

EVALUATION AND OPTIMIZATION OF THE TECHNICAL AND ECONOMIC PERFORMANCE OF MINE TRANSPORTATION SYSTEMS UNDER CONDITIONS OF OPEN-PIT MINE DEEPENING

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Abstract

This article investigates the assessment and optimization of the technical and economic efficiency of mine transportation systems under conditions of open-pit mine deepening. As the depth of an open-pit mine increases, significant changes occur in haulage distance, transportation cycle time, fuel consumption, and operating costs. The study analyzes the relationships between pit depth and transportation costs and evaluates the key factors affecting the efficiency of mine haulage systems.

The results of calculations and analyses indicate that increasing pit depth leads to a reduction in haul truck productivity, while transportation costs increase substantially. To reduce transportation expenses and improve the overall efficiency of the mine transportation system, several optimization measures are proposed, including the implementation of optimal haulage schemes, the use of high-capacity haul trucks, the improvement of in-pit road parameters, and the adoption of alternative transportation technologies.

The obtained results have practical significance for the design, reconstruction, and operation of open-pit mines, providing a basis for selecting economically efficient transportation systems and enhancing the overall efficiency of mining operations.

Keywords: open-pit mining, pit deepening, mine transportation system, haul trucks, transportation costs, technical and economic efficiency, optimization, mining engineering.

Introduction

At present, the extraction of mineral resources by the open-pit mining method remains one of the leading sectors of the global mining industry. The main advantages of open-pit mining include high production capacity, increased labor productivity, and relatively low mining costs. However, as mineral reserves are progressively extracted, the continuous deepening of open-pit mines significantly affects the technical and economic performance of mining operations.

An increase in pit depth results in longer haulage distances for ore and waste rock transportation, extended operating cycles of haulage equipment, and higher fuel and lubricant consumption. Consequently, the efficiency of the mine transportation system decreases, while

mining costs increase. In deep open-pit mines, transportation expenses often represent the largest share of total production costs and may significantly influence the final cost of mineral products. Therefore, assessing and optimizing the efficiency of mine transportation systems under conditions of pit deepening is of great importance for maintaining the competitiveness and economic sustainability of mining enterprises.

In recent years, numerous studies have been devoted to improving haulage operations in open-pit mines, increasing the productivity of haul trucks, reducing transportation costs, and optimizing haulage routes. However, most existing studies focus on individual technological parameters, while the comprehensive assessment of the impact of pit deepening on the technical and economic efficiency of mine transportation systems remains insufficiently investigated.

The aim of this research is to evaluate the technical and economic efficiency of mine transportation systems under conditions of open-pit mine deepening and to develop optimal technological solutions aimed at reducing transportation costs and improving overall production efficiency.

To achieve this objective, the following tasks were formulated:

- To analyze the influence of pit depth on the performance indicators of mine transportation systems;
- To determine the patterns of change in haulage distance, transportation cycle time, and fuel consumption;
- To assess the impact of pit deepening on transportation costs;
- To evaluate the technical and economic efficiency of mine transportation systems;
- To develop optimization measures for reducing transportation costs and improving system efficiency.

The research object is the mine transportation system of open-pit mining operations. The research subject is the changes in the technical and economic indicators of transportation processes resulting from increasing pit depth.

The scientific novelty of the study lies in the comprehensive assessment of the technical and economic efficiency of mine transportation systems under conditions of pit deepening and in the development of effective optimization solutions based on the identified patterns of transportation cost variation.

Literature Review

Improving the efficiency of mine transportation systems and reducing transportation costs in open-pit mining are among the most important scientific and practical challenges in the mining industry. As pit depth increases, haulage distances become longer, transportation cycle times increase, and operating costs rise, directly affecting the economic performance of mining enterprises. Consequently, this issue has been extensively studied by numerous researchers.

In their studies on mineral resource estimation and mine planning, Michael E. Rossi and Clayton V. Deutsch identified mine geometric parameters and mining technologies as key factors influencing economic efficiency. The authors noted that production costs increase with

greater mining depth; however, the patterns and mechanisms of transportation cost variation were not analyzed in detail.

