like lubricating oil, *etc*.
C_{Ci}	Cost of ith subassembly within the system
d	Discount rate per annum, and assumed to be constant throughout the life of the system
dt	Time difference between the planned maintenance and the opportunity
$E[C_{CA}]$	Expected cost of corrective action during investigation period for a system
$E[C_{OM}]$	Expected cost of opportunistic actions during investigation period for a system
$E[C_{ORi}]$	Expected cost of replacement of ith subassembly of the system during opportunistic action
$E[C_{Ori}]$	Expected cost of repair of ith subassembly in the system during opportunistic action
$E[C_{PA}]$	Expected cost of preventive action during investigation period for a system
$E[N_{CM_i}]$	Expected number of failure of ith subassembly of the system
$E[N_{PM_i}]$	Expected number of preventive maintenance schedule of ith subassembly in the system
$E[N_{Or_i}]$	Expected number of opportunistic repair of ith subassembly in the system
$E[N_{OR_i}]$	Expected number of opportunistic replacement of ith subassembly in the system

E[TDT]	Expected downtime for which the system is not available
INR	Indian Currency
L	Expected life of the system
L_C	labour cost per unit time
$MTTCM_i$	Mean time required to perform the corrective action of ith subassembly in the system
$MTTPM_i$	Mean time to perform the preventive maintenance of ith subassembly in the system
$MTTRA_i$	Mean time to replacement of ith subassembly of the system during opportunistic action
n	Number of subassemblies in the system
N	Do Nothing; opportunistic action
N(t/V)	Conditional number of failure
PVc	Present value of LCC
r	Repair; opportunistic action
R	Replacement; opportunistic action
R_{CA}	Revenue lost due to failure/breakdown
R_{PA}	Revenue lost due to scheduled maintenance
T	Planned operating period
T_{opr}	Actual operating time
t_{pm}	Schedule maintenance interval
t_O	Time at which the opportunity arises
V	Virtual age of the component
V_n	Virtual age of the unit at the time of the nth repair completion
$V_{(n-1)i}$	Virtual age of the component before carrying out a particular maintenance action
X_n	Preventive maintenance interval
β	Shape factor, defines the shape of distribution in Weibull
η	Scale parameter, defines where the bulk of the distribution lies in Weibull

2. Literature Review

Opportunistic Maintenance was first introduced by Radner and Jorgenson [1] and McCall [2]. Since its introduction, it has been widely implemented and reported in the literature, which shows its effectiveness in different segments of engineering. Literature pertaining to opportunistic maintenance has been reviewed and described in this section.

Zheng and Fard [3] studied an opportunistic situation with a maintenance policy based on failure rate tolerance for a system having k different types of units. A unit is replaced either when the hazard rate reaches a particular value and/or at failure in a particular time interval.

Pham and Wang [4] proposed two opportunistic maintenance policies for k-out of-n system. The minimal repairs are performed on the failed subassembly before time‘s’ (a decision variable) while corrective maintenance of all failed subassemblies is combined with preventive maintenance of all operating units after time ‘s’. Dagpunar [5] proposed a maintenance policy, where replacement of a subassembly within the system is carried out at an opportunity, which arises when some other part of the system fails and needs to be replaced. Laggoune *et al.* [6] studied a preventive maintenance approach for a hydrogen compressor installed at oil refinery, by availing the opportunities to replace preventively non-failed component that minimizes the production losses. While they further studied the

opportunistic replacement policy for the same equipment under the uncertainty associated in failure data that minimizes the expected cost per unit time while considering the general lifetime distribution [7].

Samrout *et al.* [8] presented a method to minimize the preventive maintenance cost of series-parallel systems using Ant colony optimization. Duarte *et al* [9] proposed an algorithm for maintenance management optimization of a series system based on preventive maintenance, with all the subassemblies assumed to exhibit linearly increasing hazard rate and constant repair rate.

Besnard *et al.* [10] studied an opportunistic maintenance optimization model for offshore wind power *system*. The results showed 43% of cost saving in scheduled maintenance. Besnard *et al*. [11] presented a stochastic optimization model for opportunistic maintenance of offshore wind farms. They forecasted the opportunities at corrective maintenance activities that minimize up to 32% of the total cost. The effect of opportunistic maintenance will be immense, if it can correlate with system LCC, which may be one of the criterions for equipment purchase [12]. In another study, Lad and Kulkarni [13] proposed a cost based Failure Modes and Effects Analysis (FMEA) by identifying critical failure event based on actual cost of failure to the user's, which can be helpful in estimating the system's LCC.

