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DETERMINATION OF PREVENTIVE MAINTENANCE TIME FOR MILLING ASSEMBLIES USED IN COAL MILLS

Key words: preventive maintenance, coal mill, decision-random model.

Abstract: The paper presents a determination method of the most advantageous time of preventive maintenance for milling assemblies used in the energy industry. In this particular case, we considered bowl-mill pulveriser assemblies used in power plants. Reliable operation of these assemblies is important from the point of view of continuous energy production. In addition to a reliable operation, the planned maintenance policy allows reducing the operating costs by minimizing the losses caused by unplanned failures and downtime. The decision-random model based on dynamic programming and the Bellman's Principle of Optimality was used to determine the maintenance time. In practical operation there are situations when, in order to ensure continuous production, the maintenance of a milling assembly cannot be carried out as planned, and its operation time is extended. The decision-random model presented in the paper allows determining how much this time can be extended from the economic point of view.

Wyznaczanie czasu odnowy profilaktycznej zespołów mielących eksploatowanych w młynach węglowych

Słowa kluczowe: odnowa profilaktyczna, młyn węglowy, model decyzyjno-losowy.

Streszczenie: W artykule przedstawiono sposób wyznaczenia najkorzystniejszego czasu odnowy profilaktycznej dla eksploatowanych w przemyśle energetycznym zespołów mielących. W analizowanym przypadku rozważano kulowo-misowe zespoły mielące eksploatowane w młynach węglowych jednej z elektrowni. Niezawodne funkcjonowanie tych układów jest istotne ze względu na zapewnienie ciągłości produkcji energii. Stosowanie zaplanowanej polityki odnawiania obiektów, oprócz zapewnienia niezawodnego funkcjonowania, pozwala na zmniejszenie kosztów eksploatacji poprzez minimalizację strat wynikających z nieplanowanych awarii oraz przestojów. Do wyznaczenia czasu odnowy zespołów mielących zastosowano modele decyzyjno-losowe oparte na programowaniu dynamicznym i wykorzystujące zasadę optymalności Bellmana. W praktyce eksploatacyjnej zdarzają się sytuacje, kiedy ze względu na zapewnienie ciągłości produkcji zespół mielący nie może być odnowiony w zaplanowanym terminie i czas jego eksploatacji jest wydłużany. Wykorzystując przedstawiony w artykule model decyzyjno-losowy, można określić, o ile czas ten może być wydłużony z ekonomicznego punktu widzenia.

Introduction

Reliable operation of power plants is of paramount importance due to their strategic significance for the nation's economy. They provide required power to both industry and households. The power plants operating in the National Power System must ensure that the demand for power is satisfied at all times [1]. A reliable fulfilment of this task depends directly on the maintenance and repair strategy in a plant. Such strategy should be rationalized due to the level of reliability and the costs of preventive maintenance and of losses following unforeseen failures [4, 5]. In many cases, the maintenance policy is based on the knowledge and experience of the managers responsible for the operation of process lines. Many years of experience allow managing the maintenance policy, but application of theoretical calculation models can improve its effectiveness by ensuring more precise planning of maintenance times that give better economic effects [2, 3, 6].

The paper presents a method for the determination of the optimum preventive maintenance time and for the economically based operation time of bowl-mill pulverisers used in a power plant. The analysis uses the decision-random models based on dynamic programming.

1. Description of milling assembly failures

The basic part of the analysed coal mill that prepares the coal-air mixture is a milling assembly. In this case, these are bowl-mill pulverisers with 6 mills per each power generation unit. Figure 1 presents the design of the coal mill with marked milling assembly (elements 4, 6, 7).

