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OPPORTUNISTIC MAINTENANCE OF MULTI-EQUIPMENT SYSTEM: A CASE STUDY

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SUMMARY

A case study on preventive maintenance (PM) of a multi-equipment system is presented in this paper. Each equipment of the system consists of many components/subsystems connected in series. Because of the series structure, opportunistic maintenance (OM) policies are more effective for the components of the equipment. A new OM policy based on the classification of opportunities has been proposed. Various OM policies have been evaluated using simulation modeling, and the new policy has been found to be more effective than the existing OM policies. The impact of this policy on the overall system has also been simulated. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: multi-equipment systems; series structure; opportunistic maintenance; simulation modeling

1. INTRODUCTION

This case study was conducted on a 210 MW thermal power unit, which uses pulverized coal as fuel. The boiler is served by six independent and identical pulverizers, each of which consists of a coal feeder, coal mill, primary air fan, coal carrying pipes and associated fuel burners. Only five pulverizers are required for full capacity operation, and one serves as a stand-by. When more than one pulverizer is down, the unit performs at a reduced capacity as follows: when only four pulverizers are available, the unit can generate 180 MW, and similarly when three, two and one pulverizers are available, the unit can generate 135 MW, 90 MW and 45 MW, respectively. Initial analysis of data revealed that the pulverizers alone accounted for around 15% of the total generation loss of the power unit. The consequences of the loss of generation are severe, and accordingly, minimization of generation loss by adopting suitable preventive maintenance (PM) policies for the components/subsystems of the pulverizers was considered as the objective of the study.

In industrial plants, equipment which has many components/subsystems connected in series, like the pulverizer, is common. Thereafter, the kind of impact that the equipment outage has on the overall system depends on the specific situation. Accordingly, to make the work more general in nature, the modeling exercise has been carried out in two stages. Firstly, a model has been developed only for a single pulverizer, and alternative PM policies have been evaluated using this model. Later, a model was developed for the entire fuel system considering the system constraints, and the performance of the best PM policy, found for a single pulverizer, has been studied using this model.

This paper has been organized along the following lines. In Section 2, analysis of the pulverizer data has been carried out leading to the formulation of a model for the pulverizer. A brief review of opportunistic maintenance (OM) policies, which have been found more suitable, has been presented in Section 3, and a new OM policy based on classification of opportunities has been suggested. In Section 4, the appropriate OM policies have been evaluated considering a single pulverizer. The performance of the best OM policy on the entire system has been presented in Section 5. Conclusions have been presented in Section 6 followed by references.

2. DATA ANALYSIS

Pulverizers considered in this study work under severe operating conditions, and also due to the abrasive nature of coal, the chance of pulverizer failure is very

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Table 1. Break-up of pulverizer downtime

Subsystem		Downtime (h)†	Per cent
Bunker		71.46 (26)	0.44
Seal air fan		11.08 (2)	0.07
Feeder	Feeder chain breakage	2111.17 (6)	12.98
	Feeder box	1706.64 (72)	10.49
	Feeder drive	601.38 (54)	3.70
Mill	Mill overhaul	4503.25 (5)	27.68
	Ring breakage	847.58 (2)	5.21
	Mill internal	1183.36 (70)	7.28
	Rejection system	607.52 (82)	3.74
	Loading unit	565.17 (125)	3.47
	Mill drive	3114.57 (5)	19.15
	Mill gearbox lubricating oil system	91.57 (13)	0.56
PA fan	Main unit	28.42 (4)	0.17
	Bearing lubricating oil system	99.16 (15)	0.61
Coal carrying pipes (CCP)		496.17 (132)	3.05
Burners		70.02 (39)	0.43
Others		157.27 (80)	0.97
Total		16266.44 (732)	100.00

† Figures within brackets indicate number of outages.

high. The pulverizer can be considered as a number of components/subsystems connected in series, since the failure of any component results in the stoppage of the entire pulverizer. This implies that opportunistic maintenance policies, wherein preventive maintenance of a component is carried out during the opportunities arising out of the failures of other components, are more appropriate for the components of the pulverizer.

Data were collected for a period of approximately 22 months in between two successive unit overhauls. During this period, all the six pulverizers experienced, in total, 732 outages with total downtime amounting to 16 266.44 h, resulting in a generation loss of 3.73%. Further break-up of pulverizer downtime is given in Table 1. Out of the 732 outages, a few, 18 in number, namely mill overhauls, mill gearbox failures, grinding ring breakages and feeder chain breakages, accounted for around 65% of the total downtime. These major outages resulted in the operation of the pulverizer system without a stand-by for most of the time. The effect of these major outages can be made clearer by dividing the total generation loss of 3.73% into two parts, namely loss during the period when one of the pulverizers was under major shutdown and loss during the other period. In this particular case, these losses were 4.90% and 1.43%, respectively. From this, it is seen that during the period when one of the pulverizers was under a major shutdown, the frequent failures of subsystems had resulted in a loss of 4.90%, whereas during the other period, the frequent failures of subsystems had little effect. Thus, the situation can be greatly improved by eliminating the major outages.

Mill overhaul is a scheduled PM activity, and the possibility of scheduling mill overhauls during unit overhaul was contemplated. However, due to limitation of space and supporting equipment, only one pulverizer could be overhauled at any time. Further, due to the enormous material cost of mill overhaul, it is uneconomical to sacrifice too much of a service life (at the time of unit overhaul, the remaining service life of main grinding elements, which determines the mill overhaul, might not be over). Thus, some of the pulverizer overhauls need to be scheduled outside the unit overhaul. The mill drive, which consists of a gearbox, motor and coupling, is a comparatively more reliable system. However, if a failure occurs, in most instances, it is catastrophic. Further, it was observed that the severity of the workplace and its accessibility (the drive is right under the mill) make it difficult to use on-line condition monitoring devices to detect impending failures. Accordingly, an off-line inspection followed by necessary repair actions is the effective way. Grinding ring breakages and feeder chain breakages were found to be the result of induced failures due to the failures of the components of the mill internal and the feeder box, respectively. Therefore, these failures can be reduced only by reducing the failures of the components of the mill internal and the feeder box. Accordingly, these failures can be modeled as part of the failures of the mill internal and the feeder box. Thus, at best, one can only hope to reduce the occurrence of the major outages, and the system may still suffer some major outages. In order to improve the situation all the effort should be directed to reduce the frequent failures of various subsystems.