LCC generally refers to all the costs associated with a product throughout its operating span that includes cost related to conceptual design, detailed design and development, production, product use and support, and phase out [14]. Asied and Gu [15] presented a review on the issues of LCC analysis that have been developed to provide engineers cost information that helped them in addressing at the design stage. Korpi and Ala-Risku [16] reviewed the case studies pertaining to the application of LCC in various sectors. Samarakoon *et al.* [17] studied that LCC analysis may be a helpful tool in making decisions at initial phase of a project regarding the best available and qualified technique considering economic aspects.

The integration of opportunistic maintenance with condition based monitoring has been studied by Koochaki *et al.* [18]. The authors examined the impact of opportunistic maintenance on the effectiveness of condition based maintenance (CBM), and results indicated that an opportunistic maintenance strategy enhanced the effectiveness of CBM.
From the literature review, it is concluded that the maintenance cost can be reduced by incorporating the opportunistic maintenance throughout the systems operating span; as the cost of simultaneous maintenance actions on various subassemblies and/or components is less than the total cost of individual maintenance actions, and thereby, affects at the LCC of the system. A lot of research on opportunistic maintenance has been reported in a literature, but there seems to be paucity in its integration with LCC and system availability. The proposed work in this paper is a step in this direction, which would be helpful for the cost reduction by incorporating the opportunistic maintenance while maintaining the required availability. The next section deals with the mathematical modeling and problem formulation

3. Mathematical Modeling

Actually, LCC is the summation of cost estimates, from inception to disposal of the system [14]. From mechanical systems users' point of view, the LCC includes acquisition cost, operating cost, maintenance cost, failure costs, *etc*. But this may differ from case to case. For example, some users may want to evaluate the LCC in terms of maintenance cost. In this case, it comprises of maintenance cost only. In this work, the authors have studied the effect of opportunistic actions on the LCC of the system and considered

acquisition cost, corrective maintenance cost and preventive maintenance cost for each sub-assembly under this.

The acquisition cost is the fixed amount that the customer pays for the purchase of system at the initial stage. The corrective maintenance cost depends upon the number of failures or corrective actions.

Corrective actions are the appropriate maintenance/repair actions that are taken to remove/repair and/or replace the failed subassembly. The corrective action cost comprises the labour cost, component cost, fixed cost of carrying out the maintenance action and associated loss of revenue. Thus, expected cost of corrective action during investigation period $'E[C_{CA}]'$ for a system is given below;

$$E[C_{CA}] = \sum_{i=1}^{n}\{(MTTCM_i \cdot (R_{CA} + L_c) + C_{Ci} + C_{Fix}) \cdot E[N_{CM_i}]\} \quad (1)$$

where, $MTTCM_i$ is the mean time required to perform the corrective action of a particular component/subassembly within the system.

C_{fix} is the fixed cost to perform the corrective action, which includes the costs of material required like lubricating oil, *etc*.

C_{Ci} is the cost of ith subassembly within the system.

L_C is the labour cost per unit time.

$E[N_{CM_i}]$ is the expected number of failure for a particular component/subassembly of the system.

R_{CA} is the revenue lost due to sudden failure and/or breakdown.

Preventive maintenance is a scheduled maintenance actions aimed at the prevention of failures, in general, and accidents in particular. Preventive maintenance activities include equipment checks at specified periods so they replace or repair worn parts before they cause system failure. The model for calculating the expected cost of preventive action during investigation period $'E[C_{PA}]'$ for a system is given below;

$$E[C_{PA}] = \sum_{i=1}^{n}\{(MTTPM_i \cdot (R_{PA} + L_C) + C_{fix}) \cdot E[N_{PM_i}]\} \quad (2)$$

where, $MTTPM_i$ is the mean time to perform preventive maintenance action of a particular component/subassembly in the system.

C_{fix} is the fixed cost to perform preventive action, which includes the costs of material required like lubricating oil, *etc*.

L_C is the labour cost per unit time.

$E[N_{PM_i}]$ is the expected number of preventive maintenance actions for each component/subassembly of the system.

R_{PA} is the revenue lost due to scheduled maintenance.

The maintenance of non-failed components either with scheduled or corrective maintenance of failed component is known as opportunistic maintenance. Whenever a system is grounded for maintenance work, there may be an opportunity to do maintenance of other components which have not yet failed, but have reached their threshold limit or need maintenance work in the immediate future. The threshold limit can be defined by the user and/or manufacturer, based on their time to failure, residual life, reliability threshold or failure cost.