Research conducted by William Hustrulid and Mark Kuchta focused on the technological characteristics of truck haulage systems in open-pit mines, including haul truck productivity and haul road parameters. Their studies demonstrated that the productivity of haulage equipment decreases as haulage distance and road gradient increase. Nevertheless, the economic consequences associated with pit deepening were not comprehensively evaluated.

In his works on mining engineering, Howard L. Hartman emphasized that mine transportation is one of the most significant components of mining production costs. According to the author, transportation expenses in deep open-pit mines may constitute a substantial share of total mining costs. At the same time, the selection of optimal transportation schemes should be examined individually for each mine, taking into account its geological and technological conditions.

The SME Mining Engineering Handbook provides comprehensive information on the technical and economic characteristics of truck, rail, and conveyor transportation systems used in open-pit mining. According to this source, pit depth, production capacity, and operating costs are among the primary criteria for selecting an appropriate transportation method. However, issues related to the mathematical modeling of transportation cost variations caused by pit deepening have not been sufficiently addressed.

In recent years, several researchers have focused on the optimization of mine transportation systems. These studies have examined haul truck route optimization, fuel consumption reduction, rational placement of loading and unloading points, and digital modeling of transportation processes. The findings indicate significant opportunities for reducing transportation costs and improving the utilization efficiency of mining equipment.

The literature review demonstrates that although numerous studies have investigated individual technical or economic aspects of mine transportation systems, the comprehensive assessment of the interrelationships among transportation costs, haulage distance, fuel consumption, and haul truck productivity under conditions of increasing pit depth remains insufficiently explored. Therefore, further research aimed at evaluating and optimizing the technical and economic efficiency of mine transportation systems in deep open-pit mines is both relevant and necessary.

In this study, the patterns of transportation cost variation associated with pit deepening are analyzed, and technological as well as organizational solutions aimed at improving the efficiency of mine transportation systems are proposed.

Research Methodology

In this study, changes in the efficiency of mine transportation systems resulting from open-pit mine deepening were evaluated using an economic-mathematical modeling approach. The primary objective of the research was to determine the impact of pit depth on transportation costs and to identify optimal transportation parameters that ensure minimum operating costs. Open-pit mines utilizing truck haulage systems were selected as the research object. The calculations considered pit depths ranging from 100 to 500 m. The effects of increasing pit

depth on haulage road length, transportation cycle time, and operating costs of haulage equipment were analyzed. The study employed systems analysis, techno-economic assessment, statistical data processing, and regression modeling methods. Transportation costs were assumed to consist of fuel consumption, maintenance and repair expenses, depreciation costs, and labor expenditures.

The relationship between pit depth and transportation costs was described using a mathematical model. In the model, pit depth (H) was considered the independent variable, while the transportation cost per tonne of rock mass (Ct) was treated as the dependent variable. Based on the calculation results, a regression equation was developed to determine the pattern of transportation cost variation with increasing pit depth.

The efficiency of the transportation system was evaluated using the following indicators:

- Transportation cost per tonne of rock mass;
- Productivity of haulage equipment;
- Fuel consumption;
- Transportation cycle time;
- Share of transportation costs in total mining costs.

The obtained data were processed using Microsoft Excel and statistical analysis software to calculate the corresponding economic efficiency indicators. Based on the results, practical recommendations were developed to reduce transportation costs and improve the efficiency of mine transportation systems under conditions of increasing pit depth.

Mathematical Model

The transportation cost dependence on pit depth can be expressed by the following regression relationship:

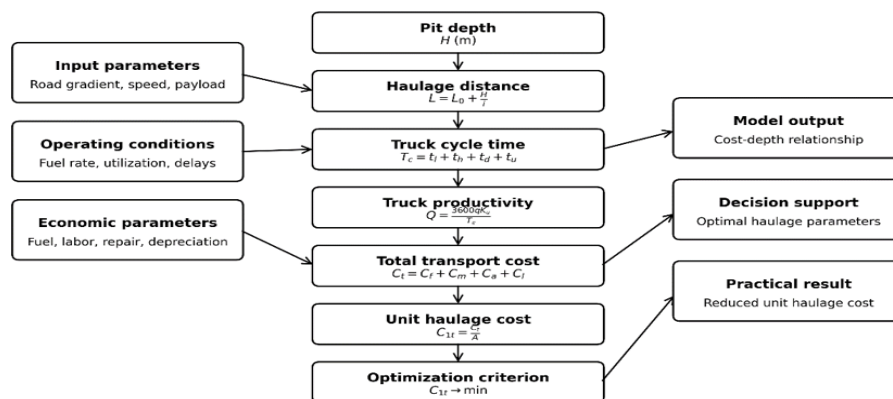
$$C_t = a + bH$$

where:

