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Optimal planning of extracting works at the quarries of non-ferrous metallurgy of Kazakstan

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Almost all the ore deposits of ferrous, non-ferrous and rare metals of Kazakstan, are exploiting by the open-cast method, are the complex-structural, multi-component ones. Their rational working requires precise organization of extracting works. In this connection it is necessary to set up the best intercommunications between drilling-blasting, excavating-loading and transport works. This requires the stable functioning of the quarry for dispatch of ore raw material of required quality with minimum of corresponding expenses.

For this purpose, proceeding from the quarry's ore output and the assumed parameters of the exploitation system, the first problem about rational arrangement of excavating-loading equipment in extracting faces is solved. By solving the problem the model with dynamic, adapting properties had been used. It was solved numerically by the method of statistical tests. By setting up the necessary link between type-sizes of excavating-loading and transport equipment, the minimum prime cost of loading and transportation of 1 ton of mining mass from the face to the receiving station was adopted as the criterion of optimality.

Depending on the type of excavating-loading equipment, the efficiency function may be different. By using wheel loaders, their displacement between the faces is possible, therefore, the efficiency function of the problem may include expenses for their displacement. By using excavators like power shovel, the problem's restrictions must exclude its displacement between the faces. The efficiency function consists of minimum expenses for loading, proceeding from set of volumes of extraction from the faces, satisfying required quality.

The volumes of extraction from the faces, satisfying required quality of ore in output stream, are determined by the method of statistical tests. Sample range is given, proceeding from the restrictions for maximum productivity of the excavating-loading equipment. Volumes of extraction, not satisfying required quality, are cut off. The efficiency function meaning is then determined and minimized.

Keywords: Excavating-loading equipment, its placing in extracting faces, optimal load-carrying capacity, specific expenses for loading and transportation of mining mass.

Discussion and new observations

Optimization of extracting works technology at the complex-structural, multi-component deposits is possible by the establishment of a set of technological solutions, that would ensure minimum of expenses for extraction and reaching of demanded quality of ore.

The following questions are considered: the rational placing of excavating-loading equipment (ELE), determination of optimal load-carrying capacity of transport means by prescribed productivity of ELE, distribution of load on extracting faces and minimization of the cost of excavating-loading and transportation works by reaching preset quality of ore in necessary volume. The sequence of examined problems is shown at the Figure 1.

ELE placing in extracting faces. Proceeding from the quarry's productivity on ore and adopted parameters of expoitation system, first the problem of rational placing of excavating-loading equipment in extracting faces is solved. Technical characteristics and economic indices of work of excavators, loaders and bulldozers were given. Equipment placing must provide minimum expenses for realization of works preset volume.

The problem statement. In extracting works of quarry the equipment of p types is used, the total amount of every type is N_j (j=1,...,q). Productivity of every unit P_j of equipment differs at every i-th section. Planned volume of work V_i at the i-th section, work resource R_j of the j-th unit of equipment for the planning period, cost of machine-shift C_j of the j-th equipment are known.

Total expenses for equipment work on the unit of dispatched raw material during the planning period are made up of expenses of all the types of equipment at every section and may be adopted as the criterion of efficiency (optimality), i.e.

$$W = \sum_{i=1}^{n}\sum_{j=1}^{q} N_{ij} \cdot \frac{C_j}{P_{ij}} \rightarrow \min. \qquad [1]$$

During the problem solving the following constraints must be kept:

On the works volume (planning volume at every section must be carried out)

