UDC 622.27.012.3.001.63

Optimization of the Movement of Transfer Points on the Horizons in the Deep Iron Ore Open Pit

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The optimization problem statement of the movement dynamics of all the ore transfer points of the open pit in spatial, temporal and technological relationships that meet the general technical and economic requirements and conditions was formulated for the first time. The technique of solving this problem, which is based on decision theory, what allows to take into account informalizable and low formalizable mine engineering factors. As a consequence, the efficiency of the solutions obtained increases compared to traditional practice and mathematical methods.

Keywords: IRON ORE OPEN PITS, MINING TRANSPORT OPERATIONS, FLOWCHARTS, MOVEMENT OF TRANSFER POINTS, MOVEMENT OPTIMIZATION

Introduction

It is known that at the moment at most modern iron ore open pits in Ukraine mining operations achieved significant depth of development, while in the near future it is expected to continue the present sink rate, and in some cases even increase it. The growth of the depth of pits causes the inevitable increase in the distance transportation of mined rock. Besides, the growth of the pits depth causes pushback of the mining operations front on the horizons, what also leads to increasing transportation distances of mined rock. These factors determine the application of flowcharts of mining transport operations with the use of combined transport, particularly rail-road. Thus they try to reduce the cost of transporting the mined rock by the use of more cost-effective rail transport.

The distinguishing characteristic of such flowcharts is the presence of transfer points (TP). Creating a TP is associated with the costs for its construction and the cost of the edges cutback due to the necessary increase in the width of some work platforms. At the lower horizons under TP a pillar, which may include ore, is established. Over time, this pillar will restrain planned pushback of the mining operations front, what may be a cause of schedule adjustments or dismantling of TP. The TP dismantling is also accompanied by costs.

On the other hand, the TP can be used for rail transport for delivery the ore from the TP to the crushing-and-preparation plant and the overburden rocks to the dump pits. Besides, the TP warehouses increase the reliability of the flowcharts of mining transport operations and allow, if necessary, to perform separate or general storage and shipment of ore varieties, blending and/or homogenizing ore quality. Similarly, they allow, if necessary, to perform separate or general storage and reloading of the overburden rocks of various kinds.

During the open pit operation an increase in distances of mined rock delivery by automobile transport reduce the periodic movement of TP to the lower horizons (i.e. increase the distance of delivery for rail transport). In practice, the frequency analysis of the feasibility of changing the location of TP is usually equal to one year, due to the fact that major changes of transportation distance are caused by the schedule.

Thus, the efficiency of the flowchart of mining transport operations is determined by the TP location on the horizons (distribution of distances of transportation by road and rail) by the years of the open pit service.

The main known problems statements associated with determining the dynamics of the movement of TP on the horizons are previously considered by the authors in [1]. According to the results of the analysis it was concluded that a characteristic feature of these productions is their speciality. For example, in [2] rational distance between the horizons of concentration is defined, in [2, 3] - a transfer step of TP in the combined rail-road and road-conveyor transport, in [4] - the location of some TP on one horizon in the combined road-conveyor transport. None of these problems takes into account the spatial nature of the TP arrangement, the connection with the dynamics of mining operations (schedule), the possibility of the location of several TP at different levels.

Due to the above stated, the problem of the spatial optimization of the dynamics of movement of the ore transfer points on the horizons in the iron ore open pit is crucial.

Methodology

This problem should be solved at the design stage as well as at the operational stage of the open pit. At the design stage it can be solved in conjunction with the scheduling problem of mining operations, transportation routes and distribution of ore streams. The need to solve it on the stage of operation is caused by deviations of the actual mining operations from the project schedule and the actual development of the transport routes from the project.

In this paper we solve the problem for the operation stage of the open pit.

Obviously, the optimization of the dynamics of the distribution of ore transfer points in the iron ore open pit in both problems should be considered in a given interval of time (usually 5-8 years). Therefore, the main source of data for this problem is corrected schedule and the actual development of the routes for the first year of the specified time interval. For the next years, the development of the routes is pre-defined by estimates of the distances of transportation.

