On the problem of vehicles assignment in the conditions of open-cast mining

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Abstract. The problem of optimal truck-excavators assignment is considered. A new objective function is offered, which takes into account the performance of a given amount of work and the capacity of each truck and excavator. Different solutions are offered and an example of a problem solution is provided.

1. Introduction

The basic technological processes that accompany the open-cast mineral deposits development are: mining, capping (including organization and performance of blasting works), ancillary work (including re-excavation, trimming, stacking, etc.), reclamation. Almost all of these works are carried out with the use of excavators. Often mined minerals and rocks are removed by means of auto truck transportation. Of course, there are non-transport technologies and railway transportation. However, in the conditions of open-casts mining in Kuzbass Coal Basin the motor transport of coal and rock is used most often.

Given the need to reduce production costs, the solution to the problem of optimal trucks assignment for transportation of extracted minerals and overburden rocks will improve the economic efficiency of the mining enterprise. Moreover, it should be understood that the planning and management of technological production processes are now reaching a new level of responsibility – decisions taken on the basis of professionalism and engineering intuition, are ineffective because they do not take into account a number of opposing factors. To solve such problems it is necessary to use formal methods which can be well implemented with the help of computers.

2. Optimization criterion

Problems of this type belong to the class of allocation tasks and are solved by the use of linear programming methods. In [1-3] several approaches to solution of this class of problems in mining industry are considered. They are based either on the strategy of minimization of the cost for implementation of the specific scope of work, or on the strategy of maximization of the performed amount of work using the available equipment. However, in practice, the situation is different – it is needed to execute the planned volume of mining, overburden or other work during the the planning period (for example, one shift or one month).

Deviation from the specified scope of work can be taken as an optimization criterion:
\[ \Delta W = \sum_{j=1}^{M} \left| W_j^* - \sum_{i=1}^{N} k_{ij} \cdot W_{ij} \right| \rightarrow \text{min} \]  

(1)

where:
- \( W_j^* \) – the planned work load for one month for the \( j \)-th excavator, \( j \) – type of an excavator, [m\(^3\)/month];
- \( W_{ij} \) – the work load of the \( i \)-th truck during the work with the \( j \)-th excavator, \( i \) – type of the truck, \( i \in N \), [m\(^3\)/month], and is defined by the formula:

\[ W_{ij} = k_{ij}^{TR} \cdot k_{ij}^{EU} \cdot G_i \cdot \frac{V_{ij}}{L_{ij}} \cdot K^{(i)} \]  

(2.1)

or

\[ W_{ij} = k_{ij}^{TR} \cdot k_{ij}^{EU} \cdot H_{ij} \cdot K^{(ii)} \]  

(2.2)

where:
- \( k_{ij}^{TR} \) – technical availability coefficient of the \( i \)-th truck, \( k_{ij}^{TR} \in [0;1] \) [share units]; technical availability coefficient of the planning period can be determined from the results of the enterprise work for the period prior to the planned one;
- \( k_{ij}^{EU} \) – fleet utilization coefficient is the degree of utilization of the \( i \)-th truck during the work with the \( j \)-th excavator for the planning period. Here it is determined as a percentage of \( k_{ij}^{TR} \):
  \[ k_{ij}^{EU} = \frac{D_{ij}^{TU}}{D_{ij}^o} \]  

where \( D_{ij}^{TU} \) – the amount of days of the \( i \)-th truck being in the operative condition, \( D_{ij}^o \) – the amount of operation days of the \( i \)-th truck working with the \( j \)-th excavator; the fleet utilization coefficient for the planned period can be determined from the results of the enterprise work for the period prior to the planned;
- \( G_i \) – mined rock volume, transported by the \( i \)-th truck, [m\(^3\)];
- \( V_{ij} \) – average speed of the \( i \)-th truck, [km/h] (here not only the speed of movement is taken into account, but also the time of loading and unloading the truck when working with the \( j \)-th excavator, and also the complexity of the road profile and road conditions);
- \( L_{ij} \) – distance of the mined rock transportation by the \( i \)-th truck from the \( j \)-th excavator, [km];
- \( K^{(i)} \) – conversion factor for the reduction to a single dimension of the planning period, for example: for the monthly planning \( K^{(i)} = 720 \) h;
- \( H_{ij} \) – production rate of the \( i \)-th truck for transportation of the mined rock when using \( j \)-th excavator, [m\(^3\)/shift];
- \( K^{(ii)} \) – conversion factor for the reduction to a single dimension of the planning period, for example: for the monthly planning \( K^{(ii)} = 60 \) shifts of 12 hours.

