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MANAGING THE EXPLOITATION LIFE OF THE MINING MACHINERY FOR A LIMITED DURATION OF TIME

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Abstract: The paper discusses the theoretical concept and illustrates the practical application of models with limited interval based on dynamic programming, suitable for optimization of exploitation life of mining machinery that have a shorter life cycle such as: bulldozers, scrapers, dumpers, excavators equipped by a smaller capacity operating element, as well as some others machinery.

Keywords: Operations research, dynamic programming, machinery exploitation life, management, decision making, optimization, bulldozers, dumpers, scrapers, excavators.

1. INTRODUCTION

In achieving profitable production as a target task, the contemporary mining finds its main support in both production equipment and machinery. The operating efficiency of mining machinery depends on reliability of its functioning, technical-technological performances, handling, (management) maintenance, logistic support, adaptability – adjustment relations between machinery and properties of environment, etc. Regardless of the construction and construction quality, exploitation management and maintenance, no failure machinery exists. The consequences of machinery failure have direct negative economic effects through production losses, repair costs as well as eventual losses resulting from stopping the work of other machineries within the conditioned technological chain at mine. Thus, the mining machineries, generally operating under extremely heavy conditions, are required to be highly reliable and safe at work on the one hand, and on the other to be easy for maintenance and low demands. The opinion prevails that the decision on purchasing machinery, apart from the usual key criteria such as purchase conditions, purchase costs, machinery performance and other of the related kind, is equivalently effected by the expected exploitation costs and machinery maintenance costs during its "work life". Therefore, decision making about the equipment and machinery replacement is a management task of utmost importance.

The reasons for machinery replacement at mines may be different, and they are generally classified into one of the four categories: physical aging of machinery, "moral" wearing, technical-technological and functional expiration (or non-adaptability).

Machinery is considered to be wearing out when it is not possible to replace vital spare parts through maintenance, to carry out overhaul or provide the production capability exceeding the minimum level required. Instead of production capability, the minimum time of availability or operating readiness of the machinery can be used as an alternative criterion.

Machinery is treated as "morally" worn out when its exploitation is no longer economically viable: permanent engagement over time, steady increase of exploitation costs (containing the value of maintenance costs and the costs of overhaul, apart from the machinery purchase), its production capability decreased so that, taking all this into consideration, the argument-based conclusion proves the uselessness of utilization of such a machinery. The evaluation of this uselessness can be intensified by acknowledging the fact that almost identical or technically more sophisticated machinery appears at the market, offering lower purchase costs and higher operating efficiency.

Machinery that is technically and technologically out of date refers to the machinery whose technical, technological and production-economic performances considerably lag behind the performances of the same class of machinery offered at the market.

Being functionally out of date or non-adaptable represents a potential cause for the requested machinery replacement. Machinery that is functionally out of date is the one that no longer operates in the way expected from it at a mine, even if the machinery is still capable of carrying out its tasks. Non-adaptability may refer to the environment and the surrounding conditions or technical-technological production system the machinery is implemented into. In both cases it does not mean that the machinery is technically or technologically out of date, but that it not fit for the operation under particular working conditions or for the work in coupling with other machineries within the system.

The problem that represents the objective of this paper is reduced to finding out the optimum momentum when it is desirable to replace the existing machinery by a new one, viewed from the chosen economic standpoint. Establishment of such a momentum is equal to defining the optimum machinery exploitation life. It is useful that such information is available to the mine management at the time of installation (purchase) of the relevant machinery, so that the appropriate strategy of its exploitation can be made, describing everyday machinery engagement regime, determining the control process of its operations and establishing the system of preserving its production capability. Therefore, the knowledge on the optimum momentum of machinery replacement provides conditions for establishing of the optimum strategy of machinery management during its exploitation.