The main technological requirements are: providing the transportation and transshipment of volumes of the stope according to the schedule and the plan for its processing.

As follows from the above, at the beginning of the analysis of factors determining the economic efficiency of the flowchart of mining transport operations, the optimality criterion should take into account the dynamics of the TP distribution on the horizons (the dynamics of changes in transportation distances by road and rail) and the cost of construction, the edge cutback due to the necessary increase in the width of the work platforms and dismantling, as well as the expenditure for extraction-and-loading and transhipping operations by years of service.

That is why the suggested in the well-known papers [2-4], optimality criteria can not be used without modification, since they reflect the special nature of the problems and performances and they do not fully take into account these factors.

Mathematical model of the problem

Based on the above, there was suggested a criterion of optimality $З_t$ in the following form:

$$E_t = E_{ett} + \sum_{i=1}^{N_t} E_{it}^a \rightarrow \min , \qquad (1)$$

where E_{ett} – total expenditure for extraction-and-loading operations, ore transportation and transhipping operations in the *t*-th year

$$E_{ett} = \sum_{k=1}^{K}\sum_{i=1}^{N} c_{ki}x_{ki} + \sum_{i=1}^{N}\sum_{j=1}^{M} c_{ij}x_{ij} , \qquad (2)$$

here $$c_{ki} = c_{e-l} + c_a \cdot l_{ki} , \qquad (3)$$

$$c_{ij} = c_{tr} + c_r \cdot l_{ij} , \qquad (4)$$

where c_{e-l} – the cost price of extraction-and-loading operations, UAH/t; c_a – the cost price of ore transportation by automobile transport, UAH./t·km; l_{ki} – the transportation distance from the *k*-th ore-face to the *i*-th transfer point, km; c_{tr} – the cost price of the transhipping operations (discounting amortization), UAH/t; c_r – the cost price of ore transportation by rail, UAH/t·km; l_{ij} – the transportation distance from the *i*-th transfer point to the *j*-th receiving office, km; x_{ki} – mass of the ore, transported from the *k*-th ore-face to the *i*-th transfer point, t; x_{ij} – mass of the ore, transported from the *i*-th transfer point to the *j*-th receiving office, ; E_{it}^a – amortization of the expenditure connected with the construction of the *i*-th transfer point in the *t*-th year, UAH; N_t – the amount of the transfer points operating at the same time in the *t*-year; if $t_i^a \geq t_i^e$, then $E_{it}^a = \dfrac{E_i}{t_i^a}$ and

$$t_i = t_i + 1 ; \qquad (5)$$

$$\text{if} \quad t_i^a < t_i^e , \quad \text{then} \quad E_{it}^a = \frac{E_i}{t_i^a} = 0 , \qquad (6)$$

where E_i – the expenditure connected with the construction of the *i*-th transfer point, UAH; t_i^a – time of amortization of the expenditure connected with the construction of the i-th transfer point, years; t_i^e – estimated time of the i-th transfer point, years.

The suggested criteria (1) does not take into account the cost of the TP dismantling, as the value of this expenditure is much less than of the considered components.

It also does not include the costs of the edge cutback for the construction of the TP. First of all, instead of the edge cutback the working platforms of the upper faces are made narrower, and second of all, the edge cutback is always located in the final pit boundary, and the appropriate volume of the mined rock will still be removed. The difference in time of the associated costs should be considered by a reduction to a single time. But in short terms of the edge cutback (several years) it can be assumed that the effect of discounting would be compensated by taking into account inflation.

The method of finding solutions to the model (1) - (6). Based on the principle of providing an acceptable level of adequacy with minimal simplicity as a mathematical model was used the canonical system of constraints of the transportation problem with intermediate storages [5] and the optimality criterion (1). The method of solution - Newton's method.