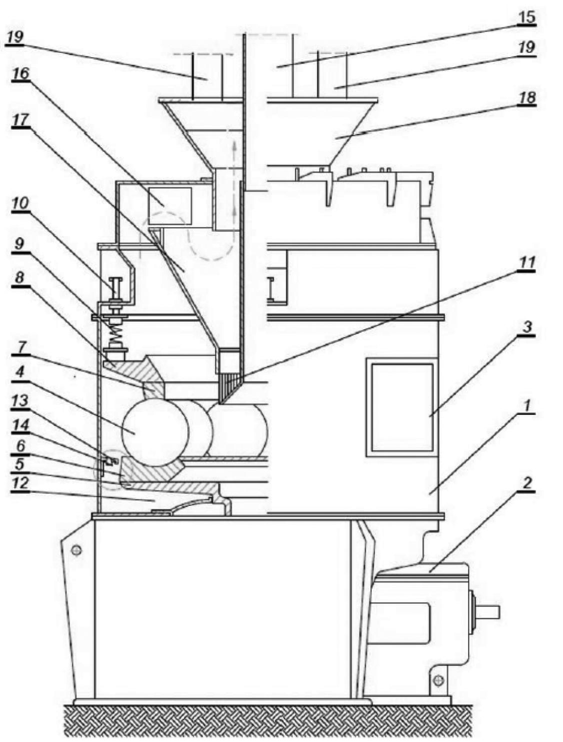

Fig. 1. Coal mill construction: 1 – mill jacket, 2 – drive gear unit, 3 – installation door, 4 – milling ball, 5 – mill yoke (bowl), 6 – crushing ring (ball race), 7 – pressure ring, 8 – thrust ring, 9 – pressure spring, 10 – tensioning bolt, 11 – pivoting apron, 12 –pyrites chamber, 13 – through ring, 14 – air nozzle, 15 – chute, 16 – separator guide, 17 – separator chute cone, 18 – outlet head, 19 – dust ducts [14]

The coal is fed through the chute (15) and falls onto the rotating crushing ring (6) with rolling balls (4) where it is comminuted and ground. The force necessary to comminute the coal is obtained by the pressure on the stationary pressure ring (7) exerted by four units (8-10) with an adjustable pressure force which depends on the hardness of pulverised coal and the required dust parameters. The pulverised coal is blown out by a stream of air to the sieve where the separated coarser particles are sent back to be reground. The proper coal-air mixture is sent through the dust ducts (19) to the boiler burners.

Difficult operating conditions cause quick wear and damage to the mill components, resulting in unplanned downtime and losses. The main form of wear that appears in the milling assembly is the abrasive wear of crushing and pressure rings, which deteriorates the grinding effectiveness and reduces the dust quality when critical values are passed. There is also fatigue-type damage in the form of ball and race cracking (Fig. 2).

a) b)

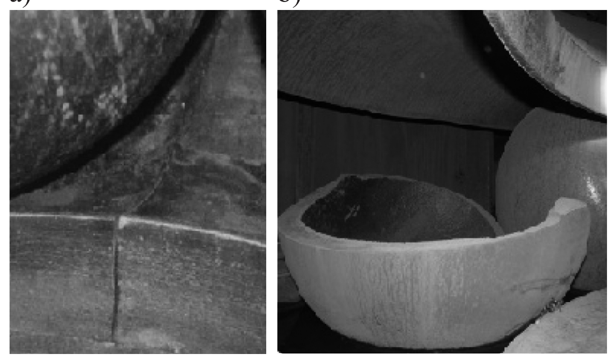

Fig. 2. Milling assembly damage: a – race cracking, b – ball cracking [14]

The data collected for the analysis included data on the damage of milling assemblies from 6 years of operation. The collected data (72 values of time-to-failure of the assemblies) were used to determine the form and parameters of the probability distribution of the time to the first failure. The l-Kolmogorov goodness of fit test with the a = 0.05 significance level gave no grounds for rejecting the hypothesis about the fit between the time-to-failure and the normal distribution: N(15498 [h]; 3419 [h]).