The decision for opportunistic alternatives for component repair/replacement depends upon the minimum cost of the opportunistic action. However, in this work, the opportunistic maintenance decisions are based on failure cost (threshold limit) for each module. The three opportunistic actions i.e. 'Do Nothing' (N), 'Repair' (r) and 'Replacement' (R) are to be executed. The expected cost under N will be zero as this decision implies no maintenance action to be performed.

The model for estimating the expected cost of replacement and repair under opportunistic maintenance is given by:
Expected cost of replacement;

$$E[C_{ORi}] = \sum_{i=1}^{n}\{(MTTRA_i \cdot (R_{CA} + L_c) + C_{Ci}) \cdot E[N_{OR_i}]\} \quad (3)$$

and the expected cost of repair;

$$E[C_{Ori}] = \sum_{i=1}^{n}\{(MTTPM_i \cdot (R_{CA} + L_c)) \cdot E[N_{Or_i}]\} \quad (4)$$

where, $E[N_{Or_i}]$ and $E[N_{OR_i}]$ are the expected number of opportunistic repair and opportunistic replacement of ith subassembly respectively.

The expected cost of opportunistic maintenance depends on the minimum cost of the three alternatives, which further depends upon the failure cost associated with a particular component and is estimated as :

$$E[C_{OM}] = E[C_{ORi}] + E[C_{Ori}] \quad (5)$$

Let the expected life of the system be 'L' years and the cost structure of corrective, preventive and opportunistic maintenance remain the same throughout its life. Thus, LCC for the system expressed in terms of the present value of cost is;

$$PVc = \sum_{i=1}^{n} C_{aqi} + \sum_{j=1}^{L}\{\frac{1}{(1+d)^j}(E[C_{PA}] + E[C_{CA}] + E[C_{OM}])\} \quad (6)$$

The opportunistic actions that are incorporated in the schedule maintenance do enhance system operation. The maintenance actions are therefore required but need time and resources, and thereby, improve system availability. Therefore, it is required to develop an availability model based on the maintenance actions to meet the objective. The availability is defined as the ratio of actual operating time to the planned operating time. Mathematically,

$$A = \frac{\text{Actual Operating Time}}{\text{Planned Operating Time}} \quad (7)$$

Let the planned operating time in any investigation period be $'T'$ hours. In any investigation period, let, E(TDT) be the average time for which the system is not operating due to maintenance action.

Thus, actual operating time, T_{opr}, in any investigation period can be calculated as follows;

$$T_{opr} = T - E(TDT) \quad (8)$$

$$A = \frac{\text{Actual Operating Time}}{\text{Planned Operating Time}} = \frac{T_{opr}}{T} = \frac{T - E(TDT)}{T} \quad (9)$$

In the above equation, E(TDT) includes total time required for all maintenance actions.

In general, mechanical systems receive one or more of the following kinds of maintenance actions (Corrective actions, Preventive actions, and opportunistic maintenance) during their useful life.

It is assumed that the system is down only due to maintenance actions and the downtime due to other reasons is not considered. Then, Expected down time E[TDT] in any investigation period can thus be estimated as:

$$E[TDT] = \sum_{i=1}^{n}\{E[N_{CM_i}] \cdot MTTCM_i + E[N_{PM_i}] \cdot MTTPM_i + E[N_{OR_i}] \cdot MTTRA_i + E[N_{Or_i}] \cdot MTTPM_i\} \quad (10)$$

where, $E[N_{CM_i}]$, $E[N_{PM_i}]$, $E[N_{OR_i}]$ and $E[N_{Or_i}]$ are the expected number of corrective, preventive, opportunistic replacement and opportunistic repair respectively, during the investigation period, suffix $'i'$ indicates the ith subassembly in the mechanical system.
$MTTCM_i, MTTPM_i$ and $MTTRA_i$ are the average time for which the component is down in each for the corrective, preventive and opportunistic action respectively.

Thus the availability can now be expressed as,

$$A = \frac{T - \sum_{i=1}^{n} \left\{ E\left[N_{CM_i}\right] \cdot MTTCM_i + E\left[N_{PM_i}\right] \cdot MTTPM_i + E\left[N_{OR_i}\right] \cdot MTTRA_i + E\left[N_{Or_i}\right] \cdot MTTPM_i \right\}}{T} \quad (11)$$

The expected number of failures, $MTTPM_i$, $MTTCM_i$, $MTTRA_i$ depends on reliability, maintainability, maintenance schedule and opportunistic maintenance for a particular component of a system.