Results and Discussion

In order to solve the optimization problem of the dynamics of movement the ore TP on the horizons in the iron ore open pit at a given time interval T there was suggested the idea of finding solutions by means of the above mentioned initial mathematical model for a variety of possible distribution of TP on the horizons for each t-th year, . From the obtained for each year set of optimal solutions corresponding to different variants of the location of TP on the horizons, the best one was chosen, corresponding to the smallest value of criterion (1). Thus the step by step procedure for obtaining the solution of the problem as a set of turn-based solutions, or a certain number of turn-ranked solutions was realized.

At first, the suggested procedure is contrary to the known principle of Bellman's optimality for multi-step problems, but it takes into account the after-effect by means of a mechanism of (5), (6) amortization of the expenditure for construction of TP and it is simpler than the multi-step solution of the problem with the integral criterion of optimality. The mathematical model and solution of this problem has not yet been received. A final answer about the effectiveness of the suggested procedure can only be obtained by comparing these two approaches.

Obviously, the mathematical model (1) - (6) takes into account only formalizable factors. Except these the efficiency of solutions obtained are influenced by informalizable factors, the impact of which can be quite substantial. It is known that the presence of such factors is a feature of most of the tasks of design and mine planning.

Perhaps, it is possible to take into account these factors to some extent by including the solutions formation of designing engineer as a decision maker (DM). In our case this means a transfer of the optimization problem of the dynamics of movement of the ore TP on the horizons of iron ore open pit from the class of mathematical programming problems to the class of problems of the decision theory [6]. The methodology of this research is considered the most appropriate for the solutions of the low formalizable problems by applying "objective" and "subjective" models [7].

In terms of content, such a transition provides priority of the designing engineer in making decisions on the results obtained for the "objective" (base) model, and raises the status of the analysis problems of the technological situation, data substantiation and analysis of the results of "objective" (basic) solutions. For this task, in particular, it means that the designing engineer, basing on his experience and qualifications, must substantiate the data for the base model (1) - (6), evaluating the possible dynamics of the volume of mined rock according to the schedule, the prospects for the development of transport communication, possible terms of the pillar establishment under the TP, the relationship of mining transport operations with the work of opening and preparation of the horizons, as well as other low formalizable factors and technological connections.

Based on the above for solving the optimization problem of the dynamics of movement of the ore transfer points on the horizons of iron ore open pit such method comprising the following steps was developed:

1) the designing engineer performs an analysis of mining transport situation at the beginning of each year of the given period T (the position of the mine sections according to the schedule, the possible zones of the TP location, the minimal and valid duration of their work, evaluation of the transportation distances);

2) preparation of data for the base model (1) - (6);

3) formation of the mathematical model (1) - (6) and serch of the solutions for each year;

4) formation of ranked set of conditionally optimal solutions of the problem;

5) analysis of the ranked set of conditionally optimal solutions of the problem and the choice of one solution.

Points 1), 2), 5) are performed by a designing engineer and points 2), 3) - in software.

Verification of the method of solving the problem

In order to confirm that the results of solving the problem correspond its formulation, based on the suggested method the optimization of the dynamics of movement the ore transfer points on the horizons in the iron ore ofen pit was carried out for typical mining conditions. The calculations were performed for a specific pit area with a characteristic arrangement of mine sections and transport connections.

Table 1. Presentation of results - the example of the optimal dynamics of moving ore TP

Horizons of the ore TP locations	Year							
	2009	2010	2011	2012	2013	2014	2015	2016
-75 m								
-90 m								
-120 m								
-180 m								
-255 m								

In accordance with the suggested methodology at the first stage of the real schedule the analysis of mining transport situation at the beginning of each year of the given period (8 years): the position of mine sections according to the schedule, the possible zones of the TP location, and the minimal and valid duration of their work, evaluation of the transportation distance.