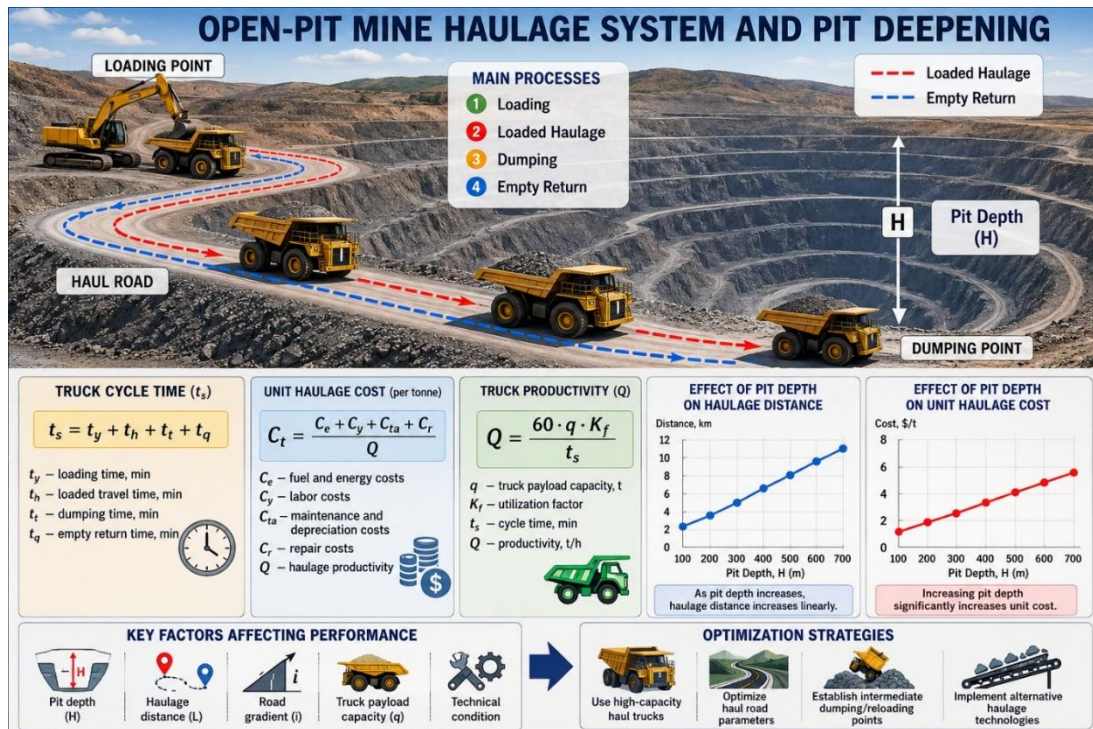
- Ct – transportation cost per tonne of rock mass (USD/t or UZS/t);
- H – pit depth, m;
- a, b – regression coefficients determined from the calculation results.

This model makes it possible to estimate the increase in transportation costs as mining depth grows and to determine economically justified transportation solutions for deep open-pit mines.

Figure 1. Methodological framework for assessing and optimizing mine haulage efficiency



Notation: H – pit depth; L – haulage distance; Tc – cycle time; Q – truck productivity; Ct – total transport cost; C1t – unit haulage cost; A – annual transported rock mass.



Results and Discussion

During the study, the influence of pit depth on the technical and economic performance of mine transportation systems was evaluated using economic-mathematical modeling. Calculations were performed for deep open-pit mines of the Muruntau type within a pit depth range of 300–700 m.

The analysis showed that increasing pit depth leads to a significant increase in haulage road length and transportation cycle time. As the pit becomes deeper, both loaded and empty return haulage distances increase, resulting in a reduction in the number of haul truck cycles completed per shift. Consequently, the overall productivity of the transportation system decreases.