$$\sum_{j=1}^{q} V_{ij} = V_i; \qquad [2]$$

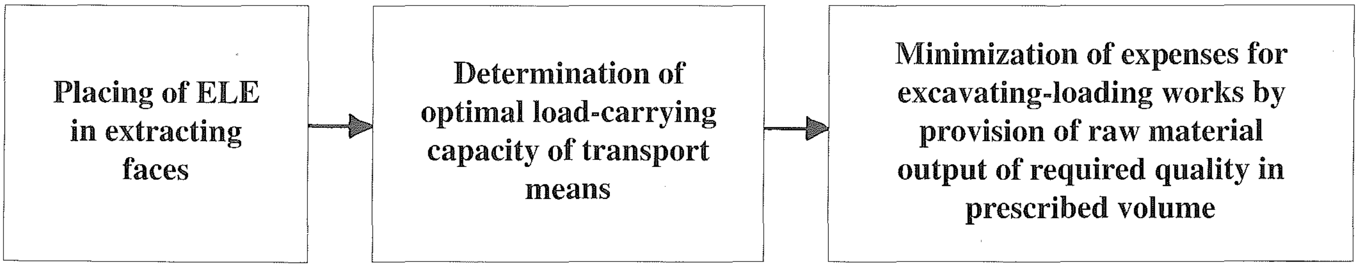

Figure 1. The problems of extracting works

on possible resources of work of equipment of different type

$$\sum_{i=1}^{n} N_{ij} \le N_j P_j, \left(j = \overline{1,q}\right), \qquad [3]$$

constraints on equipment quantity

$$\sum_{i=1}^{n} N_{ij} \le N_j, \left(j = \overline{1,q}\right). \qquad [4]$$

The problem solving in research[2] had been obtained by the method of dynamic programming. In this paper the algorithm of the problem solving by the method of random search, based on the Monte Carlo method, is proposed.

The algorithm of the problem solving may be divided into the following stages:

- *Input of initial data.* The random quantities, defining amount and type of ELE at the first section, are drawn consecutively. Sample range is assigned, based on the constraints [2–4] and on the possibility of the given equipment placing at the section. The obtained values are subtracted from the initial amount of ELE of corresponding type. The remaining amount of ELE is used for drawing of random quantities, defining the amount and type of ELE at the second section and so on until the final distribution of equipment among all the extracting sections.
- *The obtained combinations are checked* against the constraints [2–4], needless variants are cut off.
- *The criterion [1] value is determined* and its minimum is found by the method of consecutive comparison in-pairs of obtained values.

The sequence of operations, shown above with the exception of input of initial data, is carried out in a cycle with the test amounts, depending on the amount of the faces and types of ELE and is determined by the known formulae according to Rakishev[2]. Optimal plan of ELE placing includes the type and quantity of equipment at every section, ELE productivity and also the cost of excavating-loading works during the considered sub-period.

Let's take the problem from research[1] as an example. There are three extracting sections in the quarry and equipment of different types, characteristics and quantities are shown in the Table I. Planning volume by sections during the shift is 2500 m[3] on the first section, 1500 m[3] on the second and 2000 m[3] on the third one.

Because of technical conditions it is possible to use no more than two units of ELE at the first and second sections, at the third one—no more than three units. Calculations are realized according to the afore-cited algorithm. The part of combinations of the equipment placing, satisfying the problem constraints, and corresponding values of the criterion [1] are shown in the Table II. Variant of optimal placing of ELE is marked out by bold type.

The following ELE placing corresponds to minimum value of criterion 0,3532: the 1st section—one excavator ECG-5 and one loader PK-15, (ELG-5 is the mark of an excavator with the bucket's volume 5 m[3], PK-15 is the single-bucket loader with the load carrying capacity 15 t.) Tthe 2nd section—one loader PK—15, the 3rd section——two excavators ECG-8. One excavator ECG-4,6 remains in reserve. The identical result had been obtained by the method of dynamic programming in research[2], which corroborated the correctness of the chosen method.

Determination of optimal load-carrying capacity of transport means.

By determination of the necessary ratio between type-sizes of excavating-loading and transport equipment, the minimum prime cost of loading and transportation of 1 ton of mining mass from the face to the receiving station was adopted as the criterion of optimality, i.e.

$$C = C_{ec} + C_{tr} \to \min, \qquad [5]$$

where C_{ec}, C_{tr} are specific expenses for loading and transportation of mining mass correspondingly.