It was found that failures of bunker, seal air fan, mill gearbox lubricating oil system, PA fan, burners, and others (mainly consisting of electrical and instrument maintenance, and failures due to external reasons like wet coal, etc.) caused only a small percentage of downtime. Hence, no separate preventive maintenance activity has been considered for the above subsystems under the presumption that running maintenance, which is being carried out regularly, is sufficient for these subsystems. However, in the opportunistic maintenance model, they are included as a single component, or failure mode, under the name 'others'. This is necessary because failures of this component will also create opportunities for preventive maintenance of other subsystems.

Thus, for the purpose of preventive maintenance planning, the pulverizer can be considered as a series system of eight subsystems, namely: (i) feeder box, (ii) feeder drive, (iii) mill internal, (iv) rejection system, (v) mill drive, (vi) loading unit, (vii) coal carrying pipes, and (viii) 'others'. Next, the failure processes of these subsystems need to be identified. Failures of mill drive tend to be catastrophic, and during these failures the mill drive is either replaced or thoroughly maintained. Accordingly, after each failure, the mill drive unit can be assumed to be in as good as new condition, and the failure process of the mill drive can be considered as a renewal process. Accordingly, failure times or time between failures of the mill drive unit can be considered as independent and identically distributed, and thus the failure time distribution can be arrived at. However, for other subsystems, renewal cannot be taken for granted at each failure, since these subsystems are not replaced at each failure. Accordingly, for these subsystems further analysis of failure times data has been carried out using trend plots and reverse arrangement test [1,2].

The tests have confirmed lack of trend in the failure times data, and so the assumption of renewal process is justified. This is not surprising, particularly for the subsystems feeder box, feeder drive, mill internal and rejection system. These subsystems have relatively few failure modes, and all parts of a subsystem are inspected and necessary adjustments made at every failure. Maintaining all components of a subsystem as a whole is common practice in many industrial plants. Further analysis of failure time data showed that the failure time distributions of the above subsystems have an increasing failure rate property, thus justifying preventive maintenance for these subsystems. In the case of the loading unit, coal carrying pipes and 'others' subsystems, at each failure the component that fails is only replaced or repaired. That is, for these subsystems repair at failure is minimal. The possible reason for the data showing a renewal phenomenon, despite the repair being minimal, is that the failure time distributions of these subsystems could be exponential. Applicability of Drenick's law [3] seems to be the reason for this. As per Drenick's law, the failure time process of a series system will tend to be exponential. How fast it tends to be exponential will depend on time homogeneity and the number of components. In the present case, both these conditions are satisfied. Further analysis of failure time data confirmed the fitness of exponential failure time distribution for these subsystems.

Since failure time distributions of the coal carrying pipes and loading unit subsystems follow the exponential distribution, preventive maintenance is not justified. A word of caution is required here because individual components may as well exhibit increasing failure rate property, thus justifying preventive replacement of components. However, trying to adopt preventive maintenance at the component level is difficult, because it entails the tedious task of keeping the history of individual components. Under these circumstances, the appropriate preventive maintenance policy is one of block replacement type, according to which all the components are replaced/repaired at fixed intervals, irrespective of the failure history of the individual components. The existing practice is one of block type, wherein all the components are attended to during the mill overhaul. Though the number of failures as a whole seems to be high for these subsystems, considering the number of components which are prone to failure, the number of failures per component is low. Accordingly, no separate preventive maintenance activity is assumed for these subsystems apart from the work done during mill overhauls.

The lack of trend in the failure times of the subsystems having been established, the failure processes of the subsystems can be modeled as renewal processes, and accordingly, distributions for the failure times and repair times can be determined. The Weibull distribution has been tried out for failure times and repair times of the subsystems. The Weibull distribution is a versatile distribution, which shows different failure rate properties depending on the value of the shape parameter, β. When $\beta < 1$, the Weibull

Table 2. Parameters of failure time, repair time and PM time distributions

Subsystem	Failure time	Repair time	PM time
Feeder box	Weibull $\beta = 1.694$ $\eta = 1007.69$	Weibull $\beta = 1.023$ with 0.9231 $\eta = 19.17$ probability $\gamma = 5.00$ Uniform between 300.00 and 400.00 with 0.0769 probability	Uniform between 4.00 and 12.00
Feeder drive	Weibull $\beta = 1.996$ $\eta = 1437.70$	Weibull $\beta = 1.278$ $\eta = 9.09$ $\gamma = 3.00$	Uniform between 2.00 and 6.00
Mill internal	Weibull $\beta = 1.675$ $\eta = 1089.14$	Weibull $\beta = 1.107$ with 0.9722 $\eta = 11.59$ probability $\gamma = 6.00$ Uniform between 400.00 and 450.00 with 0.0278 probability	Uniform between 4.00 and 8.00
Rejection system	Weibull $\beta = 2.013$ $\eta = 932.74$	Weibull $\beta = 1.258$ $\eta = 5.88$ $\gamma = 2.00$	Uniform between 2.00 and 4.00
Mill drive	Weibull $\beta = 1.362$ $\eta = 6382.97$ $\gamma = 2200.00$	Weibull $\beta = 0.846$ $\eta = 344.68$ $\gamma = 305.00$	Uniform between 24.00 and 36.00
Loading unit	Weibull $\beta = 1.066$ $\eta = 595.59$	Weibull $\beta = 1.323$ $\eta = 4.13$ $\gamma = 0.75$	Not applicable
Coal carrying pipes	Weibull $\beta = 1.085$ $\eta = 549.34$	Weibull $\beta = 1.648$ $\eta = 3.59$ $\gamma = 0.50$	Not applicable
Others	Weibull $\beta = 0.938$ $\eta = 380.75$	Weibull $\beta = 1.277$ $\eta = 3.25$	Not applicable

β = shape parameter; η = scale parameter; γ = threshold parameter.

distribution shows a decreasing failure rate (DFR) property. When $\beta = 1$, the Weibull distribution shows a constant failure rate (CFR) property and becomes equivalent to the exponential distribution. When $\beta > 1$, the Weibull distribution shows an increasing failure rate (IFR) property. The parameter values of the Weibull distributions, obtained for the subsystems, are given in Table 2.