The recent experiences indicate the acceptance of two different criteria on optimization for finding out the optimum momentum of machinery replacement. One approach is based on the maximum net income resulting from the production engagement during its exploitation. The net income may be, according to the need, equalized with the difference between the value of the machinery production product and directly proportional production costs, namely represented by the corresponding part of the profit or accumulation resulting from machinery engagement. The other criterion of optimization is based on the minimum machinery exploitation costs during its exploitation life. From theoretical aspect, both criteria are equal. And yet, in practice the significant advantage is given to the criterion of minimum exploitation costs. The explanation and justification of such a “favour” of the criterion of minimum exploitation costs lies primarily in rationality, namely in less acquisition and data processing indispensable for these analyses.

Exploitation life of machinery lasts for a series of years. Within such long-lasting periods, numerous changes occur in both domestic and foreign economy, affecting the economic systems with different intensity and changing the frameworks and relations of economy. The directing actions of such changes affect the mines, forcing them to adapt their business policy to new conditions. From the aspect of the topic of this paper, these changes cause alteration of parameters values that are used as a quantitative base for determining the optimum life of exploitation machinery at mines. Variability of these parameters and the trend of continuous increment in maintenance and overhaul costs, depending on machinery age, reveal the principles of dynamic programming as the most viable in solving this class of tasks. Therefore, the conclusion is brought according to which all the models of machinery replacement are grounded on the philosophy characterized by dynamic programming or the methods of dynamic programming are directly used for their solution.

Two approaches are used in finding out the optimum solution covering machinery replacement. The first one refers to unlimited, and the second to limited research time interval. Within the approach with unlimited interval, contrary to the limited interval, the physical machinery life is not assumed (it is usually given by a producer). The researches with unlimited interval directly provide the period at the end of which, based on the accepted criterion of optimization, the machinery replacement should be carried out. When it comes to the approach by limited interval, at the beginning of each period the studies are made about whether the replacement of the existing machinery with the new one is economically viable.

Our experience indicate that the models with unlimited interval are suitable for application when determining the exploitation life of long-lasting mining machineries such as are bucket wheel excavators, excavator with one working element of great capacity, spreaders, belt conveyors and similar. The models with limited interval are suitable for optimizing the exploitation life of mining machinery having a shorter life cycle such as are: dumpers, loaders, bulldozers, scrapers, excavators with one working element of a smaller capacity and others.

Paper (3) published in the Proceedings of the XXXI APCOM discusses the models with unlimited interval. The subject of this paper is focused on models with limited interval.

2. MODELS WITH LIMITED INTERVAL

The interval of observation, namely analysis of the optimum life may be restricted to the physical machinery life, mostly recommended by its producer or, according to the expert recommendation, prolonged for several years depending on the machinery type. The interval includes N periods (mostly the period is equalized with a year) being identified by index k = 1, 2, 3, …, n, … N.

The purpose of optimization is to find the optimum strategy of machinery management during such a limited interval. It is expressed through making a decision at the beginning of each period within the given interval on viability of further utilization of the relative machinery. This decision is an alternative one: it is necessary to continue with exploitation of the observed machinery, namely to make a decision u_1 or replace it by new machinery, namely enforce the decision u_2. Such a system of decision making at the beginning of each period may show that during the limited interval no replacement is required, or that it is useful to carry out one, and probably more replacements of the existing ones with new machineries. Thus, it is not the question of finding out the optimum momentum for only one replacement as is the case with models with unlimited interval, but establishing the optimum strategy of machinery management that during the limited interval may (but should not) contain even more than one replacement.

The optimum strategy of machinery management might refer only to the machinery age or be simultaneously dependent on the age, as well as on falling to the period exposed to investigating the optimum management policy. The paper discusses two models where the machinery age is the only criterion for establishment of coefficient values and model parameters. Such assumption provides the given machinery, of the same age, with completely the same value for model elements within each period of the observed interval (regardless of the fact whether this period is at the beginning or at the end of an interval). The age of machinery is noted at the beginning of the period, and changes at its end. A new machinery installed at the end of the previous, namely at the beginning of the k period would be of zero age (t=0) till the end of the k period, and would be one year old (t=1) during k+1 period. As the age of machinery is determined at the beginning of the k period, the assumption should be accepted on replacement of an old by a new one at the beginning of the k period, as well. Thus, the state of the machinery S_k expressed by its age is S_{k-1}=t at the beginning of the k period, and S_k- t+1 at the end of k period, where t = 0, 1, 2, ... Should new machinery be installed at the beginning of the observed interval, then the ration $t \leq k-1$ holds for.