Determination of optimal ratio of the transport unit load-carrying capacity to the rock mass in excavator bucket is expedient to realize, using shift productivity of loading-transport complex according to Rakishev[3]. After transformation of the known correlations, the dependence of specific expenses for loading-transport works on the ratio of the transport unit load-carrying capacity to rock mass in the excavator bucket will take a form:

$$\left[C_{m.e} + a\left(q_e\xi\right)^b\right] T_c \xi + \left[C_{m.e} + a\left(q_e\xi\right)^b\right] \frac{t_{ex} + a\left(q_e\xi\right)^b T_r}{60 k_\ell q_e k_q t_{sh} \xi} \to \min, \qquad [6]$$

where $C_{m.e}$ – the cost of machine-shift of the chosen excavator under the given conditions, US dollars;

T_c – average duration of excavating cycle under the given conditions, min

t_{ex} – time of tip-lorry (locomotive-train) exchange, min

T_r – time of tip-lorry run with the exception of loading-exchanging operations, min

k_q – coefficient of use of transport load-carrying capacity (0,95–1,0)

k_l – coefficient of productivity lowering, caused by unevenness of loading-transport operations ($k_\ell \le 1$)

q_e – rock mass in the excavator bucket, *t*

Table I
Characteristics of the equipment types

ELE type	Shift productivity on the sections, m^3			Amount of ELE, pieces	Cost of machine-shift, US dollars	Time resources, shifts
	1st	2nd	3rd			
ECG-5	1500	1300	1000	2	100	400
ECG-8I	2000	1700	1500	2	120	400
PK-15	1900	1600	1300	2	110	500

Table II
Random combinations of ELE placing, satisfying the constraints of the problem

No.	The 1st section			The 2nd section			The 3rd section			W, US$
	ECG-5	ECG-8	PK-15	ECG-5	ECG-8	PK-15	ECG-5	ECG-8	PK-15	
1	1	1	0	0	0	1	1	1	1	0.46
2	0	1	1	0	1	0	2	0	1	0.473
3	2	0	0	0	1	1	0	1	1	0.437
4	**1**	**0**	**1**	**0**	**0**	**1**	**0**	**2**	**0**	**0.353**
5	0	2	0	1	0	1	1	0	1	0.45
795	1	0	1	0	1	0	1	1	1	0.46
796	0	2	0	0	0	1	1	0	1	0.373
797	0	1	1	2	0	0	0	1	1	0.436
798	1	1	0	0	1	0	1	0	2	0.466
799	2	0	0	0	0	1	0	2	1	0.447
800	2	0	0	0	1	0	0	1	1	0.369

$\xi = q_t / q_e$ – ratio of transport unit load-carrying capacity to rock mass in the excavator bucket

q_t – load-carrying capacity of locomotive-train or tip-lorry, t; (locomotive-train is the train, consisting of 5 vans)

a, b – the coefficients of power function $C_{m.t}=aq_t^b$. This function is the cost of machine-shift of the transport unit and depends on load-carrying capacity q_t, US dollars.

Optimal ratio between the transport unit load-carrying capacity and rock mass in the excavator bucket (ξ_{opt}), calculated by the proposed Formula [6] for the complex of excavator-tip-lorry, is changed within 5–7 and for the complex of excavator—locomotive-train—within 25–35.

Minimization of expenses for excavating–loading works by provision of raw material output of required quality in prescribed volume.

The problem of raw material quality stabilization is proposed to solve jointly with minimization of loading and transportation works cost by reaching of prescribed volume of output. Let there be N extracting faces (blocks of exploded mining mass), G consumers of raw material in the quarry. Volumes of ore in every block $V_{bl\,i}$, quality of ore in the face depending on the time (excavated volume) ψ_{tij}, planned quality ψ_{bj}, its permissible deviation $\Delta\psi_j$, content of harmful components in dispatched ore ψ_{hj}, planned content of harmful components ψ_{bhj} are known. The constraints on the quality of ore are the following:

$$\left|\psi_{tij} - \psi_{bj}\right| \le \Delta\psi_j, \qquad [7]$$

$$\psi_{hj} \le \psi_{bhj}. \qquad [8]$$

It is necessary to put together an optimal plan of dispatch and transportation of ore of preset quality from the i-th face to the g-th consumer, which provides a minimum of expenses for transportation by the known cost of transportation of raw material volume unit C_{ig} for the planned period T. Efficiency function of the problem will be written in form:

$$W_{Lt} = \sum_{i=1}^{N}\sum_{g=1}^{G} c_{ig}V_{ig} + \sum_{i=1}^{N}\sum_{g=1}^{G} N_{ip}C_p \rightarrow \min, \qquad [9]$$

by the following constraints:

- total productivity of the faces in every sub-period must be no less than the target of the quarry during the same time
- volume of output during the whole planned period in the i-th face mustn't exceed ore resources in this face

$$\sum_{t=1}^{T} V_{ti} \le V_{bi}; \qquad [10]$$

- total volume of ore output during the sub-period must comply with the requirements of concentrating mill (CM) and storehouse for ores mixing (SOM)

$$\sum_{i=1}^{N} V_{ti} = \sum_{g=1}^{G} S_{tg}, \qquad [11]$$

where $\sum_{g=1}^{G} S_{tg}$ -requirements of CM and SOM in the t-th sub-period;

- total volume of ore output during the sub-period can't exceed receiving capacity of CM (SOM).

The constraints [3–4] are correct also.

The proposed algorithm of such problem solving envisages application of the method of random search.

Algorithm of the problem solving may be divided into the following stages:

- The result, obtained by solving of the problem on ELE placing in extracting faces (see above), is adopted as initial variant of ELE placing. Furthermore with taking into account of the loaders' mobility and constraints [3–4, 10–11], algorithm of solving of the problem on ELE placing in extracting faces is used for defining of optimal variant on the one shift.

- With a help of random number generator the sets of volumes of ore extraction from the faces are determined. These volumes satisfy the constraints on productivity of the faces and all the quarry as a whole by taking into account of obtained placing of ELE.
- The obtained set is checked against the constraints [7, 8]. All the constraints are joined into the one with a help of the operator of logical multiplication (AND). The obtained set of random volumes of output from the faces satisfies the constraints on productivity as well as on quality.
- Every volume of extraction from the face, checked against the pointed constraints, is divided into parts in proportion to consumers amount. Proportions are determined according to the weighting fraction of each consumer in planned volume of consumption (output) for the subperiod. As the result we have the new set of random volumes of extraction from the faces, corresponding to consumers amount and satisfying constraints on productivity and quality as well as on providing the requirements of CM and SOM.
- Expenses for dispatch are determined by multiplying the obtained volumes by the dispatch cost. Expenses for transportation are determined analogically. The criterion [9] value is calculated and minimized. The optimal variant is defined.
- Transfer to the next sub-period. By summing up the prime cost for sub-periods one can obtain the results throughout all the period, i.e.

$$W_T = \sum_{t=1}^{T} W_{Lt}$$

Let's examine the method application on an example of defining the optimal ore-stream during 5 shifts. The sum of volumes of extraction from the faces is equal to CM (SOM) requirement. In the quarry there are four extracting faces, from which ore is dispatched for CM (SOM). Characteristics of ores on the faces during the planned period are shown in the Table III. The first numbers in the column correspond to zinc; the second ones, to lead; the third ones-to sulfur.

Data on average content of the components have been taken from research[3]. Quarry's productivity on ore must be no less than 3600 m^3. Requirements of CM and SOM—no less than 3000 m^3 and 600 m^3 correspondingly. Demands to ore quality are: $\psi_{b\ pb}$=1.5 per cent (planned content of lead in ore); $\Delta\psi_{pb}\leq 0.1$ per cent (permissible deviation of lead content from the planned one); $\psi_s = \leq 5$ per cent (permissible content of sulphur in ore); ψ_{bZn}=3.,0 per cent (planned content of zinc in ore); $\Delta\psi_{Zn}\leq 0.1$ per cent (permissible deviation of zinc content from the planned one). Expenses for ore volume unit transportation are shown in the Table IV.