Failure time distributions of the coal carrying pipes, loading unit and 'others' subsystems have β values very close to one, implying that they are exponential. This supports the earlier discussion. For the other subsystems, β was seen to be much greater than 1, thus justifying preventive maintenance for these subsystems. The preventive maintenance packages are assumed to consists of thorough inspection followed by necessary repair or replacement activity, as required by the inspection. The times to perform preventive maintenance (PM) have been assumed as variables, instead of constant values, because the amount of work varies at each instant depending on the condition of the components. PM times data are not available for the present situation. Accordingly, after consultation with the engineers, and with due consideration to the amount of work involved for each subsystem, PM time distributions have been assumed to be uniform.

As can be seen from Table 2, two repair time distributions were fitted for each of the feeder box and mill internal subsystems. This is according to the discussion in the previous paragraphs, wherein it has been shown that feeder chain breakages and ring breakages are the result of minor failures of the feeder box and the mill internal, respectively. These failures are modeled as major breakdowns of the feeder box and the mill internal as follows: failures of feeder box and mill internal in some instances turn out to be major breakdowns, and at that instant, repair time is taken from a different distribution. The probabilities with which failures of feeder box and mill internal turn out to be major breakdowns are estimated from the data through the following formula:

$$\text{Probability} = \frac{\text{Number of major breakdowns of the subsystem}}{\text{Total number of failures of the subsystem}}$$

Thus the pulverizer can be treated as a series system of eight subsystems, and the failure processes of the subsystems can be modeled as renewal processes. The failure and repair time distributions of the subsystems have been obtained from the analysis of the data. Also, due to the series structure, opportunistic maintenance policies are more appropriate for these subsystems. In the next section, a brief review of literature on opportunistic maintenance models is presented.

3. BRIEF REVIEW OF LITERATURE ON OPPORTUNISTIC MAINTENANCE MODELS

The concept of opportunistic maintenance (OM) stems from the fact that there is the possibility of dependence among various components in a multi-component system. For example, the cost of simultaneous maintenance actions on various components would be less than the total cost of individual maintenance actions. This is particularly true in the case of a series system, where the failure of any one component results in stoppage of the whole system, thereby providing an opportunity to carry out preventive maintenance (PM) on other components along with failure maintenance (FM) of the failed component at little additional cost. Under these conditions, maintenance decisions for one component depend on the states (ages) of the other components in the system. However, due to the very complex structure of the optimal policy, research in this area has been confined, for the most part, to two-dimensional control limit policies such as (n, N) policies, where n represents OM age and N stands for the PM age in the absence of an opportunity.

Radner and Jorgenson [4] proposed an (n_i, N) policy for a series system consisting of one IFR component and M CFR components. n_i represents the OM age of the IFR component when the ith CFR component fails, and N represents the PM age of the IFR component when there are no failures till then. An (n, N) type policy with fixed values of n and N is optimal when there is only one IFR component. When the number of IFR components is more, the optimal policy has a complicated structure wherein both OM and PM ages for an IFR component are not fixed but are variables depending on the ages of the other IFR components. This has been established by the authors who have modeled the problem using the dynamic programming (DP) approach [5–7]. When the number of components increases, the complexity of the DP model increases, and the structure of the optimal policy also becomes more complex. However, a very important result obtained from the studies which have used the DP approach is that the (n, N) type policy, which is much easier to perceive and implement, is near optimal. This might be the reason for the fact that most of the research work on opportunistic maintenance is concentrated around (n, N) type policies.

Motivated by the complexity of the problem, several researchers have proposed various models. The solution methodology adopted in various models can be broadly classified under two approaches, namely analytical and simulation. In the analytical approach, using mostly renewal theory arguments, the objective function is expressed in an analytical form in terms of the policy parameters. Thereafter, the best values of the policy parameters are obtained by solving the objective function with different values of the policy parameters. This approach becomes highly complex when the number of IFR components increases. This approach has been used for two- or three-component systems and mostly identical components.

In the simulation approach, the system behavior is simulated a number of times with the superimposition of the policy, and the average value of the objective function is obtained. This process is repeated with different values of the policy parameters and the best values are obtained. Using the simulation approach, systems with many components can be modeled with relative ease. Interestingly, in all the case studies of real-life situations, the simulation approach has been adopted [8–10]. The system considered in this study is also complex, with a large number of components. This has prompted the use of the simulation approach for the evaluation of maintenance policies.

A natural extension of the (n_i, N) policy to a system consisting of L IFR components out of a total of M components, is (n_{ij}, N_i), $i \neq j$, policy where $i = 1, \ldots, L$ and $j = 1, \ldots, M$. n_{ij} represents the OM age for component i when the system is taken down for maintenance on component j, and N_i represents the age at which PM is performed on component i when there is no earlier opportunity. This is so because the additional cost of replacing component i at an opportunity depends on the component due to which the system is taken down. However, apart from the model proposed by Sculli and Suraweera [8], all the other models consider single OM age for each of the IFR components irrespective of which other component is taken down, that is, (n_i, N_i) policy. This is due to the fact that these models assume that the additional cost of replacing component i is the same irrespective of which other component has failed. This is further due to the fact that these models assume that the extra cost involved for OM is equal to the spares cost of the components that are to be opportunistically maintained and the downtime costs are insignificant.