2. Selection and features of the maintenance model

The determination of the optimum maintenance time of a milling assembly requires selecting an analytical calculation model that best fits the operation of the analysed facility. In addition to classical maintenance/repair models which take into account the reliability factors and costs of maintenance and failures (maintenance at set age, according to schedule, with a partial repair after failure, sequentially) [2, 3, 15], the literature also describes models that aim at ensuring the required level of reliability [7, 8, 9] and take into account the possibility of performing a partial maintenance or use the information from additional checks of condition which, if possible, are carried out during the operation of the assembly [10, 11].

The policy in the analysed plant involves the repair of milling assemblies after a failure or maintenance after the specified time of operation. If it is necessary to ensure the continuous production, the operation time is extended. The solution of the problem should include both the determination of the optimum preventive maintenance time and the determination of how much the operation time can be extended so that the cost of this strategy (taking into account the increasing risk of failure) does not exceed the cost of the preventive maintenance strategy. The decision-random models (DRM) were chosen to solve this problem for the following reasons:

– They allow the determination of the optimum maintenance time in a finite time horizon of operation that is a typical feature of the analysed milling assemblies.
– They allow the determination of the economically justified extended time of operation if the preventive maintenance cannot be performed as planned.

The DRM is a method in which the time-to-repair is determined based on dynamic programming and the Bellman's Principle of Optimality [12]. It examines the calculation problem in a finite time horizon (T_h) which is discretized to periods of *Δt* duration. Decision and random phases occurring in each *Δt* period allow determining the potentials and optimum decisions at each stage of the analysis. Then, in accordance with the Bellman's Principle of Optimality, the final strategy is developed which includes the best, from the point of view of possible costs of failure and repair, time of performing the preventive maintenance of the facility [3, 13, 15]. Figure 3 presents the general decision-random graph used in the DRM.

Potentials *P*(*i*,*j*) are calculated from the following formula [3, 15]:

$$P(i,j) = p(j)\left(k_a + D(i+1,1)\right) + \left(1-p(j)\right)\left(D(i+1,j+1)\right) \quad (1)$$

where

k_a – cost of repair after failure,
k_o – cost of preventive maintenance,
$p(j)$ – probability of facility failure in the *j*th *Δt* period of operation,
$D(i+1,1)$ – costs resulting from the optimum decision in the next *Δt* period if the facility undergoes preventive maintenance,
$D(i+1,j+1)$ – costs resulting from the optimum decision in the next *Δt* period if the facility does not undergo preventive maintenance.

Probabilities *p*(*j*) are calculated based on the facility reliability function (Fig. 4), as conditional probabilities [3, 15]:

$$p(j) = \frac{R_{i=j}(t) - R_{i=j+1}(t)}{R_{i=j}(t)} \quad (2)$$

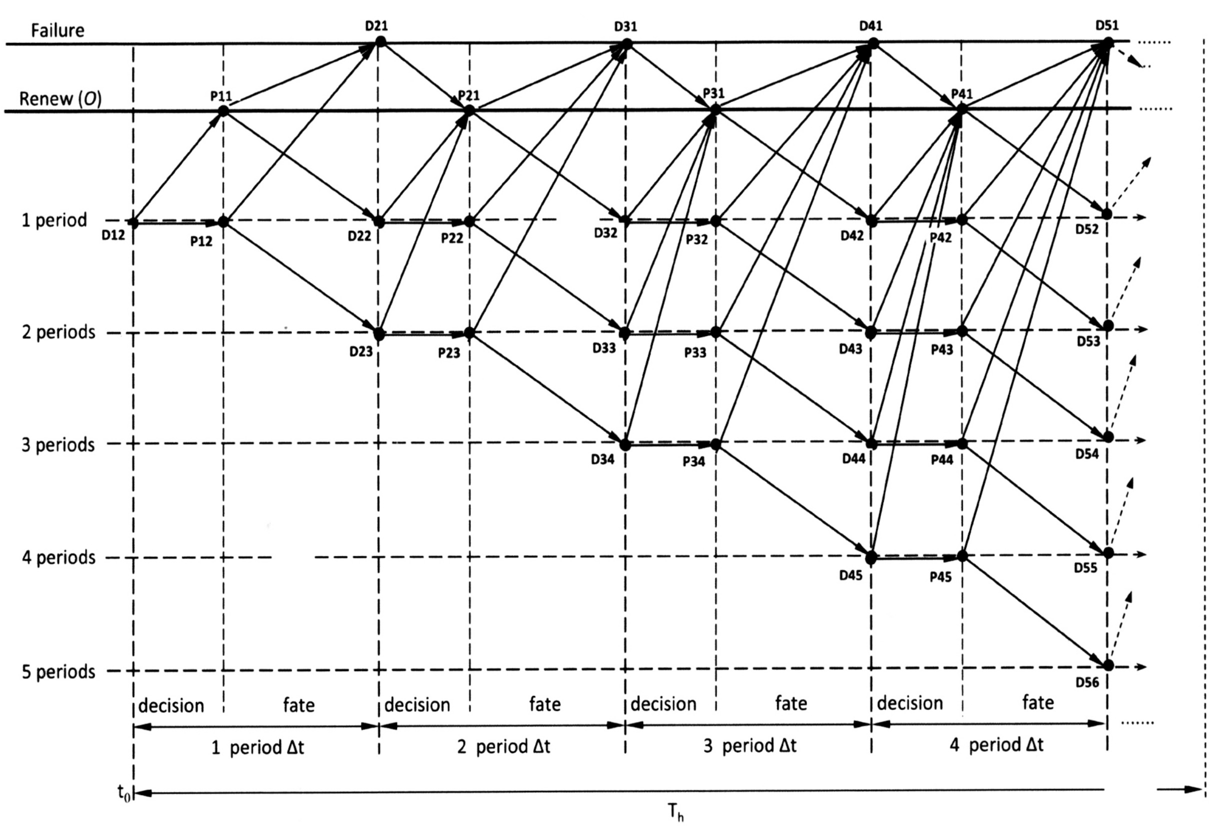

Fig. 3. Decision-random graph according to DRM [15]

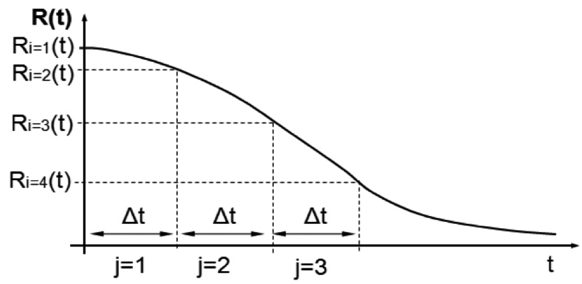

Fig. 4. Reliability function

Decisions $D(i,j)$ at each stage are determined according to the following principle [3, 15]:

$$D(i,j) = min\begin{Bmatrix} P(i,1)+k_o; & O \\ P(i,j); & N \end{Bmatrix} \quad (3)$$

where

k_o – cost of preventive maintenance,

$D(i,j)$ – defines the optimum decision: O – maintain (renew), N – do not maintain, and is a minimum value of possible costs from the jth successive Dt period in which the facility is at a given time to time $t = T_h$.

The calculated strategy is a sequence of decisions to maintain (O) or not to maintain (N) the facility in successive Δt periods. The number of decisions (k) in the strategy results from the length of time horizon (T_h) and the length of period Δt:

$$k = \frac{T_h}{\Delta t} \quad (4)$$

If the obtained strategy contains only N decisions, this means that, in the time horizon T_h, at specified costs and changes of facility reliability function, the preventive maintenance is not justified. The greatest T_h value for which preventive maintenance does not occur is the longest economically justified period of facility operation without maintenance. If the resulting strategy contains an O decision, this means that preventive maintenance is justified and the best time to perform it is time interval ($n\Delta t$, $(n+1)\Delta t\rangle$. Value n is the number of N decisions occurring before the decision O specifying the preventive maintenance. The optimum time to perform the maintenance is time obtained for T_h for which the strategy indicates the least unit costs. These costs are expressed as the value of maintenance cost (k_o) per unit of time Δt. The solution defines the time interval, because the calculations are made in a discrete manner. The accuracy of the obtained result (interval width) is equal to the Δt used in the calculations. Reducing the Δt increases the accuracy of results, but it also increases the number of necessary calculations.