Models with minimum criterion function value: Let minimum exploitation costs be selected as an optimum criterion. At the beginning of each k period, one of two possible decisions are selected: to continue the exploitation of the given machinery of – age and within k period, namely, to conduct the management policy u_1, or to replace the machinery of t year age at the beginning of the k period by a new one, so that within the k period the machinery of zero age (t=0) will be used, namely the management policy u_2 will be carried out.

Recurrence functions set dependent on two alternative machinery management policies, provide identical functioning of the system throughout all periods, except in the last one of the observed interval, and therefore are divided into two groups. The first quoted in relation,

$$z_o^k(t) = \min\begin{cases} z_1^k(t) = h(t) + z_o^{k+1}(t+1) & \text{for } u_1 \\ z_2^k(t) = A + h(o) - Ag(t) + z_o^{k+1}(1) & \text{for } u_2 \end{cases} \quad (1)$$

holds for k = 1, 2, …, n -1, while the second refers only to the last period k = n,
where: A - purchase value of a new machinery;
Ag(t) - liquidation value of a new machinery;
h(t) - costs of maintenance and periodical repairs of machinery.

$$z_o^n(t) = \min\begin{cases} z_1^n(t) = h(t) & \text{for } u_1 \\ z_2^n(t) = A + h(o) - Ag(t) & \text{for } u_2 \end{cases} \quad (2)$$

The first function $z_1^k(t)$ in relation (1) includes costs of regular maintenance and periodical repairs of t age machinery, carried out within the k-period [h(t)] and the corresponding minimum exploitation costs [$z_o^{k+1}(t+1)$] of the given machinery starting from k+1 period, as a momentum when it will be t+1 year old up to the end of the observed interval, under assumption that the machinery would not be replaced at the beginning of the k period. The second function $z_2^k(t)$ from relation (1) is based on replacement of machinery at the beginning of the k period and takes into consideration: the purchase value of new machinery (A), the costs of regular maintenance and periodical repairs of new machinery during the k period [h(o)], liquidation value of the replaced machinery t-years old [Ag(t)] and minimum exploitation costs of new machinery that at the beginning of the k+1 period would be one year old (t+1), established at the beginning of the k+1 period to the end of the n-period.

The contents of components from relation (2) is identical to the described one, but without additional minimum exploitation costs, as the last period from the observed interval is concerned.

The optimum solution is composed, in each period (k = 1, 2, …, n) of identification variables: u_1 and u_2 representing the policy of continuous exploitation of the given machinery even in the k-period (u_1), namely the policy of replacement of the existing by new machinery (u_2). In the first phase, during the procedure of conditional optimization, the optimum solution is found for each k-period (k = 1, 2,…, n) and within the same for each alternative age of machinery (t = 1, 2, ...) by the relation:

$$z_o^k(t) = \min\left[z_1^k(t), z_2^k(t)\right] \quad (3)$$

If $z_o^k(t) = z_1^k(t)$ in relation (3) then the management policy u_1 is announced the optimum one (for given k and t). Contrary to this, u_2 would be considered the optimum management policy (for given k and t) if $z_o^k(t) = z_2^k(t)$. In case $z_1^k(t) = z_2^k(t)$, the advantage of selecting is given to the management policy u_1.

Conditional optimization follows the direction that is opposite to the natural one, as it starts from the n and then through: n-1, n-2,…,2,1, and ends with the initial, first period of the observed interval.