Receiving capacity of CM bunkers is 4000 m^3 during the shift. In Figure 2 the fragment of picking-out of combinations of loads for the faces, corresponding to required quality of ore, is shown. The test quantities lay off as abscissae, content of components plots the ordinate (the curve 1 for S, the curve 2 for Zn, the curve 3 for Pb). In the Table V (V—volumes of dispatched ore, m^3) the plan of ore-transportation for 5 shifts is shown. It satisfies all the constraints by minimum expenses for transportation. In the numerator the volumes of dispatch for CM are given, in denominator—for SOM. The variation of average content of the components in the ore-stream during the planned period is shown in Figure 3.

The analysis of results shows that the ratio of maximum value of the criterion to the minimum one for the considered there-component ore-stream is an average 8–10 per cent, and a saving of means -4–5 per cent. The considered algorithm operates in cycle and doesn't store multi-size files. The calculation of a monthly plan on the major component using 5000 tests during one shift takes 8 sec. on a Pentium III computer. It is realized in the language of visual modelling VisSim. (It is the programming system for the processes simulation.)

The proposed model takes into account as well as changing mining-technological and economic conditions, serves as a means of active control by inside-quarry averaging of ores and obtaining of raw material of the required quality during the planned period[4]. The elaborated variant of the variant of the algorithm is very simple, universal, and is free of rigid restrictions for application. Due to the impossibility of obtaining precise solutions, the

Table III
Content of the components (Zn/Pb/S) in ore (%) on the faces during the planned period

Sections	Shifts				
	1st	2nd	3rd	4th	5th
1st	3.7/1.2/4.6	4.4/1.4/5.1	4.0/2.1/4.8	3.7/2.3/4.2	3.7/1.9/5.1
2nd	2.1/2.0/5.8	1.9/2.0/5.6	2.2/1.2/6.3	1.8/1.0/6.2	1.9/1.3/6.1
3rd	3.4/1.3/3.4	3.5/0.9/3.4	2.8/1.4/3.1	3.6/1.1/3.0	3.5/1.0/3.1

Table IV
Expenses for transportation of ore volume unit from the supplier to the consumer

Suppliers	Resources of the section, m^3	Consumers	
		CM (US$)	SOM (US$)
1st section	25000	0.5	0.3
2nd section	30000	0.35	0.2
3rd section	30000	0.3	0.1

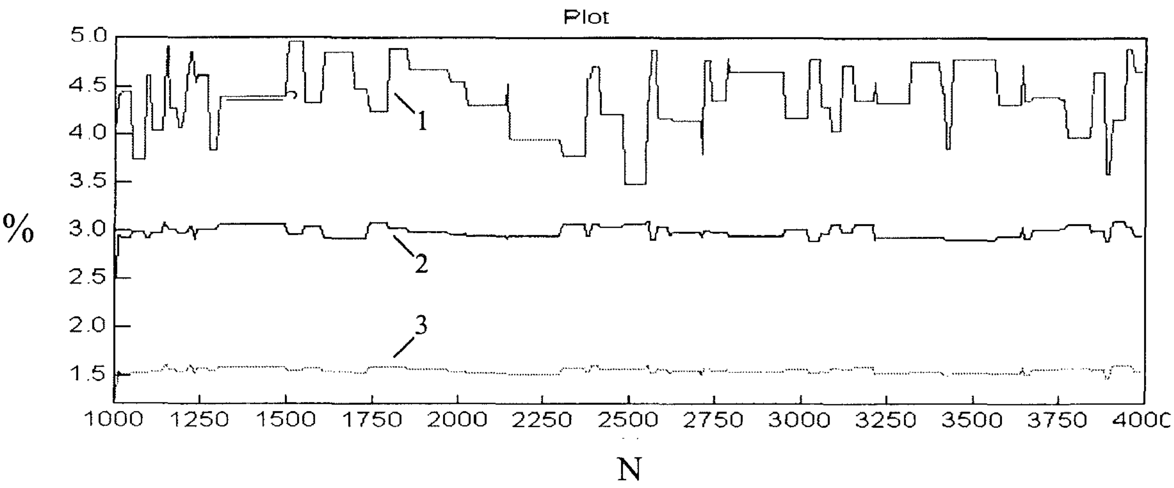

Figure 2. Fragment of combinations, satisfying the required quality of raw material with providing of the required volume of output