As stated earlier the maintenance actions affect both the cost and performance of the system, so it is required to obtain the optimum opportunistic action for each subassembly of a system, so as to ensure the required availability at minimum possible cost. Thus, a trade-off between the opportunistic alternatives is required to get the desired level of system availability at the lowest possible LCC. In other words, it can be further stated as "optimize opportunistic maintenance for each module-subassembly of a system, whose cost is included in the objective function and the availability of the system, may be considered as the constraint". Thus, the problem can be formulated as:

Minimize (LCC)
Subject to
$A \geq$ Desired level of system availability

The above formulated problem has been implemented on a real life problem, which is described in the subsequent section.

4. A Case Study

A case study is presented on the basis of work being carried out in collaboration with Burckhardt Compression, which is one of the leading compressors manufacturers in the world. The effect of opportunistic maintenance on a reciprocating compressor of Burckhardt make which is installed at an automotive Compressed Natural Gas (CNG) station in National Capital Region (NCR) is studied.

The compressor is expected to run 24 hrs. a day and the downtime cost is high. The customer expects a high level of availability, of the order of 98%, but at the minimum possible LCC. As for any other mechanical systems, such high level of availability can be achieved only through effective maintenance support. As a part of the purchase deal, the customer wanted Burckhardt to take the responsibility of its maintenance support. The required service level demands 98% availability of the compressor during a month. For maintaining such a level of service demand, the Burckhardt has required an efficient and effective maintenance support effort, which is cost incurring. With the experience gained over last 10 years, Burckhardt is inclined to provide maintenance support for the whole life. Both Burckhardt and its customers have aggressive plans of expanding their operations to new locations, thus the issue of maintenance support is of extreme importance in order to achieve their business goals.

Burckhardt provides maintenance support of corrective maintenance and scheduled maintenance for the compressor, and expends huge costs supporting it. The Burckhardt reciprocating compressor consists of 19 subassemblies, modeled as being in series, subjected to random failures over its useful life. The failure of any subassembly leads to the breakdown of the entire system i.e. compressor. Thus, the opportunistic maintenance, wherein preventive maintenance of a subassemblies is carried out during opportunities arising out of the failures of other subassemblies, are more appropriate for the subassemblies of the compressor.

It has been assumed that the reciprocating compressor operates continuously and fails randomly at any instant. It has also been assumed that repair activity and scheduled

preventive maintenance is initiated immediately upon shutdown. The sub-assemblies are replaced and repaired upon failure, and at the same time, the opportunities for preventive maintenance on other subassemblies are also undertaken. The effective operating time of the compressor is accumulated between the failures outages. The operating life of the compressor is 12 years which is equal to 72000 operating hours (as the system is on an average running 500 hrs. per month), between which the system is preventively maintained at a scheduled interval of 15000 hrs., after which, all the subassemblies of the system becomes as good as new.

The data is collected from the Burckhardt compression for a reciprocating compressor, which includes cost, preventive maintenance schedule, corrective, preventive and replacement time, and design characteristic (reliability parameter which follows the Weibull distribution) for each subassemblies, as given in Tables 1 and 2. Table 1 illustrates the different costs that are required in estimating the LCC. Table 2 provides the subassembly/Module corrective, preventive and replacement time, and their reliability characteristics. However the costs of subassemblies are not provided.

The operating cycle to which the opportunistic maintenance decisions will be incorporated is illustrated with the help of Figure 1. Let a system start degrading with the passage of time, after the operation of 't_O' hours an opportunity arises '$t_O < t_{pm}$' then there will still be 'dt' more time remaining for the scheduled maintenance. The random failure shown in the Figure1 is the consequence of maintenance decisions taken at an opportunity over the processing time in the period 'dt'. The maintenance actions at the opportunity are performed in such a way that total time for maintenance work should be less than maintenance time of a particular subassembly.

Table 1: Cost Data

Characteristics	Cost in Rupees (INR).
Fixed cost of maintenance (INR); C_{Fix}	2500
Labor cost for maintenance (INR /hr); L_c	1000
Revenue lost due to failure; R_{CA}	3330
Revenue lost due to schedule maintenance; R_{PA}	900

For a given subassembly, the failures occur according to the respective time to failure distribution. In such situations, a necessary opportunistic action on the other subassembly has been permitted. Preventive maintenances for these are due in near future. Total downtime affects the system availability; therefore the maintenance decisions taken at the opportunity decrease the probability of failure and thereby maintaining the system availability. Therefore, the optimization of opportunistic action is needed to maintain the operational objective of the system. The objective of the optimization is to generate a set of maintenance decisions that system ensured the required availability at minimum possible LCC.