The completion of the conditional optimization is proceeded by unconditional optimization. It is carried out in a natural direction starting from the first period. Within each period, the optimum management policy u_o^k is selected only on the basis of the corresponding age of machinery $u_o^k(t)$, so that the optimum strategy of machinery management is found out during the observed interval k = 1, 2, ..., n. The corresponding age of machinery in k period is equal to its age at the beginning of the k period (t = 0, 1, 2, ...). Connecting the machinery age with the corresponding period enables introduction of the following symbol

t_k – machinery age at the beginning of the k period

that represents the base for performing unconditional optimization. Finding out the optimum policy of machinery management during k period corresponds to its age t_k. Therefore, it is enough, within the process of unconditional optimization, to find out both the machinery age in the k-period (t_k) and the adequate managing policy $u_o^k(t_k)$ established during conditional optimization.

If the optimum, established at the beginning of the k period, the policy u_1 is determined

$$u_o^k = u_o^k(t_k) \to u_1 , \tag{4}$$

this facilitates the establishing of the corresponding policy in k+1 period, as the machinery age is determined at the beginning of this period

$$t_k + 1 = t_k + 1, \tag{5}$$

and therefore only $u_o^{k+1}(t_{k+1})$ is be found out.

If at the beginning of the k-period the policy u_2 is selected, it is considered at the same time that the replacement of the existing machinery by a new one is also done at the beginning of k-period and that during k-period a new machinery of zero age (t_k=0) would be used. It consequently resulted that at the beginning of k+1 period, according to relation (5) for t_k=0 the age of newly installed machinery would be one year.

The optimum strategy of machinery management during the observed interval, according to the above described, is composed of the set of mutually connected optimum management policies per periods taken by natural direction from the first to the last one.

$$u_o^1 \to u_o^2 \to \ldots \to u_o^k \to \ldots \to u_o^n \tag{6}$$

The selected optimum strategy provides formation of total minimum exploitation machinery costs during the observed interval.

A model with maximum criterion function: Let the production value, the given machinery could realize in each period, upon reduction of exploitation costs, be selected for the criterion of optimization. It is considered that the production value, marked by symbol p(t) depends only on machinery age, meaning that the machinery of the same age could provide the same production value in each period regardless its position within the observed interval. After all, such dependence is introduced for all types of costs in this part.

Recurrent functions are connected with the alternative policy of machinery management where the last period is divided from all previous periods. The first group of recurrent functions, contained in the relation

$$z_o^k(t) = \max \begin{cases} z_1^k(t) = p(t) - h(t) + z_o^{k+1}(t+1) & \text{for } u_1 \\ z_2^k(t) = Ag(t) + \left[p(o) - A - h(o)\right] + z_o^{k+1}(1) & \text{for } u_2 \end{cases} \tag{7}$$

holds for the first n-1 periods, where k = 1,2,…n-1, while the second group from the relation

$$z_o^n(t) = \max\begin{cases} z_1^n(t) = p(t) - h(t) & \text{for } u_1 \\ z_2^n(t) = Ag(t) + [p(o) - A - h(o)] & \text{for } u_2 \end{cases} \tag{8}$$

refers only to the last n-period. The economic interpretation of recurrent functions and their components, together with production values and optimization of contrary direction, do not differ from the quoted for the relations (1) and (2). The optimum solution, within conditional optimization, can be found by contrary directed relation (3), namely by the relation

$$z_o^k(t) = \max[z_1^k(t), z_2^k(t)], \ k = 1,2,..., n, \tag{9}$$

out of which results that the optimum policy would be determined:

u_1 if $z_o^k(t) = z_1^k(t)$ and if $z_1^k(t) = z_2^k(t)$,

u_2 if $z_o^k(t) = z_2^k(t)$.

The process of unconditional optimization remains unchanged and is completely equal to the one described in the previous variant of this model.

3. APPLICATION OF A MODEL WITH A LIMITED INTERVAL

The purpose of the following example is to illustrate the process of optimization and explain the presented concept of a model with a limited interval.