At the second stage during preparing the data for the base model (1) - (6) the following average among the iron ore open pits cost price for the calculation of the optimality criterion (1) were accepted: 0.24 UAH/t•km - for rail, 0.80 UAH/t•km - for automobile transport, 0.30 UAH/t - for the extraction-and-loading and transshipment operations (excluding amortization). In the calculations there were considered three mine sections, fulfilled in steeply inclined layers and five TP, the current capacity of which allowed to move all the mined ore from the ore-face to the crushing-and-preparation plant, the minimal and valid term of the TP operation were accepted, respectively, 1 and 8 years. The amortization period of the excavator rail-road TP was assumed to be 3 years, and the expenditure for its construction 1.3 million UAH (the TP size: width 85 m and length 800 m). In this example, there were taken the same types of excavators working in the faces and on the overload. The step of the horizon overbreak was considered 15 m, and the step of TP movement within the horizon - 500 m.

On the basis of the prepared in such way original data at the third stage of the procedure in accordance with the formal language of the procedure of Microsoft Excel "Solver" there was established a mathematical model (1) - (6) and a search of solutions for each target year was performed.

Formation of the ranked majority of conditionally optimal solutions for each target year was not carried out, i.e. one optimal, solution was determined (fourth stage).

The results of solving the problem presented in the **Table 1**.

As the table shows, the solution of the optimization problem of moving the ore TP in the iron ore open pit identified five horizons (-75, -90, -120, -180 and -255 m), in which the TP should operate 8 years. Further movement of TP below the horizon -255 m was not considered because maximum depth of entry of rail transport in the practice of mining operations does not exceed 150-180 m. The obtained work period of the TP does not exceed 1-6 years, what corresponds to the accepted condition in the calculations. The optimal location of the TP within a horizon is determined by the number of optimal variant in the process of sorting out.

With the increase of the mining depth the movement of the TP in the deeper horizons is carried out (from -75 to -255 m) with variable steps, what corresponds to this process in practice. Thus, the analysis of the example of implementation the suggested method showed that the obtained results agree with the real dynamics of the process of iron ore mines.

In the course of the verification procedure there was performed an analysis of changes in the components of the optimality criterion (1) (**Figure 1**).