For a continuously operating system, in particular for the system considered in this study, downtime costs are more predominant. Further, neither the FM or PM downtimes are constants, but vary over a wide range depending on the amount of work done at each outage. Moreover, the extra downtime incurred due to OM is also not constant. At each instant, the resultant downtime during FM and OM is the maximum of FM downtime of failed component and PM downtimes of OM activities. This is so because FM and OM activities are performed by different crews simultaneously. Thus, in the simulation model, instead of assuming any fixed values for FM and PM downtimes, at each instant, they are generated from the corresponding distributions. This kind of approach was also adopted by Bala Krishnan [10]. Both PM and failure maintenance (FM) activities are performed by permanent employees of the organization. Thus, manpower cost is fixed and need not be considered while evaluating alternate maintenance policies. This is the practice in many systems, and a realistic treatment may instead consider the available manpower as a constraint, so that there is a limit on the number of activities that can be carried out simultaneously. This is so because the subsystems are situated at different places and carrying out OM by the crew performing FM will generally increase the downtime. Maintenance actions, both FM and PM, are mostly adjustments and repairs, and components are replaced only if required. Also spares cost, except in the case of major outages, is insignificant as compared to enormously high downtime costs. Accordingly, in this study, manpower and spares costs have been neglected, and instead of minimization of cost, minimization of pulverizer downtime has been considered as the objective.

(n_{ij}, N_i) policy, which seems to be exhaustive, still neglects one more option, i.e. whether the system is taken down for FM or PM of component j. This gives rise to a more encompassing (n_{ijk}, N_i), $i \neq j$ policy, where $i = 1, \ldots, L$; $j = 1, \ldots, M$; and $k = 0$ or 1. $k = 0$ represents that the system is taken down for FM of component j, whereas $k = 1$ represents that the system is taken down for PM of component j. All this complexity arises due to the fact that the extra time required to replace component i at an opportunity depends on which component (j) causes the system to be taken down, and also on whether the system is taken down for FM or PM on component j. There could be a simpler and better policy if the viewpoint is slightly changed. It can be assumed that at the time of a failure or PM outage of a component, after initial inspection, the expected downtime can be reasonably estimated to fall within two narrowly specified limits. This is not an unrealistic assumption, since an experienced worker can give these estimates. Once these estimates are obtained, the opportunity can be classified according to the expected downtime. Now, the OM ages for each component can be specified corresponding to each opportunity class, irrespective of the component taken down and also regardless of whether it is taken down for FM or PM. Thus the policy becomes an (n_{ij}, N_i) policy, with j representing the opportunity class. In the next section, using a simulation approach, the above-mentioned OM policies, namely the (n_i, N_i) policy, (n_{ij}, N_i) policy based on component failed and (n_{ij}, N_i) policy based on classification of opportunities, have been evaluated, assuming unlimited manpower availability.

4. EVALUATION OF OM POLICIES

A simulation model for the pulverizer has been developed using a discrete-event framework, and the work has been done in FORTRAN on a PC. It has been assumed that the pulverizer operates continuously, whenever it is available. It has also been assumed that repair activity is initiated as soon as a failure occurs. Under these conditions, the process essentially consists of two events; failure and repair completion, occurring continuously in that order. The operating time of the pulverizer accumulates in between the failures. Since the life of the mill rings is approximately 15 000 h, and after which the entire pulverizer is overhauled, the simulation process is continued for 15 000 h of operating time, and the results are obtained for that run. After this, all the components of the pulverizer are considered as new, and the process is repeated for another 15 000 h of operating time. This process is repeated for a number of times, and the mean values of the results of all the runs are obtained.

For each run, the process starts with the pulverizer being in new condition. That is, the ages of all the subsystems are kept as zero initially. Failure times for all the subsystems are generated from the corresponding distributions. The failure time of the pulverizer is equal to the minimum of failure times of the subsystems, since failure of any one subsystem results in the failure of the pulverizer. The operating time of the pulverizer is incremented by the failure time of the pulverizer. The ages of the subsystems, and the number of failures of the subsystems and the pulverizer, are updated. Repair time for the failed subsystem is generated from the corresponding distribution, and the cumulative downtimes of the pulverizer and the subsystem are updated. Since the failure processes of the subsystems follow renewal processes, after every failure the subsystems are as good as new. Accordingly, the next failure time of the failed subsystem is generated from the corresponding distribution, and the failure times of the other subsystems are updated. The next failure time of the pulverizer is arrived at, and the operating time of the pulverizer is incremented accordingly. The process is repeated continuously till the operating time of the pulverizer reaches 15 000 h. Then the results are stored for the run, and the process is repeated for several runs. Finally, the mean values of the results of all the runs are obtained. The process has been simulated for 1000 runs, and it has been found, based on the standard deviation of the results, that 1000 runs are more than sufficient for 95% confidence level and ±5% accuracy.

Initially the process has been simulated with only failure maintenance of all subsystems, and the results from simulation were found to be in close conformity with actual data. The expected downtime of the pulverizer has been around 19% of the operating time. The failure time distribution of the mill drive turned out to be a Weibull distribution, as discussed in the previous section, with a threshold parameter or guaranteed life of 2200 h. Based on this, a rather simple preventive maintenance (PM) strategy can be adopted for the mill drive. After every 2200 h of operation, PM is carried out on the mill drive, which consists of a thorough inspection and necessary adjustments/repairs. However, if the condition of the mill drive is bad, the unit is replaced with a spare, and the removed unit is overhauled at the maintenance base. With this policy, failures of the mill drive can be completely eliminated, and the downtime is also reduced because major overhauling of the mill drive is done at the base. However, a sufficient amount of spares should be kept available. Since the probability of mill drives of more than one pulverizer requiring replacement at the same time is very low, one spare unit might be sufficient for the present case. One may question the reasonability of the above strategy, since the PM age is specified overcautiously. However, failures of the mill drive are often catastrophic in nature, and the repair cost is enormous. Accordingly, if both downtime cost and repair cost are taken into consideration, the PM age might be on the lower side, and taking threshold value as PM age will not seriously distort the result. Under the suggested strategy, the mill drive can be viewed as a life-limited component. When its age reaches the life-limit, PM is performed, and the chance of a failure before the life-limit is zero. This simple policy resulted in significant reduction in downtime from 19.21% to 13.45%.