Table 1. (first part)

k	*t*	*h(t)*	*g(t)*	*A* = 600
				Ag (t)
1	0	30	1.00	600
2	1	40	0.80	480
3	2	52	0.62	372
4	3	66	0.48	288
5	4	80	0.34	204
6	5	95	0.26	156
7	6	115	0.18	108
8	7	145	0.12	72
9	8	190	0.08	48
10	9	250	0.05	30

Table 1. (second part)

n=10, *A + h(o)* = 600 + 30 = 630			
$z_1^{10}(t)$	$z_2^{10}(t)$	$z_o^{10}(t)$	$u_o^{10}(t)$
30	30	30	u_1
40	150	40	u_1
52	258	52	u_1
66	342	66	u_1
80	426	80	u_1
95	474	95	u_1
115	522	115	u_1
145	558	145	u_1
190	582	190	u_1
250	600	250	u_1

Let the producer estimates that the bulldozer may not be used, under usual working conditions at pit for longer than 10 years (n=10). The purchase value of a new bulldozer is $ 600 thousands. The costs of regular maintenance are estimated as well as the costs of periodical repairs h(t) for each period within the observed interval. The liquidation value Ag(t) for bulldozer is also calculated at the beginning of each period. All the initial elements of a model, contained in the first part of Table 1, are expressed in thousands of dollars.

Table 2.

k	t	h(t)	$z_o^{k+1}(t+1)$	$z_1^k(t)$	$z_2^k(t)$	$z_o^k(t)$	$u_o^k(t)$
9	0	30	40	70	70	70	u_1
	1	40	52	92	190	92	u_1
	2	52	66	118	298	118	u_1
	3	66	80	146	382	146	u_1
	4	80	95	175	466	175	u_1
	(5)	95	115	210	514	210	(u_1)
	6	115	145	260	562	260	u_1
	7	145	190	335	598	335	u_1
	8	190	250	440	622	440	u_1
8	0	30	92	122	122	122	u_1
	1	40	118	158	242	158	u_1
	2	52	146	198	350	198	u_1
	3	66	175	241	434	241	u_1
	(4)	80	210	290	518	290	(u_1)
	5	95	260	355	566	355	u_1
	6	115	335	450	614	450	u_1
	7	145	440	585	650	585	u_1
7	0	30	158	188	188	188	u_1
	1	40	198	238	308	238	u_1
	2	52	241	293	416	293	u_1
	(3)	66	290	356	500	356	(u_1)
	4	80	355	435	584	435	u_1
	5	95	450	545	632	545	u_1
	6	115	585	700	680	680	u_2
6	0	30	238	268	268	268	u_1
	1	40	293	333	388	333	u_1
	(2)	52	356	408	496	408	(u_1)
	3	66	435	501	580	501	u_1
	4	80	545	625	664	625	u_1
	5	95	680	775	712	712	u_2
5	0	30	333	363	363	363	u_1
	(1)	40	408	448	483	448	(u_1)
	2	52	501	553	591	553	u_1
	3	66	625	691	675	675	u_2
	4	80	712	792	759	759	u_2
4	0	30	448	478	478	478	u_1
	1	40	553	593	598	593	u_1
	2	52	675	727	706	706	u_2
	(3)	66	759	825	790	790	(u_2)
3	0	30	593	623	623	623	u_1
	1	40	706	746	743	743	u_2
	(2)	52	790	842	851	842	(u_1)
2	0	30	743	773	773	773	u_1
	(1)	40	842	882	893	882	(u_1)
1	(0)	30	882	912	912	912	(u_1)

The process of conditional optimization, based on the usage of relation (2), started from the last period (n=10) (the second part of Table 1) and concluded with the first period (k=1), Table 2. For each of these periods the value of auxiliary functions $z_1^k(t)$ and $z_2^k(t)$, was calculated and then, by their comparison based on relation (3) the corresponding management policy during the given period for each alternative of machinery age is established. Establishment of values of auxiliary functions is a simple process requiring no additional explanation. But, it should be noted that the unchanged value of each component $A+h(o)+z_o^{k+1}(1)$ for k-period ($k \leq n-1$) from the auxiliary function $z_2^k(t)$ of the relation (1) is given in Table 3.