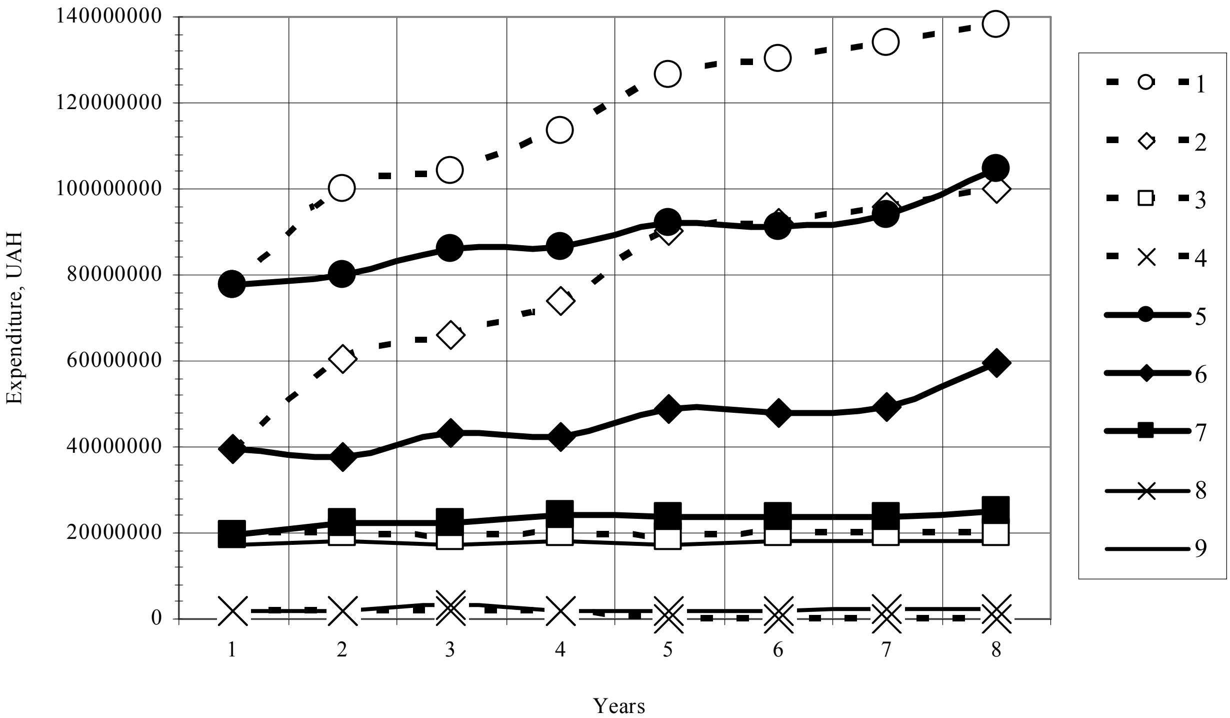

Figure 1. Example of changing the values of the optimality criterion (1) and the expenditure when optimizing the dynamics of the movement of ore TP by years of open pit use: 1, 2, 3, 4 - respectively, the total expenditure (the value of the optimality criterion (1)), the expenditure for the ore delivery by automobile transport to the TP, the expenditure for the ore delivery by rail to the crushing-and-preparation plant and the amortization in the fixed location of the TP, UAH; 5, 6, 7, 8 -,respectively, the total expenditure for the ore delivery by automobile transport to the TP (the value of the optimality criterion (1)), the expenditure for the ore delivery by rail to the crushing-and-preparation plant and the amortization charges for optimized movement of the TP, UAH, 9 - the total expenditure for loading operations and transshipment work in both cases, UAH.

Analysis of changing the components of the optimality criterion (1) was performed by comparing the two options: first option - all the TP are operating for the entire set period of 8 years without moving (permanently located at depths of -75, -90 and -180 m), second option - optimization of the dynamics of movement of the ore TP on the horizons in the iron ore open pit according to the suggested methodology.

As it can be seen from the graphs, the total expenditure for moving the ore in the second option is smaller than in the first one. Moreover, their rate of growth is lower than in the 1st option. In both cases, the value of the cost of transportation by automobile transport is the highest, compared to others, accounted in the task. The cost of shipping ore by rail to the crushing-and-preparation plant in the second option is increasing due to increasing transportation distances when moving the TP. Amortization charges for the construction of the TP are higher in the second option than in the first one in connection with the construction of new TP during their moving. The total expenditure for extraction-and-loading and transshipment operations in the first and second options is equal, since in this case the extraction-and-loading equipment of the same type was accepted.

Thus, the analysis of changes in the value of the optimality criterion (1) and its expenditure components while optimizing the dynamics of the movement of the ore TP by years of operation on the typical iron ore open pits example show their correspondence to the nature of their actual changes in practice.

Conclusions

The optimization problem statement of the movement dynamics of all the ore transfer points of the open pit in spatial, temporal and technological relationships that meet the general technical and economic requirements and conditions was formulated for the first time.

The technique of solving this problem, which is based not only on the theory of conventional mathematical optimization, but also on the decision theory, what allows to take into account informalizable and low formalizable mine engineering and other factors, the influence of which can be very substantial. As a consequence, the efficiency of the solutions obtained increases compared to traditional practice and mathematical methods.The verification of methods on a typical numerical example confirmed its efficiency.The prospect of further research is optimization of the movement dynamics of ore and overburden TP on the horizons in the iron ore open pit.

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* Published in Russian

** Published in Ukrainian

Received July 28, 2011

Оптимизация перемещения перегрузочных пунктов по горизонтам в железорудном глубоком карьере

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Впервые сформулирована постановка задачи оптимизации динамики перемещения всей совокупности рудных перегрузочных пунктов карьера в пространственной, временной и технологической взаимосвязи, удовлетворяющей общим технико-экономическим требованиям и условиям. Разработана методика решения данной задачи, которая основывается на теории принятия решений, что позволяет учесть неформализуемые и слабоформализуемые горнотехнические факторы. Как следствие, повышается эффективность получаемых решений и по сравнению с традиционными практическими, и математическими методами.