For the other four subsystems, namely feeder box, feeder drive, mill internal and rejection system, which showed IFR property, OM policies can be suggested now. For the mill drive also, OM policy can be suggested. However, this option has not been considered for two reasons. Firstly, the PM age of the mill drive has been specified already on the lower side. Further, most of the opportunities will be of shorter duration compared to the PM time of the mill drive and savings would be nominal. Accordingly, an OM option for the mill drive has not been considered. Instead, PM outages of mill drive are considered as opportunities to perform PM on other subsystems.

In the previous section, after reviewing the literature, it was found that an (n_i, N_i) policy with a single OM age for each IFR subsystem and (n_{ij}, N_i) policy with multiple OM ages for each IFR subsystem, depending on the subsystem j due to which the system is taken down, are the two policies that were tested for systems similar in nature to the pulverizer. A new (n_{ij}, N_i) policy based on the classification of opportunities has also been proposed. The (n_i, N_i) policy is obviously an inferior policy when compared to the other above-mentioned policies. However, this policy has also been evaluated, for the purpose of comparison. It was found that the PM age, N, is infinity. This implies that carrying out PM when there is no opportunity has no benefit. This is not surprising, because enough PM will be done during

Table 3. Results of maintenance policies

Policy	Set 1 Downtime (%)	Set 1 % reduction in downtime over previous policy	Set 2 Downtime (%)	Set 2 % reduction in downtime over previous policy
FM policy	19.21	—	19.21	—
FM policy (PM only on mill drive)	13.45	29.98	13.45	29.98
(n_i, ∞) policy	8.49	36.88	10.53	21.71
(n_{ij}, ∞) policy of type I‡	8.26	2.71	9.62	8.64
(n_{ij}, ∞) policy of type II‡	7.80	8.13	9.04	14.15

‡ For (n_{ij}, ∞) policies, the percentage reductions in the downtime are calculated based on $(n_i, \propto)$ policy.

the opportunities, and accordingly, taking the system down exclusively for PM incurs more downtime. In general, when the number of subsystems is high, as is the case for the present system, there will be more opportunities, and taking the system down exclusively for PM might be detrimental. Accordingly, the PM option when there is no opportunity has not been considered, and only (n, ∞) type policies are considered. The final results of all the policies are given in Table 3.

4.1. (n_i, ∞) policy

Under the (n_i, ∞) policy, for each of the IFR subsystems, an OM age (n_i) is specified. Whenever there is a failure of a subsystem, PM is also performed on the IFR subsystems, whose ages are greater than their OM ages at that instant. n_i for a subsystem can be specified as k_i times the mean life of the subsystem (μ_i). The best values of the k_i can be found by superimposing the policy on the original model, and repeating the simulation with different values of k_i. The search for k_is has been conducted as follows: k_i has been varied in steps of 0.10, while keeping the other k_is as 1.00. Once the best value of the k_1 has obtained, it is fixed at that value, and k_2 has been varied. This process has been repeated for k_3 and k_4. Once the cycle (varying k_1, k_2, k_3 and k_4 one at a time) is completed, the process has been repeated for a few more cycles till the point at which there is no further improvement in the objective function value. The (n_i, ∞) policy resulted in significant reduction in the downtime, and the percentage reduction is around 37 per cent over PM on mill drive policy.

4.2. (n_{ij}, ∞) policy

Under the (n_{ij}, ∞) policy, for each IFR subsystem i, different OM ages $(n_{ij}, i \neq j)$, corresponding to the failed subsystem j, have to be specified. That is, for the pulverizer, seven OM ages have to be specified for each IFR subsystem. In total, 28 OM ages have to be specified for all the four IFR subsystems. Searching for these 28 OM ages is a tedious job, unless one has some initial values to start with. For this policy, mean lifetimes cannot be taken as initial values as has been done in the case of the (n_i, ∞) policy. Woodman [11] suggested a 'rule-of-thumb' to calculate OM age in the case of a single-component system, wherein opportunities are created by external reasons, with the interval between two opportunities being T. The OM age is calculated in such a way that the expected cost, in the interval T, of deferring replacement of a component of age x at an opportunity is equal to the expected cost, in the interval T, of replacing that component during the opportunity. Sculli and Suraweera [8] extended the 'rule-of-thumb' to calculate OM ages for the components/subsystems of a tramcar where failure of any component is an opportunity for planned replacement of other components as follows. Components are considered in pairs, and the OM age for one component is arrived at given that the other component has failed. The OM age for subsystem i is calculated by using the following expression:

$$1 - \frac{M(n_{ij})}{M(0)} = \frac{C_{ij}}{C_{ii}} \qquad (1)$$

where:

n_{ij} = OM age for subsystem i when subsystem j has failed

$M(x)$ = mean time to failure of a subsystem that has already served a time x, [M(0) indicates the mean time to failure for a new subsystem]

C_{ij} = additional cost of replacing subsystem i when subsystem j has failed

C_{ii} = cost of replacing subsystem i alone.

Once C_{ij} and C_{ii} are estimated, one can calculate the value of n_{ij} by trial and error to satisfy the above expression.

For the considered situation, C_{ij} and C_{ii} are taken as times rather than costs. C_{ii} can be taken as the expected repair time of the subsystem i. However, calculation of C_{ij} is not straightforward, because both repair times and PM times are variables and in turn the excess time is also a variable. For instance, suppose subsystem j has failed, and its repair time is a random variable, X, whose distribution function is $F(t)$. Then subsystem i is taken up for PM simultaneously, and the time to complete PM is a random variable, Y, whose distribution function is $G(t)$. The variable of interest is the extra time taken for PM beyond the repair time. If FM time is greater than or equal to PM time, the extra time will be zero; otherwise, it is PM time minus FM time. The process can be represented as staying in one of the following states:

State 0—both repair on subsystem j and PM on subsystem i are not completed
State 1—repair on subsystem j completed but PM on subsystem i not completed
State 2—repair on subsystem j not completed but PM on subsystem i completed
State 3—both repair on subsystem j and PM on subsystem i are completed.