1. \( k_{ij} \) – indication of using the \( i \)-th truck during the work with the \( j \)-th excavator, can be:
   - \( k_{ij} = 0 \), if the \( i \)-th truck does NOT work with the \( j \)-th excavator,
\( k_{ij} = 1 \), if the \( i \)-th truck operates with the \( j \)-th excavator.

Besides, the following restrictions apply for \( k_{ij} \):

- with any excavator more than one truck can operate:
  \[ \sum_{j=1}^{M} k_{ij} \geq 1, \]
- any truck can be operated with only one excavator:
  \[ \sum_{i=1}^{N} k_{ij} \leq 1, \]

- choosing the initial values \( k_{ij} \), the conditions of compliance of certain truck models for the work with specific models of excavators must be taken into account (these ratios are set constants and are not changed further for the solution of the optimization problem).

Also non-negativity condition of variables should be kept, that is:

\[ W_{ij}^* > 0, \quad W_{ij} > 0, \quad G_{ij} > 0, \quad V_{ij} > 0, \quad L_{ij} > 0. \]

When using this optimization criterion (1) in the MES-systems [4] it is convenient to use formula (2.1), which explicitly involves the average speed of trucks movement. Information about the average speed can be obtained automatically from satellite vehicle tracking systems used on the open-cast mines.

Formula (2.2) is used in the case if it is impossible to obtain information on the actual average trucks speed, and at the mining enterprise the norms for transportation of the mined rock are used.

The presented optimization criterion (1) does not take into account the types of material to be transported. If the output norms for transportation of different types of the mined rock (coal, rock piles and diluted run rock mass) are significantly different from each other, then the formula (1) is represented as follows:

\[
\Delta W = \sum_{j=1}^{M} \left| \sum_{b=1}^{B} W_{bj}^* - \sum_{i=1}^{N} k_{ij} \cdot W_{ij} \right| \rightarrow \min 
\]  

(1.1)

where: \( W_{bj}^* \) – the planned amount of work for a month for the \( j \)-th excavator with \( b \)-th rock mass type, \( j \) – type excavator, \( j \in M \), \( b \) – rock mass type, \( b \in B \), [m\(^3\)/month]. In this case formula (2.2) also can be represented as follows:

\[
W_{ij} = k_{ij}^{TR} \cdot k_{ij}^{EU} \cdot \sum_{b=1}^{B} (H_{b,ij} \cdot K_b^{(III)})
\]  

(2.3)
where: $H_{bij}$ – the $i$-th truck output norm for transportation of the $b$-th mined rock type when using $j$-th excavator, [m$^3$/shift]; $K_{b}^{(III)}$ – the estimated number of shifts for transportation of the $b$-th mined rock type.

Furthermore, this problem, in general, is open, since the total performance does not match the excavator trucks performance:

$$\sum_{j=1}^{M} W_j^{*} \neq \sum_{j=1}^{M} \sum_{i=1}^{N} k_{ij} \cdot W_{ij}.$$ 

Thus, it is necessary to make it a closed problem. If the trucks production capacity is higher, then it can be done either by introducing a fictitious excavator (in this case, unclaimed trucks would not be used in the process), or by changing the trucks operating conditions (for example, if the open-cast mine has several dumps then some trucks can be assigned to transport the rock to the remote dumps, i.e. $L_{ij}$ increases). If the excavators production capacity is higher, then the fictitious trucks are introduced into the problem condition (in other words, the question of attracting additional production capacity during the planning period is solved), or the problem of organization concerning the excavator is solved (e.g. at the excavator is a subject of scheduled preventive or other repair works).

