A Cost-Effective RCM Policy for Periodically Inspected Equipment Items

Michael N. Zule, Ph.D., ALD Ltd., Israel
Zigmund M. Bluvband, Ph.D., ALD Ltd., Israel

1 Preventive Maintenance in the RCM Methodology

1.1 Preventive Maintenance Versus Corrective Maintenance

All maintenance tasks can be divided into two basic categories: Corrective and Preventive. Corrective maintenance (CM) is performed after an item has reached a specified failure state, while Preventive maintenance (PM) is to be applied before a failure can occur. It's well known that PM policy may successfully affect reliability and availability of an item whose failure rate increases (i.e., in the 3rd zone of the bathtub-shaped hazard curve).

Each company operating modern equipment needs to find some balance between expenditures for Preventive maintenance and total losses caused by failures. In general, PM is more effective than CM for complex equipment [1,2]. At least 13 major returns with which PM has rewarded its users are listed in Handbook [1]. The most important advantages of PM, in comparison with CM are as follows:

- reduction of forced outages owing to prevention of unexpected failures;
- decreasing of production losses as maintenance tasks can be scheduled only for planned down-time periods;
- avoidance of equipment breakdown.

Most PM activities can be categorized according to three main approaches:

1) Time-Directed policy specifies maintenance to be performed at predetermined operating time intervals. Service operations (including alignments, adjustments, lubrication, etc.); scheduled repair or replacement of limited-life items and periodic product overhauls comprise this policy.
2) Condition-Directed policy specifies all types of inspections / diagnostics along with following on-condition maintenance activities. It prescribes periodic or continuous assessment of an item actual state in order to determine the most fitting and cost-saving maintenance tasks along with optimal time when to perform them. Continuous condition monitoring, scheduled inspection, on-condition restore are elements of this policy.
3) Hidden Failure Finding is intended to discover hidden equipment failures and verify that hidden functions are still can be performed. As a rule, hidden functions are emergency or redundant ones, they need special consideration and are beyond the scope of our study.

1.2 How RCM Prevents "Over-Expense" While Using Preventive Maintenance Policy

Reliability-Centered Maintenance (RCM) is a methodology for thorough cost-effectiveness comparison of all PM tasks available [3,4]. Wide implementation of RCM in various sectors of industry has proved that it really facilitates development of the PM strategy and enables to prevent failures of critical equipment parts. For instance, in Japan RCM usage at nuclear and thermal power plants reduced about 30—45% of their forced outage rate due to maintenance optimization [5].

The main dilemma solved by RCM is clear: reducing the intervals between restorative actions prevents failures but increases maintenance cost, and vice versa — expanding the operating periods between preventive interventions reduces direct maintenance expenses but drastically enlarges losses caused by forced outage and equipment breakdown.

RCM considers all PM tasks, but encourages the application of Preventive Condition-Directed Maintenance (PCDM) policy. RCM logic results in Time-Directed scheduled replacement only if none PCDM task is feasible. PCDM policy can appear more beneficial than Time-directed one because of the double economic effect:

(a) Reducing unnecessary Time-directed PM tasks (by converting to Condition-directed PM and on-condition monitoring, repair at the timing of your choice);

(b) Preventing incipient failures and avoiding the forced outage.

The principal problem addressed below can be formulated as follows:

To develop a method of prediction of the most efficient time point (schedule) for item's repair or replacement according to its current actual operating state and elapsed operating time. Minimal total expected maintenance and downtime cost per unit time is a criteria for such optimization.

1.3 Inspection Information as a Basis for Optimal RCM

Obviously, the more diagnostic information on current item physical conditions (technical state) we manage to obtain the more precise estimation of the inspection and repair time can be achieved.

As indicated in [4], nondestructive diagnostic technology is highly developed nowadays. It involves a large number of various techniques and applications. Part of them applicable for gradual deterioration analysis are as follows: Fiber-optic inspection; Lubricant analysis; Dye penetrate measurement; Leak detection, etc.

Developed Failure Reporting and Maintenance Information software system was used to collect field data on critical parameter deterioration processes for different types of mechanical and electromechanical parts, including :

- diesel engine with "Maximal pressure in crankcase chamber" and "Oil consumption" characterizing ring, piston and cylinder wear-out;
- mechanical gear with "Thickness of pinion's teeth";

- electrical motor with "Gap in the bearings";
- tire with "Depth of tire's tread".

Field data set for each performance parameter degradation process consists of about 11—16 time-series realizations. Each parameter measurement is performed during periodical inspection with certain time interval.