The process moves from state 0 to state 1 or 2, and then to state 3. The probability of staying in state 1, at any time t, is given by

$$P_1(t) = F(t)(1 - G(t)) \tag{2}$$

The expected value of excess time taken for PM is equal to the expected time the process remains in state 1, and is given by

$$C_{ij} = E[Z] = \int_0^\infty P_1(t)\,\mathrm{d}t = \int_0^\infty F(t)(1 - G(t))\,\mathrm{d}t \tag{3}$$

The OM ages have been specified as k_i times n_{ij}, and search has been conducted to find out the best values of the k_is along similar lines to the previous case. For this policy, while conducting the search, the OM ages of a subsystem have been considered as a set, and all the OM ages of a subsystem have been varied by the same factor. This policy has resulted in further reduction of downtime over the (n_i, ∞) policy.

4.3. *(n_{ij}, ∞) policy based on classification of opportunities*

This policy is based on the assumption that after initial inspection, repair times and PM times can be estimated with reasonable accuracy to fall within two closely specified limits. This is not an unrealistic assumption, since an experienced worker can give these estimates. For the purpose of classification of opportunities, the upper and lower limits, between which the downtime has to be estimated, have been specified at 2 h apart. For the pulverizer, this resulted in seven classes, with outages up to 2.00 h duration being class 1 and outages between 10.00 h and 12.00 h being class 6. Outages beyond 12.00 h of duration have been classified as one class, namely class 7, because the maximum of the PM times of the subsystems is 12.00 h. Under the proposed policy, OM age is specified corresponding to the opportunity class rather than the subsystem that failed. Initial values for OM ages have been calculated using the rule-of-thumb described in the previous section. The only change in this case is that j represents an opportunity class instead of a failed subsystem. Within each class, downtime has been assumed to follow the uniform distribution. The simulation exercise has been carried out using these initial values, and further search has been conducted as described earlier. The (n_{ij}, ∞) policy based on classification of opportunities, which may be called the (n_{ij}, ∞) policy of type II for the sake of simplicity, has resulted in further reduction in downtime over the (n_{ij}, ∞) policy based on subsystem failure, which may, for the sake of simplicity, be called the (n_{ij}, ∞) policy of type I.

4.4. *Discussion*

In order to illustrate the effectiveness of the (n_{ij}, ∞) policy of type II, the following example may be considered. When a loading unit fails, its repair time could take any value, say 2.50 h, 6.08 h, etc. All the opportunities arising due to the failures of the loading unit are considered as the same under the (n_{ij}, ∞) policy of type I, and for the IFR subsystems there is a single OM age with respect to the failures of the loading unit. However, in the case of the (n_{ij}, ∞) policy of type II, opportunities arising due to the failures of a subsystem are treated as different depending on the repair time, and different OM ages are specified for the IFR subsystems depending on the class of the opportunity. In this way, the (n_{ij}, ∞) policy of type II discriminates more effectively between opportunities, by penalizing the opportunities of shorter duration and favoring the opportunities of longer duration. This results in much lesser excess OM time with the (n_{ij}, ∞) policy of type II. However, when a subsystem fails, the (n_{ij}, ∞) policy of type II requires additional information, namely an estimate of the expected downtime. However, asking for this

Table 4. Final OM ages for the (n_{ij}, ∞) policy of Type I

Subsystem i	Subsystem j							
	Feeder box	Feeder drive	Mill internal	Rejection system	Mill drive	Loading unit	Coal pipes	Others
Feeder box	—	63	17	132	0	240	280	332
Feeder drive	2	—	0	75	0	240	288	460
Mill internal	7	31	—	84	0	194	233	310
Rejection system	0	2	0	—	0	103	123	253

Table 5. Final OM ages for the (n_{ij}, ∞) policy of Type II

Subsystem i	Class j						
	1	2	3	4	5	6	7
Feeder box	816	544	316	156	58	10	0
Feeder drive	115	38	5	0	0	0	0
Mill internal	516	277	97	15	0	0	0
Rejection system	758	105	0	0	0	0	0

information is not too demanding, and, in fact, may be more practical, because managers tend to decide on the PM actions only after they get a reasonable idea of the downtime due to the initiating action.

The final OM ages have turned out to be significantly different for both the (n_{ij}, ∞) policies. To make things clearer, the final OM ages, in hours, for both the (n_{ij}, ∞) policies, are given in Tables 4 and 5. As can be seen from Table 5, the OM ages for the subsystem feeder drive are very low. This can be explained as follows: by taking low OM ages, at almost all opportunities, the feeder drive will be taken up for OM. Once this happens, the rejection system can be taken up for OM at no excess time or very little of it. There will be some benefit for the subsystems feeder box and mill internal also. This is due to the assumption of unlimited manpower availability. However, when this policy has been implemented for the entire fuel system with manpower restrictions, the OM ages were found to be larger than the single pulverizer case, even for the feeder drive. At this point, the three positive OM ages (others are zeros) of the feeder drive have been varied further, but there is no improvement in the value of the objective function. In fact, in an opportunistic framework, what happens for the total system is more important than that for the individual subsystems. Further, the decisions are so interrelated that a decision for one subsystem will also have its effects on all the other subsystems.

When considering different policies, an aspect of interest is the relative amount of improvement one achieves by going for different policies. To make the comparison more useful, the policies have been evaluated with different PM time distributions. Much wider uniform distributions have been used for PM times in this case. The lower and upper limits of the uniform distributions for the subsystems are as follows: feeder box: 4 and 24; feeder drive: 2 and 12; mill internal: 4 and 18; and rejection system: 2 and 8. That is, for this case, the PM time will be more than that of the previous case. The final results for both the cases are given in Table 3 under set 1 and set 2, with set 1 corresponding to the previous case and set 2 to the present case.

It can be seen that the (n_i, ∞) policy has resulted in large reductions, 36.88% and 21.71%, in downtime over FM (with PM only on mill drive) policy. The (n_{ij}, ∞) policy of type I has resulted in further reductions of 2.71% and 8.64% over and above the (n_i, ∞) policy, for sets 1 and 2, respectively. The corresponding reductions for the (n_{ij}, ∞) policy of type II are 8.13% and 14.15%. Clearly the (n_{ij}, ∞) policy of type II outperformed the (n_{ij}, ∞) policy of type I. The (n_{ij}, ∞) policies have resulted in larger reductions, over and above the (n_i, ∞) policy, for the case with wider PM distributions. It can be said that the longer the PM time, the more advantageous it is to go for OM policies with multiple OM ages.