3. Determination of preventive maintenance time and the time of operation without maintenance

The determination of maintenance strategy for the analysed milling assemblies was performed on a computer program written in the Matlab environment, which executes the presented calculation procedure according to the DRM [15]. The calculations were made for selected values of costs proportion k_a/k_o. The reliability function was formulated in accordance with the normal probability distribution of time-to-failure which has been estimated in section 1: N(15498 [h]; 3419 [h]). For used costs proportions, the most advantageous periods of operation before preventive maintenance (Tab. 1) and the longest economically justified periods of operation without maintenance ($T_{h(\max)}$) were calculated and presented in Tab. 2. The length of period Δt, which determines the accuracy of calculations, was assumed as 1 month, because this value is sufficient from the point of view of practical operation in the analysed plant.

The obtained results indicate that, for short time horizons $T_{h,}$ the resulting strategies do not include preventive maintenance. When the maximum T_h value is reached for a given k_a/k_o proportion, the strategy changes to the one which includes preventive maintenance. By further extending the $T_{h,}$ it is possible to determine the optimum time-to-maintenance which occurs when the costs of strategy with preventive maintenance is minimum. The greater the k_a/k_o values, the shorter are the time-to-maintenance periods.

The calculated longest periods of operation without maintenance ($T_{h(\max)}$) also depend on the cost proportions k_a/k_o. The greater the k_a/k_o, the shorter are the economically justified periods of operation without maintenance ($T_{h(\max)}$).

A practical aspect of using the results involves calculating the most advantageous time of the operation of a milling assembly before its preventive maintenance, for a given costs proportion k_a/k_o, and determining the time by which the operation of such assembly without maintenance can be extended so that the extension is economically justified. For example, if the costs proportion k_a/k_o for a milling assembly is equal to 2, the optimum time-to-maintenance is (16-17$\rangle$ months, and a possible extension of the operation time should not exceed 3 months because the determined $T_{h(\max)}$ is 20 months.

Conclusions

A practical use of analytical calculation models can bring beneficial results in the form of the improved effectiveness of the operation process. It allows a more precise determination of searched values, or defining