Table 2: Reliability Characteristic and Different Time of Repair for Different Subassemblies

Module-Subassembly	β	η	$MTTPM_i$ (Hrs)	$MTTCM_i$ (Hrs)	$MTTRA_i$ (Hrs)
# 1	1	100000	8	9.6	2
# 2	1	100000	8	9.6	2
# 3	1	100000	8	9.6	2
# 4	1.1	100000	36	43.2	36
# 5	1.1	25000	5	6	1
# 6	1.1	100000	36	43.2	36
# 7	1.2	30000	12	14.4	4
# 8	1.2	20000	5	6	1
# 9	1.2	20000	5	6	1
# 10	1.2	20000	12	14.4	12
# 11	1.2	125000	3	3.6	0.5
# 12	1.2	125000	3	3.6	0.5
# 13	1.4	40000	5	6	1
# 14	1.4	40000	5	6	1
# 15	1.4	40000	5	6	1
# 16	1.4	40000	3	3.6	0.5
# 17	1.4	40000	3	3.6	0.5
# 18	1.5	100000	12	14.4	12
# 19	1.6	50000	12	14.4	12

Thus, the problem for the Burckhardt can be formulated as given below.

Minimize LCC ($PVc = \sum_{i=1}^{n} C_{aqi} + \sum_{j=1}^{L}\{\frac{1}{(1+d)^j}(E[C_{PA}] + E[C_{CA}] + E[C_{OM}])\}$)

Subject to

$$A \geq 0.98$$

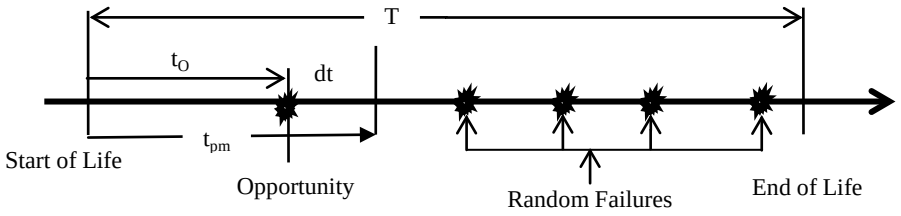

Figure 1: Mechanism of Opportunistic Maintenance

It is required to estimate the number of different maintenance actions; which are then incorporated into a model to assess the system LCC. The preventive maintenance is scheduled at an interval of 15000 operating hrs. which is of imperfect type, thus the system is 4 times preventively repaired during its operating life.

The expected number of failures (corrective maintenances) needs to be calculated in each year by considering age at the start of that year and restoration achieved after each maintenance action. The age at the start of the each year depends on the age at the end of

the previous year and the degree of restoration achieved by maintenance actions. Every time when a corrective, preventive and/or opportunistic repair is performed, the age is changed thereby affecting the number of failures. Lad and Kulkarni [19] developed the model to calculate the conditional number of failures as;

$$N(t|V) = -(V_n/\eta)^{\beta} + \left(\frac{t + V_n}{\eta}\right)^{\beta} \quad (12)$$

where, η is the characteristic parameter of a subassembly in a Weibull distribution.
β is scale parameter of a component/subassembly/system in a Weibull distribution.
V_n is the virtual age after incorporating the nth maintenance action.

The concept of virtual age was first introduced by Kijima [20]. Under this concept, a unit accumulates age during each period of operation. After each failure of component, the maintenance action, "removes" some of the accumulated ages. Consider a unit of equipment that at any point of time, is in either of the two states i.e. functioning or repair; assume that the unit is initially (at time t=0) functioning. Let X_n denote the duration of the period between the $(n-1)^{th}$ repair completion, and the nth repair; let V_n denote the virtual age of the unit at the time of the nth repair completion. Kijima's model of virtual age is given as;

$$V_n = V_{n-1} + (1-a)X_n, \quad \text{such that } 0 \le a \le 1, \text{ and } V_0 = 0 \quad (13)$$

where, *a* is some constant, known as restoration factor, which captures the degree of equipment restoration achieved through repair action. While using system improvement model shown in Equation 13, different degrees of restoration are used for inspection, corrective, preventive and overhauls. Thus, the length of an interval for which the equipment functions depend on the virtual age of the equipment at the beginning of the interval. It is to be noted that perfect repair (a=0), and minimal repair (a=1) are both special cases of this virtual age model. The virtual age is calculated on the basis of incorporated maintenance actions and their restorations, which is put in Equation No. 12 to estimate the expected number of failures.