5. FUEL SYSTEM MODELING

In the previous section, OM policies were evaluated under the assumption of unlimited manpower. In this section, the impact of the (n_{ij}, ∞) policy based on classification of opportunities, which was found to be the best, has been studied for the entire fuel system. As mentioned earlier, the fuel system consists of six identical and independently operating pulverizers, with one serving as stand-by. When more than one pulverizer is down, the unit performs at reduced capacity. Thus, in this case, minimization of power generation loss has been considered as the objective. Further, the available manpower is limited. Thus, when more than one pulverizer has failed, some of them will be waiting for repair. Moreover, during opportunities, only a limited number of subsystems can be maintained opportunistically. Accordingly, the OM activities have to be prioritized and selection should be based on the priority. With these constraints, the performance of the (n_{ij}, ∞) policy based on classification of opportunities has been studied.

The work force in the boiler section of the maintenance department is organized into eight gangs. The gangs are so organized that they are self-sufficient in skills so that any gang can perform any work in the boiler section. Out of the eight repair gangs, two gangs are engaged in the running maintenance of various equipment of the boiler section (main boiler, ID and FD fans, pulverizers, and others), which is carried out during the general shift. The other six gangs are distributed over three shifts, with two gangs allotted for each shift. These gangs are engaged in reconditioning work of the removed components, and attend to any problems of the equipment as and when required. Accordingly, at any time, two gangs are available for the corrective or preventive maintenance of the equipment. Further, it has been the practice in the unit to arrange pulverizer and other equipment overhauls, and repair of any major breakdowns of the equipment on a contractual basis. Since the number of failures observed for other equipment is very low compared to that of pulverizers, it can be safely assumed that two gangs are available for the maintenance of the pulverizers alone.

A simulation model has been developed in FORTRAN on a PC using a discrete-event framework. The model, though similar to that of the single pulverizer model described in the previous section, differs in logic in many ways. Here also the process essentially consists of failure and repair completion events of the pulverizers. In the single pulverizer model, failure and repair events occur one after the other sequentially. However, in the fuel system model, this may not be so. After the failure of a pulverizer, its repair completion event is scheduled in clock time. Before the repair completion, another pulverizer may fail, and thus the process might not go sequentially from failure event to repair event and so on. In the single pulverizer model, repair on the failed pulverizer is taken up immediately. However, in the case of the fuel system model, due to the limited availability of manpower, repair on a failed pulverizer may not be taken up immediately. Thus, two stacks, namely repair stack and waiting stack, have been created. The repair stack consists of repair activities that are currently being processed, and the waiting stack consists of repair activities that have to be initiated as and when manpower is available. Whenever a failure occurs, the repair activity is stored in either the repair stack or the waiting stack, as the case may be. When the repair completion event occurs, one repair gang becomes available, and accordingly, one activity from the waiting stack, if any, is transferred into the repair stack. In the case of the single pulverizer model, the possibility of performing OM has to be checked at the time of failure events only. However, in the case of the fuel system model, the possibility of performing OM has to be checked at the time of failure event and also at the time of the repair completion event.

In the single pulverizer model, pulverizer overhaul (normally performed approximately after 15 000 h of operating time) was considered as the terminating point for each run. For each run, all the subsystems of the pulverizer being in as good as new condition was considered as the initial condition, and the behavior of the pulverizer was observed between pulverizer overhauls. However, in the fuel system model, overhauls of the pulverizers have to be included as events occurring in the process. This is so because generation loss is affected by all pulverizer downtimes, even due to overhauls. Since all the pulverizers are not overhauled at the same time, the system being in zero state (that is, all the pulverizers in as good as new state) cannot be taken as the initial condition for each run. In this case, what should be of interest is the steady-state or long-run value of the objective function. For this purpose, the model has to be run for a very long period of time, so that the objective function attains a steady-state value, wherein the effect or bias of the initial conditions is eliminated. The same thing can be achieved by dividing the total run length into convenient intervals, and then considering each interval as a single run. In the present case, it has been observed that the period between two successive unit overhauls is approximately 22 months. Accordingly, 15 000 h of clock time has been considered as the length of each run. The simulation exercise has been started with the initial condition of all pulverizers being as good as new. The final conditions of each run have been stored, and have been taken as the initial conditions for the subsequent runs. In this way for each run, different initial conditions are considered so that the effect or bias of the initial conditions is eliminated. While calculating the mean result of the simulation, results of the first run have not been taken into consideration.

The process has been simulated with the existing policy of only failure maintenance on subsystems. Pulverizer overhauls have been scheduled in such a way that, at any time, only one pulverizer is scheduled for overhaul. The expected generation loss has been found to be 6.35% as against 3.73% that actually occurred during the study period. However, the number of failures/outages of the individual subsystems showed close conformity between the simulation results and the actual data. The actual data have been used to arrive at the failure time and repair time distributions of the subsystems of the pulverizer. The close conformity between the simulation results and the actual data with regard to the number of failures/outages of the individual subsystems is a confirmation of the fact that the behavior of the individual pulverizers in simulation is similar to the reality. The system performance is the result of superimposition of the behaviors of the individual pulverizers. It has been observed that the percentage of time during which the system suffers the loss of two or more pulverizers is much less for the actual data as compared to simulation results. It is not only the number of outages but also the manner in which the outages, in particular the major outages, have occurred that significantly affect the generation loss. At this point, the results of individual simulation runs have been studied. It has been observed that the generation loss for individual runs varied from as low as 3.53% to as high as 9.74%, with an average of 6.35%. The actual data can be considered as the result during a very fortunate period, in which the simultaneous occurrence of major outages was minimal. The simulation result is the mean of many realizations of the system, whereas the actual data are the result of only one realization of the system. Thus, the simulation result is the true representation of the long-run behavior of the system.