According to the calculated data presented in Table 1, when pit depth increased from 300 m to 700 m, the haulage distance increased from 4.8 km to 10.4 km. During the same period, the transportation cycle time increased from 26 minutes to 50 minutes. As a result, haul truck productivity decreased from 510 t/h to 262 t/h, representing an overall productivity reduction of 48.6%.

The analysis of transportation costs indicated a continuous increase in the cost of transporting one tonne of rock mass as pit depth increased. At a pit depth of 300 m, the transportation cost was estimated at 2.45 USD/t, whereas at a depth of 700 m, it reached 5.14 USD/t. This represents an increase of more than 2.1 times. Such growth can be explained by longer haulage distances, increased fuel consumption, and higher operating costs of transportation equipment. The relationship between pit depth and transportation costs was evaluated using regression analysis. The results revealed a strong positive correlation between these variables. The obtained regression equation is presented below:

$$C_t = 0.43 + 0.0067H$$

where:

- C_t – transportation cost (USD/t);
- H – pit depth (m).

The coefficient of determination was found to be $R^2 = 0.98$, indicating that approximately 98% of the variation in transportation costs can be explained by changes in pit depth. This result confirms the high reliability and predictive capability of the developed model.

Graphical analysis showed that the growth rate of transportation costs becomes more pronounced at depths exceeding 500 m. This finding suggests a gradual decline in the economic efficiency of truck haulage systems in deep mining horizons. Therefore, as pit depth increases, the modernization of transportation systems and the implementation of advanced technological solutions become increasingly necessary.

Based on the research results, the following measures are recommended for reducing transportation costs in deep open-pit mines of the Muruntau type:

- Utilization of high-capacity haul trucks;
- Optimization of haul road longitudinal gradients;
- Improvement of dispatching and fleet management systems;
- Implementation of combined truck–conveyor transportation systems.

Thus, the conducted research confirms that increasing pit depth has a significant impact on the technical and economic efficiency of mine transportation systems. The obtained results may serve as a scientific and practical basis for forecasting transportation costs, selecting optimal haulage parameters, and improving the overall economic efficiency of deep open-pit mining operations.

Table 1. Influence of pit depth on haulage system performance
(Muruntau-type open pit model)

Pit depth, m	Haulage distance, km	Cycle time, min	Productivity, t/h	Transport cost, \$/t
300.0	4.8	26.0	510.0	2.45
400.0	6.1	31.0	430.0	2.98
500.0	7.5	37.0	360.0	3.62
600.0	8.9	43.0	305.0	4.31
700.0	10.4	50.0	262.0	5.14

Conclusion

In this study, the impact of open-pit mine deepening on the technical and economic performance of mine transportation systems was evaluated using an economic-mathematical modeling approach. The research results demonstrated that increasing pit depth leads to longer haulage distances, extended transportation cycle times, and higher operating costs.

According to the calculation results, an increase in pit depth from 300 m to 700 m caused the haulage distance to rise from 4.8 km to 10.4 km, the transportation cycle time to increase from 26 minutes to 50 minutes, and haul truck productivity to decrease from 510 t/h to 262 t/h. At the same time, the transportation cost per tonne of rock mass increased from 2.45 USD/t to 5.14 USD/t.

Regression analysis revealed a strong relationship between pit depth and transportation costs. The coefficient of determination for the developed model was $R^2 = 0.98$, confirming its high accuracy and reliability for predicting transportation cost variations under different mining depth conditions.

The study findings indicate that transportation costs become a major component of total mining costs in deep open-pit operations. In particular, a significant acceleration in transportation cost growth was observed at depths exceeding 500 m. This highlights the necessity of transportation system optimization when developing long-term mine planning and operational strategies.

Based on the obtained results, the main directions for reducing transportation costs in deep open-pit mines of the Muruntau type include:

- The use of high-capacity haul trucks;
- Improvement of haul road design parameters;
- Implementation of digital dispatching and fleet management systems;
- Application of combined truck–conveyor transportation technologies.

The results of this research may serve as a scientific and practical basis for determining optimal transportation system parameters, forecasting transportation costs, and improving the overall economic efficiency of deep open-pit mining operations during both mine design and operational stages.

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