2 Remaining Lifetime Prediction Methods

2.1 Class of Items Under Analysis and Main Stipulations

◊ A restorable item which can be a part of a long-time using equipment or a single-unit system is under our consideration.
◊ Major failures of an item are caused by gradual deterioration which determines steadily increasing failure rate.
◊ Item's gradual deterioration is due to depletion of some physical property or material which can be assessed directly or indirectly.
◊ Item's current operating state can be identified by a critical performance parameter (or vector) whose current value $A_c(t)$ can be measured during regular inspection at any operating time.
◊ The item's deterioration status, when a critical performance parameter exceeds the predefined control limit A_{lim} is interpreted as its critical failure.

2.2 Deterioration Process Model

Analysis of the collected realizations of critical performance parameters allows to specify mathematical model describing adequately item's deterioration process. A stochastic model of monotone change of a critical performance parameter which provides the best fit to actual degradation data is as follows:

$$A(t) = V_k t^{\alpha} + Z(t),$$

where α is a power index, which indicates inherent mechanism of physical degradation of each critical performance parameter and, hence, is its constant attribute defining the sharp of the parameter's trend;
V_k is a random index of parameter speed change, which is considered to be constant for any particular item over the observed operating interval;
$Z(t)$ is stationary normal random process, identifying actual data deviations from the trend of each realization.

Statistical analysis of field data allowed to identify the main properties of the process $Z(t)$. Its expectation function is obviously equal to zero. It has been approved that time dependence of its variance is stochastically insignificant. Hence, a process's standard deviation may be treated as constant σ_z for each particular parameter. An autocorrelation period also appears to be constant and can be estimated using the same field data. Thus, the autocorrelation of this process may be approximated with a triangular-shaped (i.e. linear) function $\rho_z(\theta)$.

2.3 Conditional Failure Probability Distribution

As demonstrated in [6], for wide classes of equipment items, the logic of RCM methodology drives to the problem of remaining lifetime prediction. In other words, it is necessary to assess how long an item can be kept in operating mode without repair (i.e., residual lifetime τ) in order to determine an optimal compromise between potential lifetime utilizing and forced by failure outage.

We should find a conditional failure probability that a realization $A\ (t)$ of a critical parameter exceeds its predefined limit A_{lim}, i.e. probability of event: $A\ (t) > A_{lim.}$ Considering the condition, that critical parameter value is equal to A_c (obtained by inspection) at the operating time t_c, we can define the conditional probability of a failure, which may occur before the instant $t_c+\tau$

$$P\ \{t_c+\tau<T\} = P\ \{A(t_c+\tau) > A_{lim}\ \ |Z(t_c) = A_c - V_k t_c^{\alpha}\} =$$

$$= P\ \{Z\ (t_c+\tau) > A_{lim} - V_k (t_c+\tau)^{\alpha}\ |\ Z\ (t_c) = A_c - V_k t_c^{\alpha}\}.$$

Now we can apply trivial transformation rules for conditional and truncated bivariate normal distribution to the two correlated and normally distributed random variables $Z(t_c)$, $Z(t_c+\tau)$, in order to derive the required conditional distribution of the residual lifetime:

$$F\ \{\tau\ |\ A_c\} = \varphi\ \{[M\ (\tau) + \rho_Z\ (\tau)\ D_c - 1] / \sigma\ (\tau)\} / \varphi\ \{[M\ (\tau) - \rho_Z\ (\tau)\ D_c] / \sigma\ (\tau)\}$$

where: $\varphi\ (y) = \frac{1}{\sqrt{2\pi}} \int_0^y e^{-\frac{u^2}{2}} du;\qquad M\ (\tau) = V_k\ (t_c+\tau)^{\alpha}$

$$D_c = A_c - V_k t_c^{\alpha};\quad \sigma\ (\tau) = \sigma_Z \sqrt{1-\rho_Z^2(\tau)}\ .$$

Graphs of this distribution and its density function for a few sets of source data are presented in [7]. The obtained conditional failure distribution has been thoroughly checked against actual inspection data and acceptable prediction accuracy has been approved: mean relative error of prediction has not exceeded 14%.

Since the conditional distribution has been found, we can easy calculate a mean remaining lifetime, its variance and other characteristics of the residual life.

4 PCDM Policy Based on Remaining Lifetime Prediction

Two relatively simple models optimizing a balance between the total expenditure for PM (including manpower, equipment, other facilities and necessary Corrective maintenance due to unprevented breakdowns) and total losses caused by failures will be described below.

4.1 Optimal decision in case of predetermined inspection interval

Assume, the Maintenance Plan has been already developed for the entire system with the certain inspection interval T_{ins} and the item under consideration can be preventively repaired only during inspection downtime.