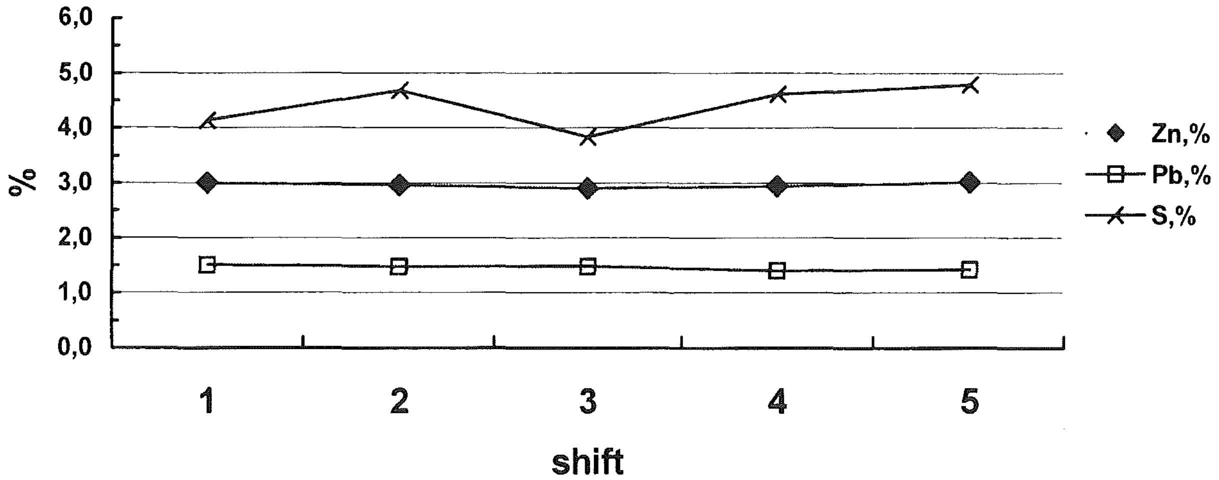

Figure 3. Variation of average content of the components in ore-stream (Shift - quantities lay off as abscissae, content of components plots on the ordinate)

Table V
Plan of ELE placing, dispatch and ore-transportation during 5 shifts

Sections	Shifts									
	1st		2nd		3rd		4th		5th	
	V, m3	ELE, pieces	V, m3	ELE, pieces	V, m3	ELE, pieces	V, m3	ELE, pieces	V, m3	ELE, pieces
1-st	20 4	1-ECG-5	594 118	1-PK-15	506 101	1-PK-15	882 176	1-ECG-5	1078 215	1-ECG-5
2-d	930 186	1-PK-15	1328 26	1-PK-15	437 87	1-PK-15	1202 240	1-PK-15	1027 205	1-PK-15
3-d	2085 417	2-ECG-8	1120 224	1-ECG-8	2056 411	2-ECG-8	937 187	1-PK-15	896 1179	1-PK-15
Zn, %	3.00		2.97		2.91		2.95		3.02	
Pb, %	1.51		1.48		1.49		1.41		1.43	
S, %	4.14		4.69		3.85		4.62		4.8	
Criterion value	1492		1549		1572		1582		1611	

proposed numerical method gives the set of solutions the most similar to the searched one.

Conclusions

- The optimum relation between the load-carrying capacity of the transport unit and the weight of rock in the excavator bucket, calculated by proposed procedure, varies between 5 and 7 for the excavator-tip-lorry complex and between 25 and 35 for the excavator-locomotive-train complex. This relation is used to determine the necessary amount of major mining and transport equipment and to calculate corresponding capital and operating expenses.

- Calculations show that the model application allows for reduction in expenses for ore and its dispatch and transportation by 8–12 per cent by exploitation of the complex-structural multi-component deposits.
- The elaborated variant of the algorithm is very simple, universal, free from rigid restrictions for application. The last ones are usual for the methods of linear and non-linear programming. When precise solution couldn't be obtained, the proposed numerical method gives a set of solutions, most approximate to the sought one.

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