Now, as in the single pulverizer case, the PM strategy on mill drive has been implemented for the system, and it has resulted in significant reduction in generation loss from 6.35% to 4.43%. The primary benefit from PM on the mill drive is that the percentage of times the system has stayed in the states of two or more major outages having occurred has decreased significantly. Now OM policy on the four subsystems, namely feeder box, feeder drive, mill internal and rejection system, can be implemented. Before this, a mechanism should be developed to prioritize the OM activities, because only a limited number of OM activities can be taken up at a time due to the manpower restriction.

Dekker and Smeitink [12] faced the same problem of prioritizing the OM activities. However, the problem considered by them is significantly different from the present one. They considered a system of n components. Preventive replacement of components was done at opportunities created by external reasons. Failures of components were not considered as opportunities to replace other components. Preventive replacement of each component takes one unit of time. Opportunities are of restricted duration, and accordingly, a limited number of components can only be replaced at the time of opportunity. Since the opportunity process is external to the system, analysis becomes simpler and each component can be analyzed independently. They considered a block replacement type policy, according to which, a component i is replaced preventively, if at an opportunity, the time since the last preventive replacement, t_i, exceeds a control limit, t_i^*. The long-term expected cost for component i, $\phi_i(t_i^*)$, is calculated. At the time of opportunity, for the components that qualify for OM the expected cost of differing preventive replacement, $n_i(t_i)$, is calculated, and $n_i(t_i) - \phi_i(t_i^*)$ is used as the ranking criteria. This criterion was found to be better than other criterion based on random selection and a heuristic.

In the present case, the opportunity process is internal to the system, and the decisions on components are so interrelated that calculation of cost/downtime on the above lines is rather difficult. However, as mentioned earlier, the rule-of-thumb used to calculate the initial OM ages applies similar logic. Accordingly, $(1 - M(x_i)/M(0) - C_{ij}/C_{ii})$, where $M(x_i)$ is the mean residual life of subsystem i having an age of x_i, has been used as the ranking criterion. This way the ranking criterion takes into account residual mean life in relation to the mean life of the subsystem, and expected excess time in relation to expected repair time. Using this priority rule, further search has been conducted to find optimum OM age values, as in the case of single pulverizer model. The generation loss is reduced to 2.96% with the adoption of OM policy.

An obvious question is, what are the savings in monetary terms? It is difficult to quantify precisely. Since almost all the thermal power units have similar fuel systems, the work done in this study can be

Table 6. Results of fuel system simulation

	FM only	PM on mill drive	OM policy
1 stand-by pulverizer	6.35	4.43	2.96
2 stand-by pulverizer	2.29	1.30	0.66

implemented in all the other thermal power units. Considering the existing installed capacity, a mere 1% reduction in losses, at the all India level, can give a benefit equivalent to around 1000 MW of additional capacity, which has a gestation period of 4 to 5 years and an initial cost of Rs 40 000 million. Added to this is the extra revenue and better power supply to the customers. The unit considered in this study has one stand-by pulverizer. In the case of smaller units, for which provision of stand-by capacity is rare, the OM policy is still more useful and the savings would be much higher.

The simulation model for the fuel system has been developed essentially to study the performance of the OM policy. The model can be used for other purposes also, in particular to study the system design aspects, such as optimizing the amount of stand-by capacity. The existing fuel system consists of six pulverizers, with one pulverizer serving as a stand-by. Suppose the capacities of the pulverizers are enhanced so that only four pulverizers are required for the full capacity of the unit. In this case, outages of three or more pulverizers only results in generation loss. Suppose the capacities are so enhanced that outages of three, four, five and six pulverizers result in 25, 50, 75 and 100% of capacity loss, respectively. The process has been simulated under the assumption that the capacity-enhanced pulverizers also exhibit similar failure characteristics. The generation losses for the original and modified system under different policies are given in Table 6.

It can be seen that provision of one more stand-by pulverizer gives tremendous improvement. The generation loss for the system configuration of two stand-by pulverizers and failure maintenance only is less than the generation loss for the system configuration of one stand-by pulverizer and an OM policy. However, it can be seen that significant benefits can also be achieved through PM and OM policies for the improved system configuration. With the adoption of PM and OM policies for the improved system configuration, the generation loss can be reduced substantially, making it nominal. It has been observed that some of the newer installations of 210 MW units are being designed with a fuel system configuration of $4 + 2$ pulverizers (that is, 4 operating and 2 stand-by pulverizers). Based on the work done for a 210 MW unit with the fuel system configuration of $5 + 1$ pulverizers, it can be concluded that it is better to design the newer installations of 210 MW units with the fuel system configuration of $4 + 2$ pulverizers. Further, in the case of existing installations of 210 MW units with the fuel system configuration of $5 + 1$ pulverizers, the possibility of converting the configuration of the fuel system to $4 + 2$ pulverizers can be explored. Moreover, in both the cases, the OM policy should be adopted. Similar studies can be taken up on their capacity units as well.

6. CONCLUSIONS

The following conclusions can be drawn from this case study:

1. It is a fact that for the components of a series system opportunistic maintenance policies of (n, N) type are more appropriate than simple age-based maintenance policies. In the literature, it is seen that most of the models consider single OM age for each IFR component. It has been demonstrated that policies with multiple OM ages for each IFR component are better than the policies with single OM age for each component. In general, the relative advantage of going for policies with multiple OM ages increases with increasing PM time/cost. A new policy based on classification of opportunities has been proposed and found to be outperforming the other policies. It has been observed that this policy discriminates more effectively between opportunities than other OM policies.
2. It has been found that PM age, N, tends to be infinity. In general, when the number of components is high, the number of opportunities will also be high, and enough PM will be done during opportunities. Performing PM even when there is no opportunity may have a detrimental effect. It can be said that OM policies of type (n, ∞) are sufficient in the case of systems with a large number of components.

3. Simulation modeling has been found to be very effective in evaluating OM policies, and also in modeling complex systems. Alternative design considerations have been evaluated with relative ease for the complex system considered in this work.

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