In this case, we may compare efficiency of immediate preventive repair (i.e. cost per unit operating time for immediate preventive repair C_P/t_c.) with operating until next inspection. The last option is estimated as total expected cost per unit operating time by the end of the inspection interval:

$$E(T_{ins}) = \frac{C_P + (C_F - C_P)\,F\{T_{ins} \mid A_c\}}{t_c + T_{ins} - \int_0^{T_{ins}} x\,dF\{x \mid A_c\}}$$

where C_P and C_F denote the cost of preventive and failure repair, respectively; $F\{x \mid a_c\} = F\{x \mid A(t_c) = A_c\}$ is a conditional probability of a failure given a critical parameter value is equal to A_c at the operating time t_c.

The optimal decision here is clear:

- If $C_P/t_c < E(T_{ins})$, then immediate preventive repair is justified.
- Otherwise, this item is recommended to operate until the next inspection.

4.2 Trade-off between potential lifetime utilizing and total failure expenses (optimal period till the next inspection)

If an item's inspection and repair can be performed at any scheduled time, then we may estimate optimal residual lifetime of this item τ_{opt}. Total expected cost per unit operating time should be calculated as a function of remaining lifetime using the above expression for $E(\tau)$. The required optimal residual lifetime τ_{opt} is such argument value, which minimizes this functional. Taking into account methodical and diagnostic inaccuracy, source data ambiguity and other possible deviations, it's better to yield interval estimations of optimal residual lifetime.

The cost-effective PCDM policy may be formulated as follows:

- If $\tau_{opt} \geq T_{ins}$, then this item is allowed to operate until the end of the standard inspection interval, when this procedure should be repeated.
- If $0.1T_{ins} \leq \tau_{opt} < T_{ins}$, then the item is allowed to operate by the end of the calculated inspection interval τ_{opt}. At that time it should be inspected and this prediction procedure should be performed again.
- If $\tau_{opt} < 0.1T_{ins}$, (i.e. the optimal residual lifetime becomes too small to be worth utilizing) the item is recommended to be preventively restored immediately. Selected coefficient 0.1 may be, obviously, replaced by other reasonable portion.

To investigate and verify developed PCDM policy, an advanced Monte Carlo model was created. It permits to simulate various stochastic degradation processes along with majority existing classes of maintenance strategies. Results of simulations approve significant benefits of the created PCDM policies in comparison with other existing maintenance strategies. For instance, estimated total repair and downtime cost per unit time for the above described PCDM policy is 11—12% less than for the Corrective Maintenance due to considerable reducing of forced outage and about 9% less than relevant results of Time-Directed PM strategy due to decreasing of unnecessary preventive repairs. Experience accumulated shows that the developed RCM application is most cost effective if losses of failure consequences are much more than preventive remedial actions expenses.

Summary

The developed RCM application includes the continuous planning of Preventive Condition-Directed Maintenance (PCDM) tasks and making decision when each task is to be undertaken. The new PCDM policy requires the periodical prediction of an item's remaining life-time which is based on the current technical state of an item and its elapsed operating time. Such data can be obtained by means of non-destructive inspection and diagnostics.

The developed conditional probability distribution is used to:

- predict Expected remaining lifetime and its other statistical characteristics
- estimate Optimal Time Interval to next inspection
- ascertain efficiency of immediate preventive repair versus operation until next scheduled inspection

It has been approved that the new policy actually provides the most efficient time schedule evaluation for an item's overhaul or replacement according to its current actual operating state and elapsed operating time.

An advanced software package has been developed in order to collect and accumulate the results of periodical inspections and report failures occurred as well as to calculate Expected Residual Life-time, Optimal Time Interval to the next inspection, Total Expected Maintenance and Downtime Cost, and other important characteristics using the conditional failure probability function. Its thorough verification versus actual inspection results has shown acceptable level of prediction accuracy and consistency.

References

1. Maintenance Engineering Handbook. Third Edition. Lindley R. Higgins, Editor-in-Chief, L. C. Morrow, Editor. McGraw-Hill, 1977.
2. Handbook of Reliability Engineering and Management. W. Grant Ireson, Clyde F. Coombs, Jr., Editors-in-Chief. McGraw-Hill, 1988.
3. Smith, Anthony M. Preventive-Maintenance Impact on Plant Availability. In:: Proceedings of Annual Reliability and Maintainability Symposium, IEEE, 1992, pp. 177-180.
4. Smith, Anthony M. Reliability-Centered Maintenance. McGraw-Hill, USA, 1993.
5. Onodera Katsushige, Katoo Yoomei. A Successful Preventive Maintenance Program for an Electric Power Plant. In: Proceedings of Annual Reliability and Maintainability Symposium, IEEE, 1993, pp. 146-153.
6. Zule, M., Bluvband, Z. RCM policy: new method of residual lifetime prediction according to item's actual operating state. In: Proceedings of IASTED International Conference "Reliability, Quality Control and Risk Assessment", Washington, 1992.
7. Zule, M., Bluvband, Z. The computerized approach to optimal maintenance policy for aging systems. In: Proceedings of the 9th International Conference of the ISQA, Israel, 1992.