Table 1. Calculation results – period of preventive maintenance

k_a/k_o	T_h [month]	Strategy	Unitary cost [k_o/month]	Time of preventive maintenance [month]
1.4	21	*NNNNNNNNNNNNNNNNNNNNN*	0.08536	–
	22	*NNNNNNNNNNNNNNNNNNNNNN*	0.08672	-
	23 (max)	*NNNNNNNNNNNNNNNNNNNNNNN*	0.08761	-
	24	*NNNNNNNNNNNNNONNNNNNNNNN*	0.08530	(13-14〉
	25	*NNNNNNNNNNNNNNONNNNNNNNNN*	0.08245	(14-15〉
	…	...	…	…
	33	*NNNNNNNNNNNNNNNNNNONNNNNNNNNNNNNN*	0.07030	(18-19〉
	34	*NNNNNNNNNNNNNNNNNNNONNNNNNNNNNNNNN*	0.06996	(19-20〉
	35	*NNNNNNNNNNNNNNNNNNNNONNNNNNNNNNNNNN*	0.06989 (min)	(20-21〉
	36	*NNNNNNNNNNNNNNNNNNNNONNNNNNNNNNNNNNN*	0.06992	(20-21〉
	37	*NNNNNNNNNNNNNNNNNNNNNONNNNNNNNNNNNNNN*	0.07016	(21-22〉
	38	*NNNNNNNNNNNNNNNNNNNNNONNNNNNNNNNNNNNNN*	0.07050	(21-22〉
	39	*NNNNNNNNNNNNNNNNNNNNNNONNNNNNNNNNNNNNNN*	0.07089	(22-23〉
	…	…	…	…
1.5	34	*NNNNNNNNNNNNNNNNNNNONNNNNNNNNNNNNN*	0.07156 (min)	(19-20〉
1.6	33	*NNNNNNNNNNNNNNNNNNONNNNNNNNNNNNNN*	0.07303 (min)	(18-19〉
1.8	32	*NNNNNNNNNNNNNNNNNONNNNNNNNNNNNNNN*	0.07553 (min)	(17-18〉
2	31	*NNNNNNNNNNNNNNNNONNNNNNNNNNNNNN*	0.07760 (min)	(16-17〉
2.5	30	*NNNNNNNNNNNNNNNONNNNNNNNNNNNNN*	0.08190 (min)	(15-16〉
3	28	*NNNNNNNNNNNNNNONNNNNNNNNNNNNN*	0.08523 (min)	(14-15〉
4	27	*NNNNNNNNNNNNNONNNNNNNNNNNNNN*	0.09050 (min)	(13-14〉

Table: 2. Calculation results – the longest economically justified time of operation without maintenance

k_a/k_o	T_h [month]	Strategy	Unitary cost [k_o/month]
1.4	18	*NNNNNNNNNNNNNNNNNN*	0.08022
	19	*NNNNNNNNNNNNNNNNNNN*	0.08186
	20	*NNNNNNNNNNNNNNNNNNNN*	0.08366
	21	*NNNNNNNNNNNNNNNNNNNNN*	0.08536
	22	*NNNNNNNNNNNNNNNNNNNNNN*	0.08672
	23 (max)	*NNNNNNNNNNNNNNNNNNNNNNN*	0.08761
	24	*NNNNNNNNNNNNNONNNNNNNNNN*	0.08530
	…	…	…
1.5	22 (max)	*NNNNNNNNNNNNNNNNNNNNNN*	0.08967
1.6	22 (max)	*NNNNNNNNNNNNNNNNNNNNNN*	0.09262
1.8	21 (max)	*NNNNNNNNNNNNNNNNNNNNN*	0.09614
2	20 (max)	*NNNNNNNNNNNNNNNNNNNN*	0.09808
2.5	19 (max)	*NNNNNNNNNNNNNNNNNNN*	0.1048
3	18 (max)	*NNNNNNNNNNNNNNNNNN*	0.1084
4	17 (max)	*NNNNNNNNNNNNNNNNN*	0.1165

the optimum solutions in terms of assumed criteria. It is important that the applied model should fit the specific character of operational practice in the analysed system. In case of analysed milling assemblies, the use of DRM allowed determining the following:

– The optimum (from the economic point of view) time-to-maintenance for various cost proportions k_a/k_o, and
– The longest time of assembly operation without maintenance which is economically justified because the unit cost of such strategy (taking into account the growing probability of failure) does not exceed the cost of the strategy which includes preventive maintenance.

The application of determined time-to-maintenance or extending its maximum up to the determined $T_{h(\max)}$ value brings about a reduction of general operating costs of the assembly as well as the costs of repairs and downtime.

The advantage of applied calculation model lies in the fact that the solution can be determined with the accuracy required by the operational practice and that the solutions can be presented depending on the costs of failures and maintenance that can be variable.

It is important that, in the case of a change of operating conditions or parameters (e.g., material parameters) of new milling assemblies, the probability distribution of time-to-failure be verified, because this directly affects the obtained results.

A significant number of Poland's power plants are coal-fired facilities where the coal-air mixture is prepared in coal mills. Hence, the presented methodology can also be used to determine the maintenance time of such milling assemblies used in other power plants.

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