Before making the calculations it is necessary to determine the fundamental ability to perform the job by the excavators available. You can use the formula for determining shift productivity of the excavator [2]:

$$W_{bj} = \frac{3600 \cdot G_{bj}^{K} \cdot k_{bj}^{E} \cdot k_{bj}^{EU}}{T_{bj}^{C}} \cdot T^{SH}$$

(3)

where: $W_{bj}$ – shift productivity of the $j$-th excavator with the $b$-th mined rock type, $j$ – type excavator, $j \in M$, $b$ – mined rock type $b \in B$ [m$^3$/shift];

$G_{bj}^{K}$ – bucket capacity of the $j$-th excavator, [m$^3$];

$k_{bj}^{E}$ – excavation rate of the $b$-th mined rock type [share units];

$k_{bj}^{EU}$ – utilization coefficient of the $j$-th excavator during the shift, [share units];

$T_{bj}^{C}$ – duration of the excavation cycle of $b$-th mined rock type [s];

$T^{SH}$ – shifts duration, [hour].

Comparison of $W_{bj}$ and $W_{bj}^{*}$ will show either a fundamental opportunity to perform excavation plan $\left( \sum_{j=1}^{M} W_{bj} \geq \sum_{j=1}^{M} W_{bj}^{*} \right)$, or inability to perform with the existing equipment $\left( \sum_{j=1}^{M} W_{bj} < \sum_{j=1}^{M} W_{bj}^{*} \right)$.

The functional structure of the model is shown in the Figure 1.
By varying signs of equipment utilization $k_{ij}$ the minimization of the objective function $\Delta W$ can be achieved. For example, the potential method can be used for this purpose, which is a modification of the simplex method for solving linear programming problems with regard to the transport problem.

3. An example of solving the problem of trucks assignment

Consider the example of solving the problem. Suppose two excavators operate at the open-cast mine: EKG-5A (bucket capacity 5 m$^3$) and Komatsu PC1250 (bucket capacity 6 m$^3$). Suppose according to the terms of mining the excavators are to extract the mined rock in the amount of 700 thousand m$^3$ (200 thousand m$^3$ and 500 thousand m$^3$, respectively) a month. The motor depot of the mining enterprise has 10 trucks: 3 trucks BelAZ 7555B (body capacity 22 m$^3$), 3 trucks Komatsu HD 785-7 (body capacity 60 m$^3$), 4 trucks Volvo A35F (body capacity 20 m$^3$). It is necessary to assign trucks if a unit have the following characteristics (Table 1). For simplicity of calculations we specify the performance characteristics of the trucks and their makes.

| Characteristics | BelAZ 7555B | Komatsu HD 785-7 | Volvo A35F |
|----------------|-------------|-----------------|------------|
| EKG-5A        | PC1250      | EKG-5A          | PC1250     |
| PC1250        |             | PC1250          | PC1250     |
The calculations made with the help of Microsoft Excel tool “Search solution” (Table 2) showed that the deviation from the plan is less than 1%. For the plan implementation it is sufficient to use 8 trucks. The remaining trucks can be left in reserve, for example, or to recalculate the problem by increasing the transportation distance of the mined rock.

**Table 2. Calculation results.**

| Trucks               | Excavators       | Result  |
|----------------------|------------------|---------|
| BelAZ 7555B No. 1    | EKG-5A 1         | Assigned|
| BelAZ 7555B No. 2    | Komatsu PC-1250 0| Not assigned|
| BelAZ 7555B No. 3    | 0                | Assigned|
| Komatsu HD 785-7 No. 1| 0                | Assigned|
| Komatsu HD 785-7 No. 2| 0                | Assigned|
| Komatsu HD 785-7 No. 3| 0                | Assigned|
| VolvoA35F No. 1      | 0                | Assigned|
| VolvoA35F No. 2      | 0                | Assigned|
| VolvoA35F No. 3      | 0                | Not assigned|
| VolvoA35F No. 4      | 1                | Assigned|