A Monte Carlo simulation model for the reciprocating compressor has been developed using discrete-event framework in MATLAB 7.12.0 (R2010a). The model is simulated and optimized for the data obtained from Burckhardt. Optimization of the random search method is used, which is an intuitive method of searching for an optimal solution. It is based on generating a set of random decisions. This generated decision is evaluated for the feasibility of test and to meet the constraints required if it meets the requirements of the corresponding stored LCC and the next iteration is generated. If the LCC given by the latter iteration is more than that of previous one then the previous LCC is replaced by the new one. The optimized results are obtained after running 100000 iterations of the MATLAB code, out of these only those set of maintenance actions that meet the availability constraints are recorded. The best solution (minimum LCC) among them is selected and the corresponding sets of opportunistic maintenance decisions are proposed. The result gives the optimized opportunistic decision for each subassembly in between the scheduled maintenance, LCC and availability. Table 3 shows the obtained result of opportunistic maintenance action for each subassembly of the compressor.

Currently, Burckhardt compression provides the maintenance support to their equipment, for which the LCC is INR 29,400,000. However, after incorporating opportunistic maintenance, the LCC comes out to be of INR 16,858,250. Thus, there is a reduction of INR 12,541,750 in LCC after incorporating the opportunistic maintenance in their traditional approach. The result shows a considerable reduction in LCC while assuring the required availability when compared to traditional approach; when an

opportunistic action has been incorporated in the current practice. The reduced LCC is substantial, as it will not only improve the customer satisfaction but also help in beating the competition. Therefore, it can be concluded that, incorporation of opportunistic maintenance in the current maintenance schedule will be helpful in attaining an efficient support at the minimum possible cost. Hence, the obtained opportunistic maintenance for the reciprocating compressor of Burckhardt compression has been recommended for enhancing their maintenance support.

Table 3: Opportunistic Actions for Subassemblies of a Reciprocating Compressor

Subassembly	Optimized Opportunistic Action During			
	I PM	II PM	III PM	IV PM
# 1	N	N	N	N
# 2	N	N	N	N
# 3	N	N	N	N
# 4	N	N	N	N
# 5	r	r	r	r
# 6	N	N	N	N
# 7	r	r	r	r
# 8	r	r	r	r
# 9	r	r	r	r
# 10	r	r	r	r
# 11	N	N	N	N
# 12	N	N	N	N
# 13	r	r	r	r
# 14	r	r	r	r
# 15	r	r	r	r
# 16	r	r	r	r
# 17	r	r	r	r
# 18	N	N	N	N
# 19	N	r	N	r
N-Do Nothing; r-Repair and R-Replacement				

5. Conclusion

The proposed work is based upon application of an opportunistic policy for a reciprocating compressor under a given maintenance schedule. The model was implemented by applying the industrial data obtained from a reciprocating compressor manufacturer. For implementing the research, a case study was conducted at Burckhardt compression. After incorporating the opportunistic maintenance in the scheduled maintenance the LCC has come out to be of INR 16,858,250, as compared to traditional LCC of INR 29,400,000. Therefore, the opportunity maintenance optimization has the potential for substantially reducing the LCC of the system while assuring the required level of operational availability.

The study is limited to the application of opportunistic maintenance on mechanical systems in general, a reciprocating compressor in particular. However, findings of the research will be useful to OEMs, service providers, customers, academicians, scientists, researchers, maintenance professionals and other persons concerned or interested, to

understand the impact of opportunistic maintenance on LCC of a system under a desired operational objective. Some of the future aspects of research are listed below; which will be helpful for carrying out further research in the field of opportunistic maintenance.

- Practically, a lot of mechanical systems are multi-unit series systems. Each unit of which has its own reliability characteristics and subsequently may need different PM technique. Integrating multi PM techniques into this kind of system will provide a potential area of research.
- A future research may consider failure consequence, based on which the optimization of opportunistic action can be made.
- The estimation of spares, resources, *etc*., can be done after incorporating the opportunistic action and its optimization.

Acknowledgement: We are thankful to the M/S Burckhardt Compression Limited, Pune, Maharashtra (India), for agreeing to jointly work with us in this research study. We express our heartfelt appreciation of Mr. Sanjay Pathak, Mr. Vinod Sharma and Mr. R. K. Sachdeva, of Burckhardt Compression Limited, for sharing their experience with us.

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