Table 3.

k	$A+h(o)+z_o^{k+1}(1)$	Optimum Strategy		$t_k + 1 = t_{k+1}$
		$u_o^k = u_o^k(t_k) \rightarrow$	Costs	
1	630+882=1512	$u_o^1 = u_o^1(o) \rightarrow u_1$	30	0 + 1 = 1
2	630+743=1373	$u_o^2 = u_o^2(1) \rightarrow u_1$	40	1 + 1 = 2
3	630+593=1223	$u_o^3 = u_o^3(2) \rightarrow u_1$	52	2 + 1 = 3
4	630+448=1078	$u_o^4 = u_o^4(3) \rightarrow u_2$	342	0 + 1 = 1
5	630+333=963	$u_o^5 = u_o^5(1) \rightarrow u_1$	40	1 + 1 = 2
6	630+238=868	$u_o^6 = u_o^6(2) \rightarrow u_1$	52	2 + 1 = 3
7	630+158=788	$u_o^7 = u_o^7(3) \rightarrow u_1$	66	3 + 1 = 4
8	630+92=722	$u_o^8 = u_o^8(4) \rightarrow u_1$	80	4 + 1 = 5
9	630+40=670	$u_o^9 = u_o^9(5) \rightarrow u_1$	85	5 + 1 = 6
10		$u_o^{10} = u_o^{10}(6) \rightarrow u_1$	115	
		Total	912	

The process of unconditional optimization is presented in Table 3, while rounding the element is marked in Tables 1 and 2. As the first period (k=1) started with the usage of a new machinery (t_0=0), it was found that this machinery should be permanently used during the first, second and third periods, as $u_o^k = u_1$ for k=1,2,3. The optimum solution shows that at the beginning of the fourth period replacement of machineries should be done and that during the fourth and all the subsequent periods the management policy u_1 should be used. The optimum management machinery strategy according to periods from the observed intervals is written by a series of optimum decisions taken from Table 3.

$$u_o^1 \rightarrow u_o^2 \rightarrow \dots \rightarrow u_o^{10} = u_1 \rightarrow u_1 \rightarrow u_1 \rightarrow u_2 \rightarrow u_1 \rightarrow u_1 \rightarrow u_1 \rightarrow u_1 \rightarrow u_1 \rightarrow u_1$$

Minimum costs of machinery exploitation during the observed interval amount to 912 thousands of dollars (the bottom line in Table 2). The itemized structure of these costs, given in Table 3, shows that they represent the costs of regular maintenance and regular repairs in all the periods except the fourth one. During the fourth period, the value of the corresponding costs amounts to 342 thousands of dollars and consist of: the purchase value of new machinery amounting of 600 thousand dollars, the costs of regular maintenance and periodical repairs of new machinery amounting to 30 thousands of dollars and adequate liquidation value for the replacement of old machinery at the beginning of the fourth period amounting to 288 thousands of dollars (600+30-288=342).

There exists no other different optimum solution that should, under the same exploitation conditions provide less value of total exploitation costs than 912 thousands of dollars and therefore the mentioned optimum strategy of machinery management should be accepted.

4. CONCLUSION

The optimum solution aimed for exploitation of machinery life, obtained in the described manner, should not be directly recommended for accepting and application to the management of a mining company. It is required primarily to carry out the overall economic analysis that includes the analysis of sensitivity, analysis of efficiency and the analysis of variability of the optimum solution.

The analysis of sensitivity should provide answers to two questions: whether the optimum momentum of machinery replacement is sufficiently reliable and whether all the required conditions for its realization could be secured.

The analysis of efficiency should cover the business effects before and after machinery replacement, while the analysis of variability includes two areas: the analysis of stability of the optimum solution according to the change in model elements, and the analysis of variability of the optimum solution due to the changes of model parameters values.

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