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**Table 2. Calculation results.**

| $k_{ij}^{EU}$ | 0.9 | 0.8 | 1 | 1 | 1 | 1 | 0.9 |
|---------------|-----|-----|---|---|---|---|-----|
| $k_{ij}^{IR}$ | 0.75| 1   |   |   |   |   | 0.5 |
| $G_i$         | 22  | 60  |   |   |   |   | 20  |
| $V_j$         | 14  | 15  | 9 | 10| 14| 15|     |
| $L_{ij}$      | 2   | 3   | 2 | 3 | 2 | 3 |     |

4. **Verification of solution feasibility**

The practical application of the proposed method of trucks assignment may be accompanied by verification of the feasibility of the solution found. It is more effective to use a two-level check of the technical capacity of production plans execution and possibility for introduction of the found trucks assignment.

Verification of the technical capacity to meet the production plans is carried out before the calculations and consists in the determination of the excavators productivity by formula (3).

The correctness of the found solutions can be verified by the statistical simulation model of the production process, built on the basis of queuing systems [1]. It is also possible to determine the service rate of trucks by each every excavator, relative and absolute capacity of excavators, their idle waiting for loading, etc.

Thus, the trucks service rate by the $j$-th excavator can be determined as follows:
\[ V_j = med \left\{ \frac{60}{\frac{T_{bj}^C}{G_j} \cdot \frac{G_j^K}{k_{bj} \cdot G_j^K}} \right\} \] (4)

where: \( T_{bj}^C \) – time of the excavation cycle for the \( b \)-th type of the rock mined by the \( j \)-th excavator, [s]; 
\( G_i \) – body volume of the \( i \)-th truck, [m\(^3\)];
\( G_j^K \) – bucket volume of the \( j \)-th excavator, [m\(^3\)];
\( k_{bj} \) – utilization rate of the \( j \)-th excavator bucket capacity when excavating the \( b \)-th type of the mined rock.

Trucks flow rate can be determined either by using output norms:

\[ \lambda_j = \frac{1}{580} \sum_{i=1}^{K_j^C} H_{bij}^X \] (5.1)

where: \( H_{bij}^X \) – number of hauls of the \( i \)-th truck per shift during transportation of the \( b \)-th type of the mined rock when using the \( j \)-th excavator, [pc/min];
\( K_j^C \) – number of trucks assigned to work with the \( j \)-th excavator.

Or by using the initial data on the vehicle operation:

\[ \lambda_j = med \left\{ \frac{1}{\frac{L_j \cdot 2}{V_j} \cdot \frac{60 + T_i^D}{60}} \right\} \] (5.2)

where: \( T_i^D \) – \( i \)-th truck unloading time, [min].

Relative capacity of the \( j \)-th excavator is defined by the formula:

\[ q_j = \frac{V_j}{\lambda_j + V_j} \] (6)

If \( q_j \) is less than 1, then the excavator will not have time to serve all coming for loading trucks – the trucks queue will be created causing the trucks downtime. If \( q_j \) is more than 1, the excavator will stand idle, waiting for the truck to be loaded. According to the calculated capacity of the excavator it is necessary to make organizational conclusions and decide whether to recalculate the trucks assignment with the modified initial conditions, or to adopt the obtained equipment assignment.
5. Conclusions
Use of the proposed method makes it possible to automate the process of trucks distribution between the excavators taking into account the optimization criterion of production plans fulfillment. Check of the specified optimization criterion on the model example successfully demonstrated the possibility of its practical application. As a result of the simulation the transport assignment was performed, allowing the technological transportation with minimal deviation from the production plan to be performed.

At the moment the implementation of the proposed method of vehicle assignment with the help of the software product “1C: ERP Mining Enterprise 2” is carried out, designed for automation of operational, managerial and regulated accounting and planning of mining enterprises.

References
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